BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 38 (1960), pp. 497-544

31. *Fundamental Research for Predicting Volcanic Eruptions.* *(Part 1)*

Earthquakes and Crustal Deformations originating from Volcanic Activities.

By Takeshi MINAKAMI,

Earthquake Research Institute.

(Read* Sept. 19, 1944; May 18, 1948; Dec. 23, 1958; Feb. 23, 1960.—Received Sept. 30, 1960.)

Contents

---

* This paper was read in its entire on twenty occasions at the monthly meetings E. R. I..

1. Introduction

Studies of volcanoes and volcanic phenomena are related to geophysics, geology, petrology, and geochemistry. Studies of volcanoes are now carried on from the standpoint of each of the associated sciences cited above and synthetic studies of volcanoes based on the above sciences are also being promoted. Even when a study is conducted from a purely geophysical point of view, considering the large physical quantities contained in volcanic phenomena, the study of volcanic phenomena may well have a special relation to seismology, geodesy, geomagnetism, and geothermy. In this paper which deals with earthquakes and crustal deformations, such problems as the difference between crustal deformations accompanying general earthquakes and those accompanying general major earthquakes, the relation between earthquakes and volcanic activity, and other problems will be discussed.

Volcanic activity, interpreted in a narrow sense, was formerly limited to the extrusion of magma in the form of molten lava and lava fragments on the ground surface, i. e. the phenomenon of volcanic eruption. At present, however, the series of phenomena including the production of magma at a depth of several tens of kilometers, the ascending of the magma, and its extrusion to the surface of the ground is regarded as volcanic activity and the series of subsequent phenomena has also become an object of study for volcanology.

Nowadays many volcanologists[1] hold the following view. Magma is produced at a depth of 50 km to 300 km under the earth's surface. The part in the earth melts or partially melts as a result of the excessive supply of heat as compared with other parts, and, on account of this the volume is increased. Consequently, because of the pressure exerted on the surroundings a strain is caused in the earth's crust. When the strain exceeds a certain limit, cracks are produced in the crust and the area is disintegrated, resulting in the occurrence of an earthquake. That is, the strain occurring in the crust is released in the form of seismic waves. On the other hand, magma intruding into the cracks formed in the crust sometimes ascends to the surface and is extruded. Considering the process of the production and ascent of magma, and in particular, the origin of magma, it is considered impossible to distinguish definitely general earthquake phenomena from volcanic phenomena. Probably the only difference may be that the

1) H. KUNO, *Bull. Volcanol.* [ii], **20** (1958), 37.

most important problem of earthquake phenomena is the propagation of seismic waves while that of volcanic phenomena is the rise and extrusion of magma, i. e., the motion of the substance itself.

If volcanic phenomena be regarded as phenomena in which magma ascends from a depth of several tens of kilometers and at last is extruded on the ground-surface, what are the phenomena caused in connexion with the above phenomena, in the earth's crust? Some-

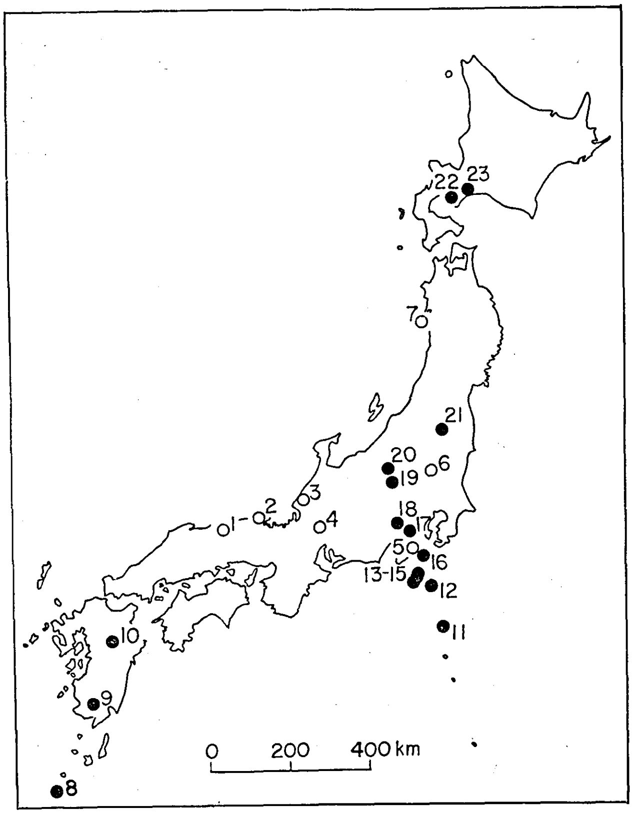


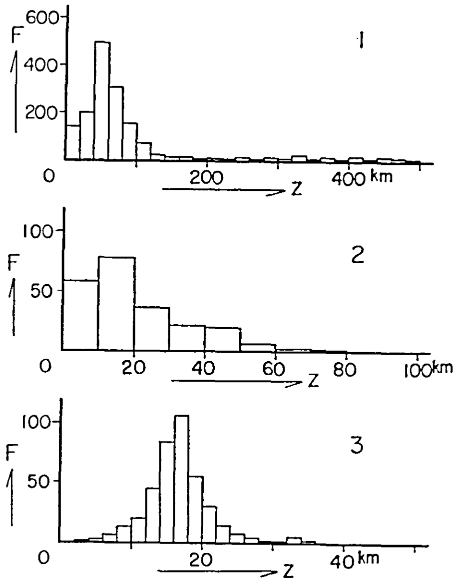
Fig. 1. Geographical position of the volcanoes (closed circle) and the earthquakes (opened circle) cited in this report.

1. Tottori earthq.,	2. Tango earthq.,	3. Hukui earthq.,
4. Noobi earthq.,	5. Ito earthq.,	6. Imaiti earthq.,
7. Oga earthq.,	8. Suwanose-sima,	9. Sakura-zima,
10. Aso,	11. Hatizyo-sima,	12. Miyake-sima.,
13. Kozu-sima,	14. Nii-sima,	15. Sikine-sima,
16. Oo-sima,	17. Hakone,	18. Huzi,
19. Asama,	20. Kusatu-sirane,	21. Bandai,
22. Usu,	23. Tarumai.	

times magma will ascend to the surface and cause a volcanic eruption, while at other times it will fail to reach the surface and will remain in the interior of the crust. From earthquake phenomena associated with the above-mentioned various types of volcanic activity, may it not be possible to obtain an accurate knowledge of volcanic activity? May it not be possible to grasp some characteristics of crustal deformations? From such aspects the problem will be discussed in this paper.

2. On the depth at which earthquakes take place

First of all, in order to investigate the depth from which general earthquakes or the so-called tectonic earthquakes originate, the writer investigated the frequency distribution of the hypocenters of the major



Fgi. 2. Frequency distribution (F) with respect to hypocentral depth (Z) for various earthquakes.
(1) General earthquakes in and near Japan.
(2) Earthquakes in Hawaii including Kilauea and Mauna-loa.
(3) Tango after-shock.

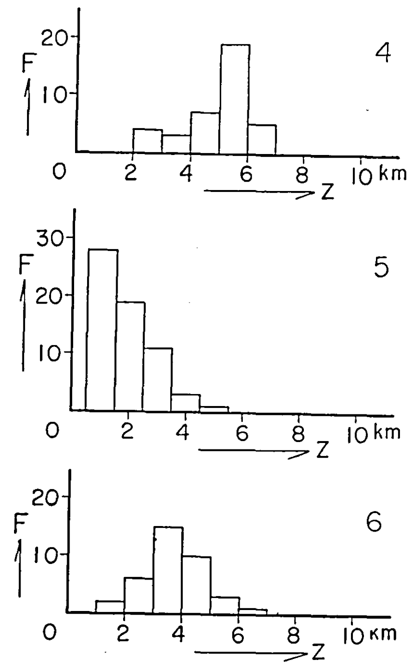


Fig. 3. Frequency distribution (F) with respect to hypocentral depth (Z) for various earthquakes.
(4) The 1930 Ito earthquakes.
(5) The 1959-1960 Hakone earthquake swarm.
(6) The A-type earthquakes which accompanied the 1944 Usu eruption.

earthquakes which have occurred in Japan and its vicinity. The major earthquakes mentioned in this paper are those over 5 in magnitude, and only those which took place from 1951 to 1958 are here considered. The hypocenters were determined by the Seismological Section, Japan Meteorological Agency[2].

The frequency distribution of the hypocenters of the above earthquakes is represented in Fig. 2 (1), which was prepared on the basis of the depths of the hypocenters disregarding the positions of the epicenters. This figure indicates the frequency of the hypocenters at depths of every 20 km, from 20 km to under 40 km, from 40 km to under 60 km and so on.

As seen in Fig. 2 (1), the maximum frequency is at depths of 40 km to 60 km. As the Mohorovičić discontinuity is supposed to lie at depths of 20 km–40 km in Japan and its vicinity, Fig. 1 shows that more than two-thirds of these earthquakes occurred under the surface of discontinuity. Moreover, it is noticeable that the hypocenters of destructive earthquakes were located in somewhat shallow parts as compared with the depths of maximum frequency (40 km–60 km).

It is rather common for destructive earthquakes to be followed by after-shocks. The frequency distribution of the focal depths of after-shocks will be here discussed. The hypocenters of the after-shocks which followed the Tango earthquake of 1927 were studied by N. Nasu[3]. In the course of his investigations unprecedentely numerous hypocenters of the after-shocks were determined. Fig. 2 (2) represents the frequency of the focal depths of after-shocks at every 2 km. According to this diagram, the maximum frequency is found at depths of under 16 km or 18 km, and shows the Gausian distribution at the same depth to be the centre. Consequently the depth of 17 km which is the maximum frequency is the mean depth of the after-shocks of the Tango earthquake and almost no after-shock originated from areas shallower than 3 km and deeper than 35 km. A characteristic of the after-shocks that followed the Tango earthquake is that in comparing the after-shocks of the several major earthquakes in Japan which have hitherto been investigated its hypocenters were the deepest.

Other examples of the frequency distribution of the focal depths of after-shocks will be given below. The after-shocks of the Oga earthquake[4] of 1939 show a distribution similar to a Gausian distribution with

2) *Japan Meteor. Agency, Seismol. Bull.*, 1951–1956.
3) N. Nasu, *Bull. Earthq. Res. Inst.*, **6** (1929), 245; **7** (1929), 133.
4) T. Hagiwara, *Bull. Earthq. Res. Inst.*, **17** (1939), 627.

13 km as the central point of evaluation, the Tottori earthquake[5] of 1943 9 km, the Hukui earthquake[6] of 1948 7 km, the Imaiti earthquake[7] of 1949 4 km respectively. The hypocenters of those after-shocks of which the depths were determined are fewer in number compared with the Tango earthquake, hence a Gausian distribution as seen in Fig. 2 is not clearly manifested.

Next, the frequency distribution of the focal depths of earthquakes originating from volcanoes will be discussed. As will be described later, earthquakes originating from volcanoes, according to the nature of the earthquake-motions and the relation of the earthquakes to volcanic eruptions, can be classified as follows: A-type earthquakes originating from somewhat greater depths in the volcano, or, from a depth of 1 km to 10 km (sometimes 20 km); B-type earthquakes originating in swarms from a shallow depth near the crater; explosion earthquakes accompanying explosive eruptions of the Vulcanian type; and volcanic micro-tremors accompanying Strombolian eruptions.

Of these four kinds of earthquakes originating from volcanoes the A-type earthquakes are almost similar in the nature of their earthquake-motions to the after-shocks of the great earthquake set down

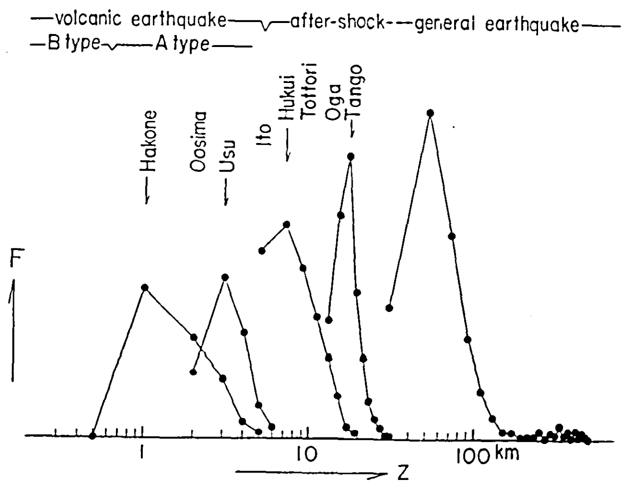


Fig. 4. Comparison of frequency distribution of hypocentral depth for general earthquake, after-shock and volcanic earthquake of the A and B types.

5) S. OMOTE, *Bull. Earthq. Res. Inst.*, **22** (1944), 223.
6) S. OMOTE, *The Hukui Earthquake of June* 28, 1948, (1950), 393.
7) T. HAGIWARA and K. KASAHARA, *Bull. Earthq. Res. Inst.*, **28** (1950), 393.

as the example in Fig. 28. Further examples are here given concerning the frequency distribution of the focal depths of A-type volcanic earthquakes. In the famous volcanic activity which gave birth to Syowa-Sinzan at the eastern foot of Usu-san[8], Hokkaido, from 1943 to 1945 the A-type earthquakes originated from depths of 1 km to 7 km with a maximum frequency of 3 km. The focal depths of the swarm earthquake which originated at Mihara-yama, Oo-sima[9], in 1938, indicate a distribution almost similar to that of the above-mentioned Usu-san.

The earthquake swarm that occurred in the Hakone volcano[10] quite recently (from September 1959 to March 1960) originated from Kamiyama, one of the central cones of the Hakone volcano, and its surroundings, and the earthquakes were very shallow, most of them being distributed at depths of 1 km to 2 km. Hence, these earthquakes should be regarded as A-type volcanic earthquakes.

Summarizing the above facts, the frequency distribution of the focal depths of tectonic earthquakes shallower than 100 km manifests a Gausian distribution with 60 km as the maximum frequency, and as to the frequency distribution of the focal depths of after-shocks, though differing with each major earthquake, the mean depth of 17 km for the Tango earthquake is the deepest, and the depth decreases in the order of the Oga, the Tottori, the Hukui, and the Imaiti earthquakes. The A-type volcanic earthquakes show a maximum frequency in still shallower parts. It is noteworthy that the focal depths of the Ito earthquake swarm[11] of 1930 were distributed with the centre at about 5 km. The focal depths were shallower than in general for the after-shocks of major earthquakes and deeper than volcanic earthquakes of the A-type, or in other words, the depths were between the above two cases. Many investigators incline to regard the Ito earthquake swarm as a kind of igneous activity in which magma under the ground intruded to a certain depth of the earth's crust. They regard the Ito earthquake swarm as an intermediate phenomena between general earthquake phenomena and volcanic phenomena. If the magma had ascended further, the magma would have been extruded and would have formed a volcano such as Syowa-Sinzan[12] or Parícutin[13].

8) T. MINAKAMI, *Bull. Earthq. Res., Inst.* **25** (1947), 71.
9) R. TAKAHASI and T. NAGATA, *Zisin,* **11** (1939), 161.
10) T. MINAKAMI, *Report on the 1959-1960 Earthquake Swarm of Volcano Hakone,* (1960), 1.
11) N. NASU, F. KISHINOUYE and T. KODAIRA, *Bull. Earthq. Res. Inst.,* **9** (1931), 22.
12) T. MINAKAMI, T. ISHIKAWA and K. YAGI, *Bull. Volcanol.* [ii], **11** (1951), 45.
13) J. GONZALEZ and W. F. FOSHAG, *Smithonian Report,* (1946), 223.

Volcanic earthquakes of the B-type[14)15)] originate in swarms from parts shallower than those of the A-type of active volcanoes. The focal depths of explosion earthquakes and volcanic microtremors are almost the same as those of volcanic earthquakes of the B-type. As far as is yet known, the focal depth of these earthquakes is shallower than 1 km from the floor of the craters, but the frequency distribution within 1 km in depth has not yet been clarified. This is a problem left to future study.

3. Characteristics of crustal deformations accompanying volcanic activity

Of the phenomena that accompany volcanic activity, crustal deformations are the most remarkable. Crustal deformations though only sometimes accompanying major earthquakes are also extremely remarkable.

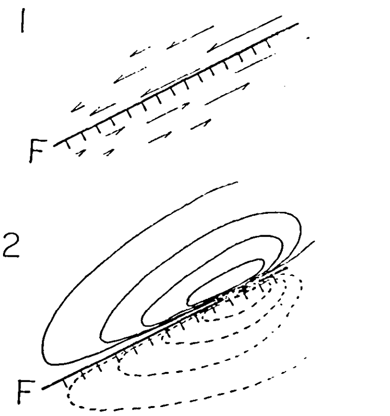


Fig. 5. Schematic illustration of the crustal deformation caused by major earthquake which produced earthquake fault (F).
1 : horizontal displacement,
2 : vertical displacement.

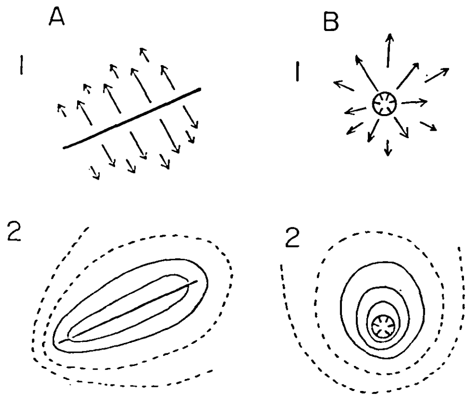


Fig. 6. Schematic illustration of the crustal deformations caused by volcanic eruption.
A : fissure eruption, B : central eruption,
1 : horizontal displacement 2 : vertical displacement
full line: upheaved area, dotted line: subsided area.

Now, in a comparison of the crustal deformations accompanying both phenomena, the characteristics of crustal deformations associated with volcanic activity will be mentioned.

14) T. MINAKAMI, S. SAKUMA, K. MOGI, and S. HIRAGA, *Bull. Volcanol. Soc. Japan*, [ii], **4** (1960), 133.

15) T. MINAKAMI, K. MOGI, S. HIRAGA and T. MIYAZAKI, *Bull. Volcanol. Soc. Japan*, [ii], **2** (1957), 77.

Resulting from major earthquakes, faults frequently appear on the earth's surface. The fault which appeared in the cases of the Californian[16], the Nōbi[17], The Tango[18], the North Izu[19], the Tottori[20], and the Hukui[21] earthquakes are well known. In each fault, the horizontal displacement is almost parallel with the fault plane, namely, with the fault line acting as the boundary and the directions of the displacement at the regions which are divided by the fault are reversed. As to the vertical displacement, in most cases the area is divided into two segments of upheaval and subsidence with the fault line as the boundary, but sometimes the area is divided into four quadrants by a straight line at right angles with the fault line. The first and the third quadrants represent upheaval, while the second and the fourth quadrants represent subsidence. Crustal deformations of such types are observed most commonly in the cases of major earthquakes.

Sometimes, accompanying volcanic activity, faultlike fissures are produced in the volcanic formation and lava is extruded from the fissures. This phenomenon was observed in the cases of the eruption of Sakurazima[22] in 1914 and that of Miyake-sima[23] in 1940. Crustal deformations in volcanoes in such cases are the same as in the case of earthquake faults with respect to reverse horizontal deformations with the faultlike fissures as the boundary, but the deformations differ remarkably from those associated with earthquake faults with respect to deformations in a right-angle direction to the faultlike fissure lines. That is to say, in the case of volcanoes, deformation manifests itself toward the horizontal direction so as to enlarge the faultlike fissures, while, on the contrary, in the case of tectonic earthquakes, deformation occurs so as to slip parallel to and toward the opposite direction along the fault plane. Hence, the direction of the former differs as much as 90° from that of the latter. Moreover, in the case where an eruption has a crater as the centre, namely, a central eruption, horizontal deformations radiate from the crater toward the outside. This was observed distinctly in the

16) A. C. LAWSON etc., *State. Earthq. Inv. Comm.*, (1909).

17) B. KOTO. *Jour. Coll. Sci., Tokyo Imp. Univ.*, **5** (1892). F. OMORI, *Bull. Imp. Inv. Comm.*, **1** (1907).

18) C. TSUBOI, *Bull. Earthq. Res. Inst.*, **8** (1930), 153.

19) Y. OTUKA, *Bull. Earthq. Res. Inst.*, **1** (1933) 530.

20) H. TSUYA, *Bull. Earthq. Res. Inst.*, **22** (1944), 1.

21) N. NASU, *Bull. Eatrhq. Res. Inst.*, **27** (1949), 27.

22) F. OMORI, *Bull. Imp. Earthq. Inv. Comm.*, **8** (1914-1922), 1. K. MOGI, *Bull. Earthq. Res. Inst.*, **36** (1957), 99.

23) S. OMOTE, *Bull. Earthq. Res. Inst.*, **20** (1942), 127.

course of the growth of Syowa-Sinzan, the Usu Volcano.

The most common vertical deformations accompanying volcanic activity are the dome-like upheavals having the crater as the centre and a subsidence of the surroundings of the upheaved area. Consequently, in volcanoes which display central eruptions, an almost circular area with the upheaved part as the centre is elevated (e. g., Usu-san[24] and Asama-yama[25]), and, in volcanoes which erupt from a faultlike fissure, and oval area having the fissure line as the longer axis is elevated (e. g., the eruption of Sakura-zima[26] in 1914). In both cases, subsidence occurs outside these upheaved areas. Hence, vertical deformations accompanying volcanic activity differ strikingly from those associated with major earthquakes accompanied by faults with respect to vertical crustal deformations as well.

As seen in the crustal deformations that accompanied the eruptions of Usu-san and Sakura-zima, sometimes the deformation is reversed after the eruption, and though the velocity is strikingly slow as compared with the deformation that directly accompanied the eruption, deformation in the reverse sense lasts. In most cases, however, the degree of recovery falls far short of the initial deformation. For example, after the great eruption of Sakura-zima of 1914 the Aira caldera (the inside) subsided to a great extent together with the skirt of Sakura-zima, and in the reverse process of deformation, i. e., continuous change lasted for more than 30 years after that. This is the most remarkable example of recovery by deformation, but still it fell short of a perfect recovery to the state of pre-eruption. Therefore it may be said that even now the deformation in recent eruptions is progressing toward a development of a subsidence topography in the caldera. Crustal deformations that accompanied major earthquakes somewhat resemble those of volcanic eruptions in that the process of deformations reversed after the outburst, but recovery in the former is not so conspicuous as in the latter.

It may be necessary to mention the magnitude of crustal deformations accompanying earthquakes and volcanic eruptions, i. e., the dimensions of an area which underwent changes and the velocity of those changes. The crustal deformations accompanying volcanic activity are generally limited to the vicinity of the volcano and the dimension is also smaller as compared with those accompanying major earthquakes.

24) T. MINAKAMI, T. ISHIKAWA and K. YAGI, *loc. cit.*, *15*).
25) T. MINAKAMI, *Bull. Volcanol.* [ii], **18** (1958), 39.
26) F. OMORI. *loc. cit.*, 27).

As seen in the case of the eruption of Syowa-Sinzan, however, sometimes the local deformation with its centre at the crater manifests upheaval as far as more than 100 m. Therefore, crustal deformations accompanying volcanic activity sometimes are more remarkable in this respect than those accompanying earthquakes. In volcanic eruptions and earthquake swarms (for example, the Ito earthquake swarm[27]), the phenomena last long and crustal deformations accompanying these phenomena are also prolonged. On the contrary, in the case of crustal deformations accompanying major earthquakes, the crustal deformations come to an end within a short time, namely, from several to ten minutes, before the earthquake vibrations of the principal shock are over. Consequently, with regard to crustal deformations accompanying volcanic activities and earthquake swarms, surveys can be carried out over again, and the development of volcanic activity and earthquake swarms and the progress of crustal deformations with respect to these phenomena can be studied in detail. Some examples will be given in the following paragraph.

4. Crustal deformations that accompanied the development of Syowa-Sinzan, from the Usu volcano

The activity of Syowa-Sinzan which began in December 1943 was really conspicuous, and, in the course of about two years ending in October 1945, earthquakes, the upheaval of the ground, the formation of new craters, the extrusion of lava and the birth of a new volcano at the eastern foot of Usu-san occurred in succession. In the course of this period precise levelling was carried out along a route crossing the rising area. This was really an epochmaking investigation, and, as a result, crustal deformations were observed in detail from the beginning of the volcanic activity to the end. Above all, it is noteworthy that the rising area was confined with the approach of lava to the level of the earth's surface. That is, the rising area that was about 2 km in radius at first gradually diminished, and it was about 1 km in radius at the time when the lava began to appear on the earth's surface. The process of diminution of the rising area is represented in Fig. 8, in which the upheaval in the three stages, i. e., the beginning of volcanic activity, the stage in which phreatic explosion occurred frequently and the stage in which a lava dome developed on the ground surface, is represented with the upheaval velocity (cm/day). By this diagram it may be understood

27) C. Tsuboi, *Jap. Jour., Astr. and Geoph.* **10** (1932-1933), 93.

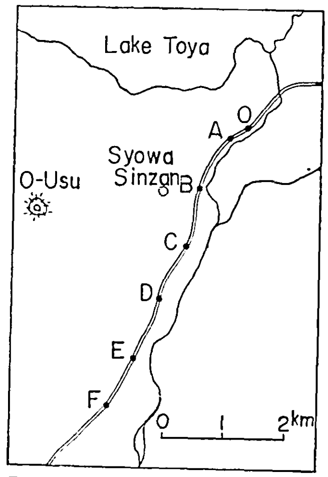


Fig. 7. Locality of levelling route near the newly formed mountain, Syowa-sinzan.

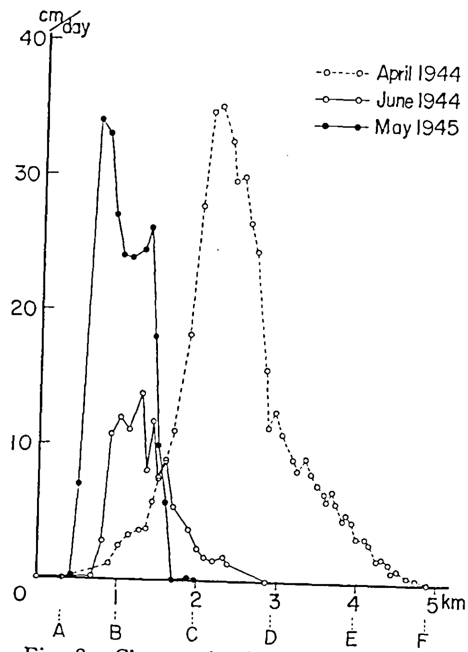


Fig. 8. Changes in the rising area in accordance with development of intrusion of viscous lava (Syowa-sinzan, Usu).

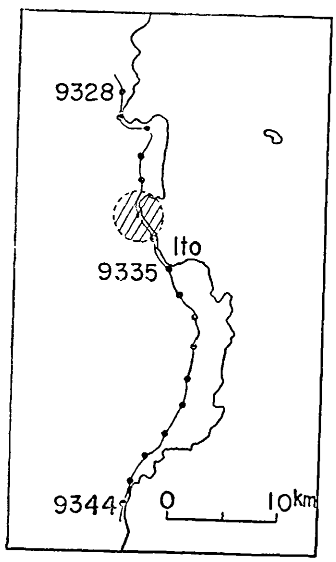


Fig. 9. Locality of the bench marks in the vicinity of Ito. hatched circle; central part of rising area.

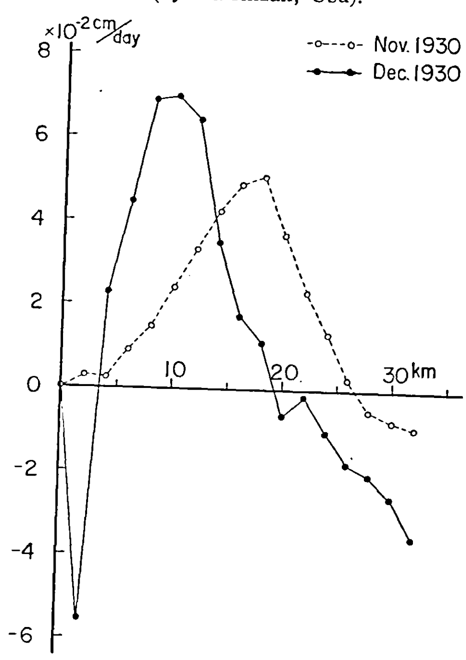


Fig. 10. Changes in the rising area with development of the Ito earthquake swarm.

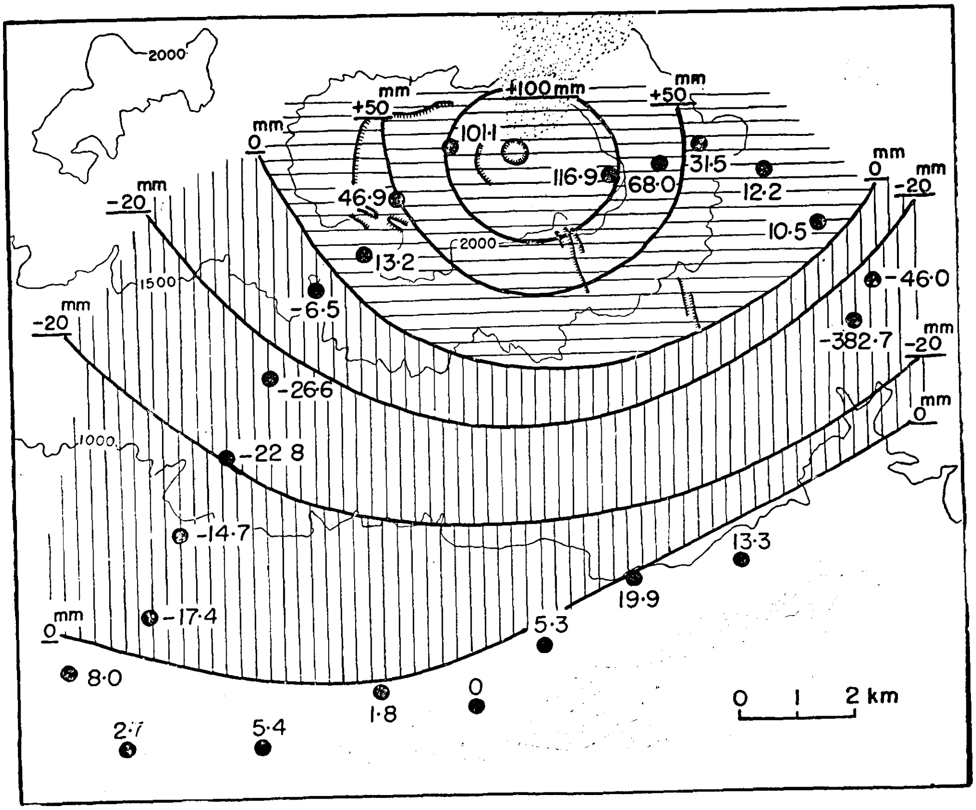


Fig. 11. Topographical deformation on and around Mt. Asama.

that the diminution in diameter of the rising area with the development of volcanic activity is an upheaval phenomenon resulting from the ascending of nearly solidified lava, namely, viscous dacitic lava, to the earth's surface.

Also in the course of the Ito earthquake swarm precise levelling was carried out three times. Through these levellings it has become possible to compare the crustal deformations in the first half of the earthquake swarm with those in the latter half. Assuming that the bench mark (No. 9328) is stable, the deformation in each stage is shown with the daily velocity (cm/day) in Fig. 10. As is shown clearly by this diagram, the crustal deformations that accompanied the Ito earthquake swarm also manifest a domelike upheaval, though it is not as conspicuous as that of Usu-san. Moreover, in the latter half of the earthquake swarm it is noticed that the rising area diminishes slightly. If it be assumed that

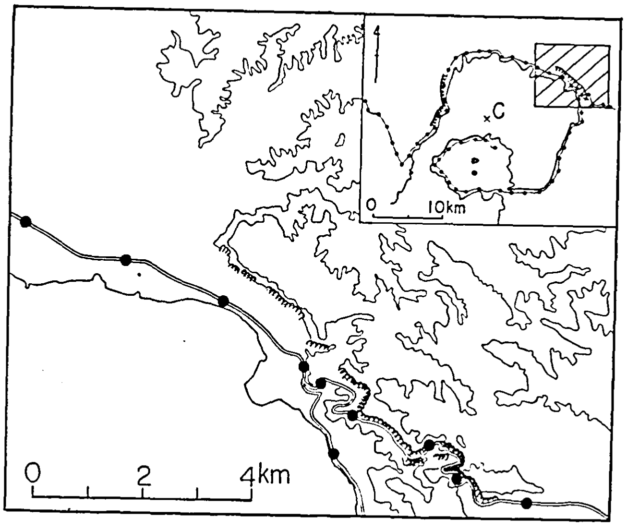


Fig. 12. Locality of the bench marks on and around Sakura-zima and the bench marks passing through the ring form fault at the margin of the Aira caldera.
C: center of subsidence.

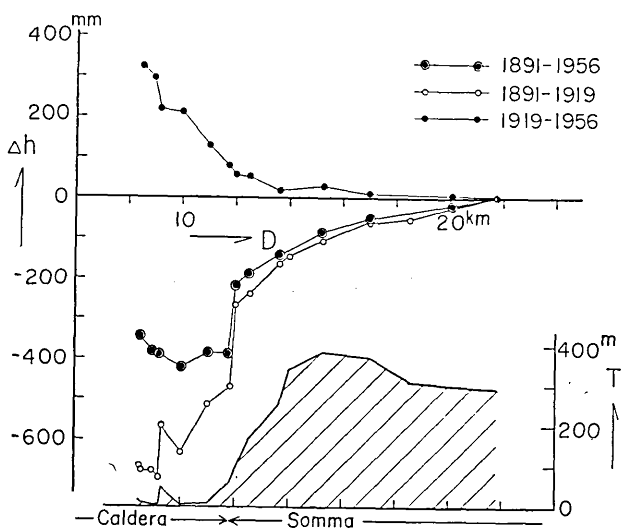


Fig. 13. Topographical deformations at the margin of the Aira caldera.
Δh, change in height of bench marks,
T, topography (height above sea-level of bench marks),
D, distance from the center of subsidence.

this earthquake swarm is a phenomenon similar to the case of Usu-san, this may also be attributed to the ascending of magma.

In general, volcanic earthquakes take place in swarms, and the Ito earthquake swarm follows this pattern. In crustal deformations always accompanying earthquake swarms, dome-like upheaval occurs in the vicinity of the epicenters. It is not clear whether earthquakes which occur in swarms differ from general earthquakes in mechanism and cause of occurrence, or whether this phenomenon is attributable to the difference in the nature of the earth's crust caused by the different depths of the source of the phenomenon, at any rate it seems to be a problem of some magnitude.

Asama-yama is famous for the fact that lava is explosively extruded in the form of lava fragments of various sizes from the summit crater. Fig. 11 represents the conditions during eruptions in recent years when a section near the crater was uplifted like a dome, while on the contrary a section including the middle flank and the skirt subsided.

Topographic changes in such a mode have been noticed in several other volcanoes. Particularly a ring-shaped subsidence that appears all over the skirt of a volcano is related to the formation of caldera and has attracted the attention of many investigators. In a volcano having a caldera not only does the depression of the caldera continue to progress more and more but also even at present* there is a case in which a steep cliff forming the brim of a somma slips down like a fault owing to the volcanic activity. For example, the results of precise levelling conducted in the vicinity of Sikine in the Aira caldera revealed the above mentioned topographic change.

Though crustal deformations accompanying volcanic activity geographically localized, there were cases in which the upheaval amounted to 100 m, as seen in the eruptions of Usu-san in 1911 and 1943～1945, and as regards horizontal displacement, deformations almost equal to the upheaval were observed.

Therefore, when the dilation (Δ) and shear (σ) are compared at their maximum values in a volcanic eruption and a destructive earthquake respectively, they become

$$\Delta=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}, \quad \sigma=\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}$$

$\Delta=10^{-1}$, $\sigma=10^{-1}$: Volcano (Syowa-Sinzan[28])

$\Delta=10^{-4}$, $\sigma=10^{-4}$: Earthquake (Tango earthquake[29])

As shown above, the crustal deformations in Syowa-Sinzan are strikingly larger than those caused by a major earthquake.

5. The nature of lava and volcanic eruption

Volcanic eruption is the phenomenon of subterranean magma being extruded as lava. However, each volcano manifests very different characteristics, at least apparently, in its mode of eruption. For example, in one volcano, lava is extruded as flowing lava; in another volcano, highly viscous lava is hurled out from the crater as pyroclastic ejecta; in another, minor eruptions are repeated continuously, and, in

* 1891–1956.

28) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **28** (1950), 143.

29) C. TSUBOI, *loc. cit.*, 27).

another, without forewarning great quantities of eruptives are extruded explosively. In accordance with the difference in the modes of eruption, there are differences in earthquakes, the crustal deformations and electromagnetic phenomena originating from volcanoes. That is, each volcano is characterized by a different mode of eruption.

The characteristics of volcanic phenomena are classified in several groups, and in many cases each characteristic is related to the chemical and petrological characteristics of the erupted lava. That is, the character of the eruptions, the intensity of the magnetization of the volcanoes, and earthquake phenomena accompanying the volcanic eruptions are characterized by the nature of the lava, i.e., basaltic, andestic, dacitic, or intermediate. The viscosity and temperature of the lava at the time of eruption also differs, and these have correlation with the nature of the eruptive phenomena.

First of all, the results of the analyses of representative lava, namely, basalt[30] (Kilauea), andestitic basalt[31] (Oo-sima and Miyake-sima), andesite[32] (Asama-yama and Sakura-zima), dacite[33] (Syowa-Sinzan) and liparite[34] (Katmai) are shown in Table 1.

Table 1. Chemical composition of various volcanic rocks. (After G. A. Macdonald, H. Tsuya, R. Morimoto, J. Ossaka, K. Yagi and R. E. Wilcox.)

	Basalt (Kilauea)	Andesitic basalt (Oo-sima)	Andesite (Asama)	Dacite (Usu)	Liparite (Katmai)
SiO_2	49.80	52.44	60.00	69.17	76.53
Al_2O_3	12.42	15.44	16.67	15.68	12.31
Fe_2O_2	1.53	3.16	1.64	1.72	0.46
FeO	9.91	10.11	5.36	2.37	0.96
Mg O	10.31	4.66	4.14	0.92	0.00
Ca O	10.32	9.74	7.87	4.00	1.01
Na_2O	1.96	1.66	2.03	3.63	4.15
K_2O	0.45	0.33	0.88	1.32	3.05
TiO_2	2.68	1.59	0.97	0.41	0.17
P_2O_5	0.29	0.12	0.07	0.20	0.05
MnO	0.13	0.10	0.25	0.20	0.04
H_2O	—	0.76	0.18	0.70	1.12
Total	99.80	100.11	100.06	100.32	99.85

30) G. A. MACDONALD, *Bull. Geol. Soc. Amer.*, **60** (1949), 1541.
31) H. TSUYA, *Bull. Earthq. Res. Inst.*, **15** (1937), 215. H. TSUYA, R. MORIMOTO and J. OSSAKA, *Bull. Earthq. Res. Inst.*, **30** (1952), 231.
32) H. TSUYA, *Bull. Earthq. Res. Inst.*, **11**(1933), 575.
33) K. YAGI, *Trans. Amer. Geoph. Union*, **34** (1953), 449.
34) R. E. WILCOX, *Geol. Sur. Bull.*, **1028** (1959), 1.

In many volcanoes, the temperature and viscosity of the lava at the time of eruption was measured and reported, though fragmentarily. Summarizing these results, we may consider that the temperature and viscosity of the lavas during eruption were near the values shown in Table 2.

Table 2. Temperature and viscosity of fresh lavas at the times of eruption.

	Temperature	Viscosity	Volcano
Basalt	1200°C	10 —10^3 poises	Kilauea
Andesitic basalt	1150°C	10^3—10^4 poises	Oo-sima
Andesite	1050—1100°C	10^5—10^7 poises	Sakura-zima
Dacite	1000—1500°C	$>10^{10}$ poises	Usu (Syowa-Sinzan)

As shown in Table 2, viscosity differs greatly according to the kinds of lava, and the difference is closely related to the nature of eruption and the forerunning and subsequent phenomena associated with volcanic eruptions. For example, highly fluid lavas such as those of Kilauea and Mauna Loa in Hawaii Is., flow rapidly down the mountainside. On the contrary, the dacitic lava which built up Syowa-Sinzan failed to flow after it was erupted on the ground surface and formed a lava dome at the position of the crater.

Quaternary volcanoes[35)–39)] are magnetized in the direction $N-S$. Assuming that the lavas constituting these volcanoes retain the direction of magnetization at the time when the lavas were erupted and cooled on

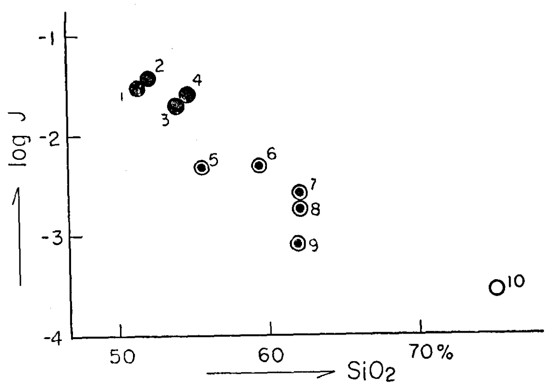


Fig. 14. The intensity of magnetization of volcanoes and the nature of volcanic rocks forming the respective volcanoes.
closed circle: andesitic basalt,
double circle: andesite,
opened circle: liparite.
1: Huzi, 2: Oo-sima, 3: Miyake-sima,
4: Hatizyo-sima, 5: Oomuro, 6: Tarumai,
7: Asama, 8: Sakura-zima, 9: Kusatu-sirane,
10: Koozu-sima.

35) T. NAGATA, *Bull. Earthq. Res Inst.*, **21** (1943), 1.
36) T. MINAKAMI and S. SAKUMA, *Bull. Volcanol.*, [ii], **18** (1956), 77.
37) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **19** (1941), 356.
38) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 499.
39) S. SAKUMA, *Jap. Jour. Geoph.*, **1** (1957), 1.

the ground-surface, it indicates that the direction of the earth's magnetic field in the Quaternary period was not very different from that of the present time. On the other hand, the intensity of magnetization differs markedly according to the kinds of lava constituting the volcanoes. That is, the intensity of magnetization of volcano consisting of basalt contains a large quantity of FeO and Fe_2O_3. Some examples of the intensity of magnetization of volcanoes will be shown in Fig. 14.

T. Rikitake, I. Yokoyama, and S. Uyeda[40][41] have conducted continuous observations on the geomagnetic changes at the foot of Mihara-yama, O-sima, since 1950. In the course of these observations Mihara-yama repeatedly erupted and extruded basaltic lava. The relationship between the changes of geomagnetism, especially the changes in the declination and the occurrence of volcanic eruptions were studied, and it was disclosed that the decreasing of the intensity of magnetization appears in the central part of the volcano a month or two before an eruption, and the changes in a reverse sense, appear after the commencement of an eruption. Of the geomagnetic changes, the former is ascribable to the fact that magentization is lost by the rise of temperature in the interior of the volcano with the ascending of magma lying under the volcano. As regards the latter, Yokoyama[42] attributes the reverse changes to the fall of temperature in the volcanic body owing to the extrusion of lava. Uyeda's interpretation[43] is different from Yokoyama's. Uyeda's view is as follows: The locality of the summit crater being as much as 700 m, higher than the magnetic observation station, when magma of high temperature ascends beyond the level of the location of the observation station, the intensity of magnetization changes on account of the rise of the geothermal temperature in the upper part of the mountain body. This change of magnetization is reversed in magnetic declination at the observation station. In either case, it is considered that the ascending of subterranean magma causes the changes in the geothermal temperature of the volcanic body and thereby the changes in the earth's magnetic field. That is, it has become possible to observe the ascending of magma in the interior of a volcano by the changes in the earth's magnetic field. Since basaltic volcanoes such as Mihara-yama are strongly magnetized as compared

40) T. RIKITAKE, I. YOKOYAMA, A. OKADA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **29** (1951), 583.

41) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **30** (1952), 71.

42) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **32** (1954), 17.

43) S. UYEDA, *read at the general meeting of Vol., Soc. Japan*, May, 1960.

with andesitic and dacitic volcanoes, and the changes of temperature in the interior are observable as changes of the earth's magnetic field on the ground surface, there arises the possibility of discerning the inner condition of such volcanoes by a different method from the method used for andesitic volcanoes.

6. Pressure exerted on volcanic bodies at the time of lava extrusion and the viscosity of lavas.

Magma which ascends and is extruded on the ground surface, is produced in depths between several tens of kilometers and 300 km. The course which magma follows from the interior of the earth to the earth's surface and the force by which magma is extruded have not yet been confirmed. With regard to various phenomena, however, observable in volcanoes in the course of the ascending of magma from the shallow depth of several kilometers and its extrusion to the ground surface, some information on measurements has been reported.

Generally speaking, comparing volcanoes which erupt lava of large viscosity with those which erupt lava of small viscosity, the former are more remarkable in the dynamic phenomena that manifest themselves before eruption, i. e., volcanic earthquakes and crustal deformations. Needless to say, the magnitude of volcanic eruptions has a relation with the above phenomena, but the above relationship, with few exceptions is noticed also in eruptions of the same scale. As stated above, in volcanoes such as Sakura-zima and Usu which extrude andesite and dacite lavas of large viscosity, local earthquakes frequently occur for several months or several days before eruptions and marked crustal deformations such as upheavals of the ground take place. On the contrary, in the case of the eruption of Mihara-yama of 1950–1951 which erupted lava of small viscosity, such phenomena were not observed. This is considered to be significant. One reason that occurs to us is that the degree of viscosity of the lava is related to the increase of the subterranean pressure needed for volcanic eruption. Now the pressure exerted in the depths of a volcano at the time of lava eruption will be considered by using a simple example.

At the time when lava of viscosity (η) ascends toward the ground surface and erupts from the lava-reservoir under the volcano through a tubelike conduit of radius (a) with mean velocity (v), the increase of pressure (Δp_1) in the reservoir is represented by

$$\Delta p_1 = \rho g \Delta l + \frac{1}{2}\rho v^2 + \frac{8\eta v l}{a^2},$$

where ρ, l, Δl are the density of lava, the length of the conduit and the ascending of the lava head respectively.

Consequently, taking into consideration the fact that the stress exerted on a volcanic body is related to the viscosity of the lava and, as shown in Table 2,[44)-50)] the degree of viscosity differs in accordance with the kind of lava, it may be expected that the increase of stress needed for the ascending of the lava differs markedly according to the nature of the lava.

In some volcanoes, there is a case where lava is extruded in the manner of dike along a long fissure. In such a case, the relation between the viscosity and the increase (Δp_2) of pressure in the lava-reservoir, assuming the width of the dike to be 2b, is represented by

$$\Delta p_2 = \rho g \Delta l + \frac{1}{2}\rho v^2 + \frac{3\eta v l}{b^2}.$$

That is, the relation is almost similar to the case where lava is extruded through a tube-like conduit.

The foregoing explanation is based on the most simple model of the relationship among the pressure which forces magma to ascend, the viscosity of the magma, and the structure of the volcano (namely, the length, diameter, etc. of the conduit).

In the case of lave eruption in a long-dormant volcano in which lava in the conduit has solidified and in the case of lava eruption which occurs in a locality where no crater existed like Syowa-Sinzan and Parícutin, a new fissure or crack forms first, and then eruption takes place. In order to open a passage for the lava to ascend through the structure of volcano, strong pressure must be exerted on the subterranean formation.

This corresponds with the case where a and b in the above formulae are extremely small. Hence, in cases where the viscosity of the lava is

44) G. A. MACDONALD, *Amer. Jour. Sci.*, **241** (1943), 241.
45) P. E. SCHULZ, *Bull. Geol. Soc. Amer.*, **54** (1943), No. 6.
46) R. H. FINCH, *Vol. Let.*, **480** (1943), 2.
47) T. HAGIWARA, *Bull. Earthq. Res. Inst.*, **19** (1941), 299.
48) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **31** (1951), 487.
49) S. SAKUMA, *Bull. Earthq. Res, Inst.*, **31**(1953), 291.
50) T. HAGIWARA and others, *Bull, Earthq. Res. Inst.*, **24** (1946), 143.

large or where a volcano lacks a vent or where the vent is very small, innumerable earthquakes or conspicuous crustal deformations ought to take place previous to eruption. That is, in many cases, at first premonitory phenomena manifest themselves and then eruption occurs. There are some examples of this mode of eruption.

Even in the case where similar lava is erupted from the same crater of the same volcano, a slight difference in the temperature of the lava will give rise to a marked difference in the viscosity of the lava. Thus, the relation between the pressure exerted on a volcanic body and the eruption, or the relation between premonitory phenomena, namely, earthquakes and crustal deformations, and the eruption, is not a constant one but must be considered as a relation which holds only within a certain range. In other words, the relation between both phenomena is established as a relation made valid by the process of probability.

7. Earthquakes originating from volcanoes

As stated above, volcanic eruptions and earthquakes originating from volcanoes are closely related to each other in various aspects. In this paragraph, the relationship between the kinds of earthquakes which originate from volcanoes and volcanic phenomena will be classified and summarized.

In respect to the relation between general earthquakes originating from depths of 20 km–100 km and volcanic activity, no definite answer has been given, but it cannot be concluded that the general earthquakes have no connection with the production of magma. However, taking the eruptions of volcanoes and earthquakes in the world as the object of consideration, there are not many actual examples of the particular time relation between great earthquakes and great volcanic eruptions.

As mentioned briefly in the paragraph on the distribution of focal depths, earthquakes originating from volcanoes can be classified in the following four groups. Definitions of these four types of volcanic earthquakes will be given here.

1. A-type volcanic earthquakes

These are earthquakes originating from the bases of volcanoes or from the depths of about 1 km to 10 km. These earthquakes occur in every volcano and particularly in many cases these earthquakes take place markedly previous to and in the first stage of eruptive activity. The nature of earthquake-motions cannot be distinguished from those of general shallow earthquakes (tectonic earthquakes). The P-phase and the S-phase of seismic waves also make themselves clearly manifest.

2. B-type volcanic earthquakes

The hypocenters are limited to an area of about 1 km in radius around the active crater. The hypocenters of these earthquakes are shallower than those of the A-type volcanic earthquakes. These earthquakes take place in swarms in the shallow part ranging from the earth's surface to depths of several hundred meters. Consequently, the surface waves predominate and the S-phase cannot be discerned distinctly. These earthquakes are frequently observed in volcanoes in which the eruptions are of the Vulcanian type, such as Asama-yama and Sakura-zima.

3. Explosion earthquakes

These are earthquakes which accompany individual explosive eruptions. The amplitude of these earthquakes is related to the magnitude of the explosive eruptions. As far the results hitherto ascertained are concerned, the initial motion is 'push' in every direction. The hypocenters are situated in the part not deep from the active crater floor. The nature of the earthquake-vibrations of these earthquakes resembles that of the B-type volcanic earthquakes, but the magnitude are larger than that of the B-type volcanic earthquakes.

4. Volcanic pulsation or continuous volcanic microtremors

In cases such as the Strombolian or Hawaiian type where eruptions are prolonged, explosion earthquakes accompanying the eruption become continuous vibrations. In volcanoes displaying Strombolian or Hawaiian type eruptions, no B-type volcanic earthquakes take place, and in many cases continuous vibrations originate from the shallow part in the vicinity of the craters. In volcanoes in which the eruptions are of the Vulcanian type, sometimes such vibrations are caused by continuous shocks in the vicinity of the bottom of the active crater. Needless to say, the main part of such vibrations consists of the surface waves.

Seismograms of the above four types recorded with seismographs which are 1 sec. in proper period and of the same type are represented in Figs. 28–31.

For convenience in description, the writer classified volcanic earthquakes into these four groups. Here the writer must refer to Omori's classification[51] of volcanic earthquakes. Omori established a volcanological observatory at Yunotaira about 2 km southwest of the crater of the

51) F. OMORI, *Bull. Imp. Earthq. Inv. Comm.*, **6** (1912), 1; **7** (1914), 1.

Asama volcano in 1910, and he made observations with seismographs and other instruments. He also studied the nature of volcanic earthquakes associated with marked volcanic activities displayed in the period 1910–1913, and, in addition, he investigated the relation between volcanic

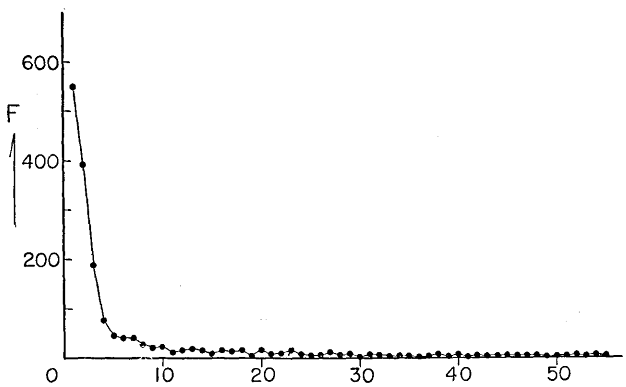


Fig. 15. Daily frequency of the after-shock of the Imaiti earthquake.

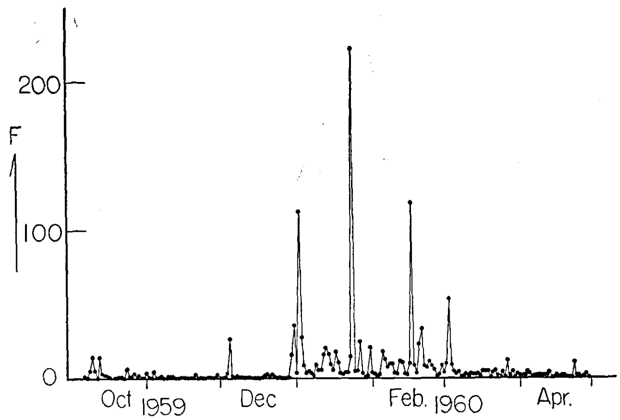


Fig. 16. Daily frequency of the Hakone earthquake swarm.

earthquakes and volcanic phenomena. This was an epoch-making study for that time. In this case, Omori classified the earthquakes originating from Asama-yama in two groups, namely, A-type and B-type. Omori defined the B-type earthquakes as earthquakes that accompany explosive eruptions or earthquakes accompanied by explosive eruptions. Omori's B-type earthquakes corrospond to the above mentioned explosion earthquakes as defined by the writer, and the former is different from the B-type earthquakes as defined by the writer. On the other hand, Omori's A-type earthquakes correspond to both the A-type and B-type earthquakes as defined by the writer. The writer must mention that Omori's A-type and B-type earthquakes are different from those as defined by the writer.

The writer has already mentioned the difference in the focal depths of general earthquakes, the after-shocks of major earthquakes, and volcanic earthquakes. Here the mode of occurrence of each of them will be discussed.

Many studies have been made on the problem of the decrease in frequency of the after-shocks of a major earthquake as time advances. The decline of after-shocks, in many cases, is represented by a hyperbola and an exponential function. Volcanic earthquakes of the A-type and B-type and explosion earthquakes take place in swarms, and volcanic phenomena themselves also occur in swarms. That is, the frequency increases gradually, reaches a maximum, and at last declines. Such swarm occurrence are repeated several times at intervals. In the case of a major earthquake, the first shock (that is, the principal shock) is strikingly different in magnitude from the after-shocks which follow. In the case of volcanic earthquakes, there is a difference in the magnitude of each earthquake, but there is no case where a specially large earthquake which could be regarded as "the principal shock" occurrs.

The decline in frequency of the after-shocks in the case of the Imaiti earthquake[52] and the changes in frequency of earthquakes in the recent earthquake swarm in Kami-yama, Hakone, are illustrated in Figs. 15 and 16. The Ito earthquake of 1930 also occurred in swarms, and it is noticeable that the Ito earthquake and volcanic earthquakes shallower in focal depth in comparison with the Ito earthquake manifest without exception a character of swarm occurrence. Then what is the cause of the swarm occurrence of earthquakes and the decline in frequency of after-shocks? Is this attributable to a difference of occurrence mechanism between volcanic earthquakes and general earthquakes? Or is it a consequence of the character of the earth's crust which differs with the depths of the hypocentres? One or two examples have been quoted by way of solving this problem, but actually it may be a problem which will be solved only in the future. However, by clarifying the geographic distribution of the initial motions of seismic waves in volcanic earthquakes the solution to this problem may be hastened.

52) *Japan Meteor. Agency, Kisho-yoran* (*Geoph. Rev.*), No. 604, (1949), 605 (1950).

8. Some examples of the hypocentral distribution of volcanic earthquakes.

1) Usu-san[53)–55)]

The eruption of this volcano in 1943–45 was characteristic. This activity will live long in the history of volcanology by reason of the birth of Syowa-Sinzan, caused by a remarkable upheaval of the ground. The hypocenters of the earthquakes (A-type and B-type) that took place in the course of the eruption are illustrated in Fig. 17. As seen in the

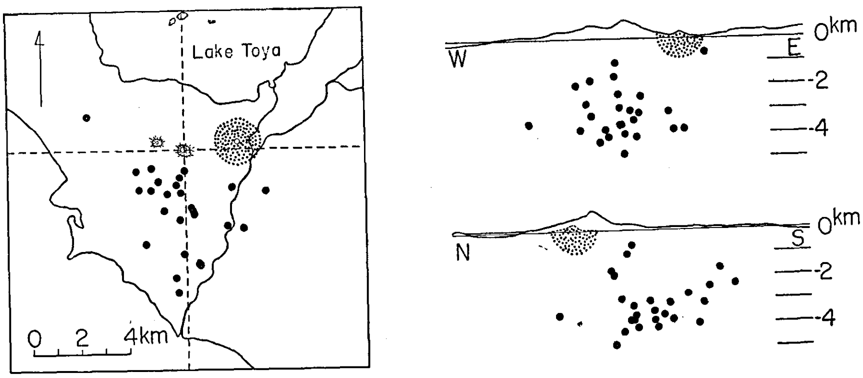


Fig. 17. Hypocentral distribution of earthquakes of the *A* and *B* types which took place in the 1944 activity of Volcano Usu.

diagram, volcanic earthquakes of the A-type are extensively distributed on the southern side of Usu-san, and their focal depths are 1–6 km. The volcanic earthquakes of the B-type on the contrary, were shown to have originated from depths within 1 km. of the earth's surface in a very limited area. In a series of volcanic activities beginning with frequent occurrences of A-type volcanic earthquakes, through upheaval and eruption, ending with the formation of a lava dome consisting of dacitic lava, the manner of the earthquake occurrence, particularly of A-type and B-type volcanic earthquakes was characteristic. That is, remarkable changes in the frequency of earthquakes of both type were manifested in the period from 1943 to 1945. All volcanic earthquakes that occurred in the early stage of activity towards the end of December 1943 were of the A-type, and there were no B-type earthquakes. At the time when the upheaval in the area at the eastern foot of Usu-san

53) T. Minakami, *Bull. Earthq. Res. Inst.*, **25** (1947), 71.

54) T. Minakami, T. Ishikawa and K. Yagi, *loc. cit.* 15).

55) T. Kizawa, *Pap. Meteor. Geoph.*, **8** (1957), 150.

was noticed by the local inhabitants, B-type earthquakes also began to occur, while at the same time the occurrence of A-type earthquakes decreased, and before long phreatic eruption began. During the period when the lava dome was forming, most of the volcanic earthquakes were of the B-type, and the occurrence of A-type earthquakes decreased considerably. The variations in the frequency of A-type and B-type earthquakes are represented in Fig. 18. This is the frequency variation

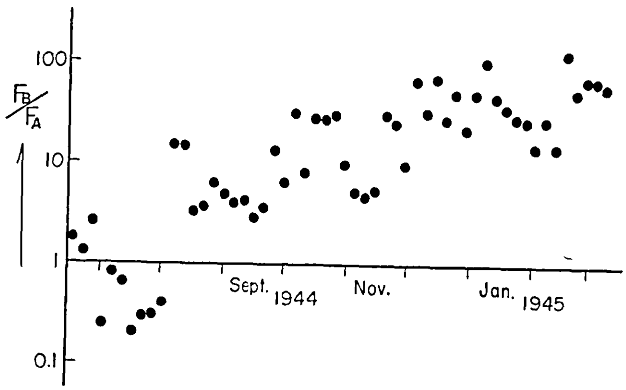


Fig. 18. Changes of the ratio between seismic frequencies (F_A and F_B) of the A and B types, which took place in the 1944 activity of Volcano Usu.

of the both types of earthquakes in the middle stage of this volcanic activity, i.e., from the beginning of the phreatic eruption to the time when the lava dome began to form. By this frequency variation, it is evident that the activity of A-type earthquakes originating from the somewhat deep part of this volcano migrated to a limited area near the earth's surface with the development of the volcanic activity, and B-type earthquakes took the place of A-type earthquakes. That is, this variation in frequency indicates that the rising area was reduced with the rise of magma from the deep part of this volcano (Fig. 8), and at the same time the hypocentres migrated near to the earth's surface, resulting in swarm occurrences of earthquakes from this area.

2) Asama-yama[56)–58)]

Asama-yama is representative of volcanoes that give off Vulcanian eruptions from the summit crater. The eruptions from the summit

56) T. MINAKAMI, *Bull. Vol. Soc. Japan*, [ii], **4** (1959), 104.
57) T. MINAKAMI and others, *Bull. Vol. Soc. Jap*, [ii], **4** (1959), 115.
58) T. MINAKAMI and others, *Bull. Vol. Soc. Jap*, [ii], **4** (1960), 113.

crater of Minami-dake, Sakura-zima, since 1955 have been activities of similar character.

Earthquakes originating from Asama-yama have been studied in relative detail since Omori's investigation which includes the remarkable eruptions extending over several years from 1910. Recently a tele recording apparatus has been adopted, and records of earthquakes, with transducers installed near the crater and in many other places of the volcano, are received at the recorder station. By this means it has been possible to detect occurrences of micro-earthquakes all over the volcano. Moreover, the hypocentre of these earthquakes can be accurately determined, and it has become possible to clarify the relationship between volcanic earthquakes and volcanic eruptions. As represented in Fig. 19, the greater part of the hypocentres swarm in an area 1 km in radius with the bottom of the summit crater as the centre (the hatched part in Fig. 19). One of the characteristics of earthquakes originating from Asama-yama is that the occurrence of A-type volcanic earthquakes originating from a

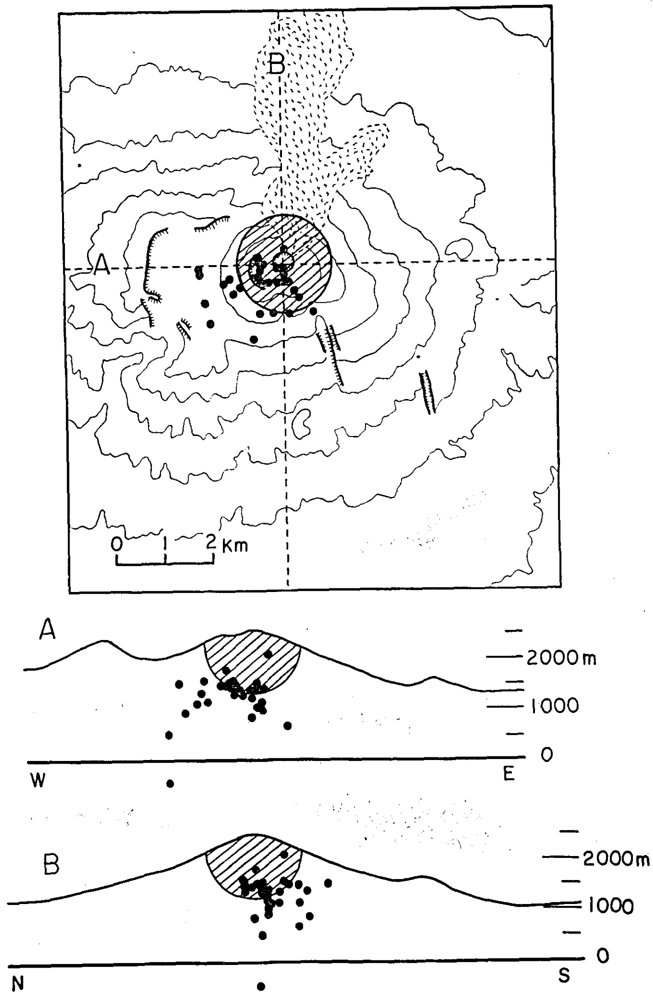


Fig. 19. Hypocentral distribution of earthquakes originating from Volcano Asama. Hatched area indicates hypocentral domain of the B-type earthquake.

somewhat deep part is very slight. Moreover, it is noteworthy also that almost no felt earthquake has occurred from Asama in the last 25 years.

The various types of earthquakes that have taken place in association with the recent activity of Minami-dake, Sakura-zima,[59] that resembles Asama-yama with respect to the physical and chemical properties of its effused lava and position of its crater are also closely related to those of Asama-yama with respect to the positions of the hypocentres and the nature of the earthquake-vibrations. The difference between earthquakes originating from the two volcanoes is that in the Sakura-zima volcano A-type earthquakes occur in relative abundance, in which felt earthquakes are involved, and the volcanic pulsations originating from the active crater are relatively remarkable as compared with Asama-yama. Sakura-zima volcano closely resembles Asama-yama in the fact that B-type earthquakes frequently take place.

3) Mihara-yama[60)-61)] and Aso-san[62)-63)]

In Mihara-yama and Aso-san that display Strombolian eruptions, the hypocentres of A-type volcanic earthquakes, as in the cases of the above-mentioned volcanoes, are distributed extensively in depths of about 1–10 km. In these volcanoes, A-type volcanic earthquakes sometimes occur previous to and during eruptions, but sometimes take place without any apparent connexion with eruptive activities. In these volcanoes, earthquakes that correspond to B-type volcanic earthquakes have not been confirmed, but the predominance of volcanic tremors or volcanic pulsation originating from the vicinity of the crater bottom may be a characteristic of the seismic features of these volcanoes. K. Sassa who investigated the various types of volcanic tremors in Aso-san reported that, besides continuous vibrations that occur in association with minor continuous explosions, surface waves of the Rayleigh type and the Love type are frequently observed. Considering the fact that these vibrations originate from the shallow part near the crater, the vibrations should correspond to B-type volcanic earthquakes in volcanoes displaying Vulcanian eruptions.

---

59) T. MINAKAMI, K. MOGI, S. HIRAGA and T. MIYAZAKI, *Bull. Volcan. Soc. Japan.* [ii], **2** (1957), 77.

60) R. TAKAHASI and T. NAGATA, *loc. cit* 9).

61) T. MINAKAMI, T. MIYAZAKI and T. TAKAHASHI, *Bull. Earthq. Res. Inst.*, **29** (1951), 359.

62) K. SASSA, *Mem. Coll. Sci. Kyoto Univ.*, [A], **18** (1935), 255, **19** (1936), 11, 171.

63) T. MINAKAMI and S. SAKUMA, *Bull. Volcan.*, [ii], **14** (1953), 79.

4) Hawaiian volcanoes[64)–71)]

In Hawaii I. there are the volcanoes, Kilauea and Mauna Loa that extrude basaltic lavas, and the Hawaiian Volcano Observatory has been striving to disclose the relation between earthquakes originating from the volcanoes and volcanic eruptions. Earthquakes that take place on the island, as seen in Fig. 2, are extensively distributed from near the earth's surface to depths of 70–80 km. When volcanic activity begins, the eruption is prolonged with resulting continuous vibrations. Viewed from the hypocentral distribution shown in Fig. 2, volcanic earthquakes including volcanic tremor (exclusive of B-type volcanic earthquakes), originate from every depth in the island. It has been reported that sometimes earthquakes occur in depths of 50–70 km a month or two before the eruptions of the above two volcanoes. This is a remarkable characteristic of the Hawaiian earthquakes that originate frequently from great depths under active volcanoes.

9. The earthquake swarm in the Hakone volcano[72)]

Earthquakes originating from volcanoes, not only A-type and B-type volcanic earthquakes but also explosion earthquakes, occur in swarms as already mentioned. These earthquakes originate from parts shallower than 10 km, and the greater number of the hypocentres of these earthquakes are distributed within 5 km of the earth's surface.

Sometimes such a swarm of earthquakes frequently takes place not only in volcanoes in eruption but also in dormant volcanoes and in volcanoes from which expectation of future lava eruptions is inconceivable. Earthquake swarms that occur at the rate of once or so in several years inside the somma of Hakone volcano belong to this category. In the recent earthquake swarm that extended over the period from September 1959 to April 1960 strongly felt earthquakes were involved. The earthquake activity was prolonged and was accompanied by rather remarkable subterranean rumblings. Consequently some inhabitants

---

64) *Univ. Hawaii, Volcano Letter.* **489** (1945)—**530** (1955).
65) R. H. FINCH and G. A. MACDONALD, *Rep. Hawaiian Vol. Obs.* (1951)-(1953)
66) G. A. MACDONALD and J. P. EATON, *Rep. Hawaiian Vol. Obs.* (1955)-(1957)
67) G. A. MACDONALD and I. B. ORR, *Rep. Hawaiian Vol. Obs.* (1949).
68) G. A. MACDONALD and C. K. WENTWORTH, *Rep. Hawaiian Vol. Obs.* (1954).
69) G. A. MACDONALD and J. P. EATON, *Hawaiian Vol. Obs.* Summary 1-2 (1956)
70) J. P. EATON and G. D. FRASER, *Hawaiian Vol. Obs.* Summary 3-7 (1956-1957).
71) A. E. JONES, *Jour, Washing. Acad. Sci.* **24** (1934), 413, **25** (1935), 429.
72) T. MINAKAMI, *Rep. on the 1957-1960 earthquake-swarm of Mt. Hakone,* (1960) 1.

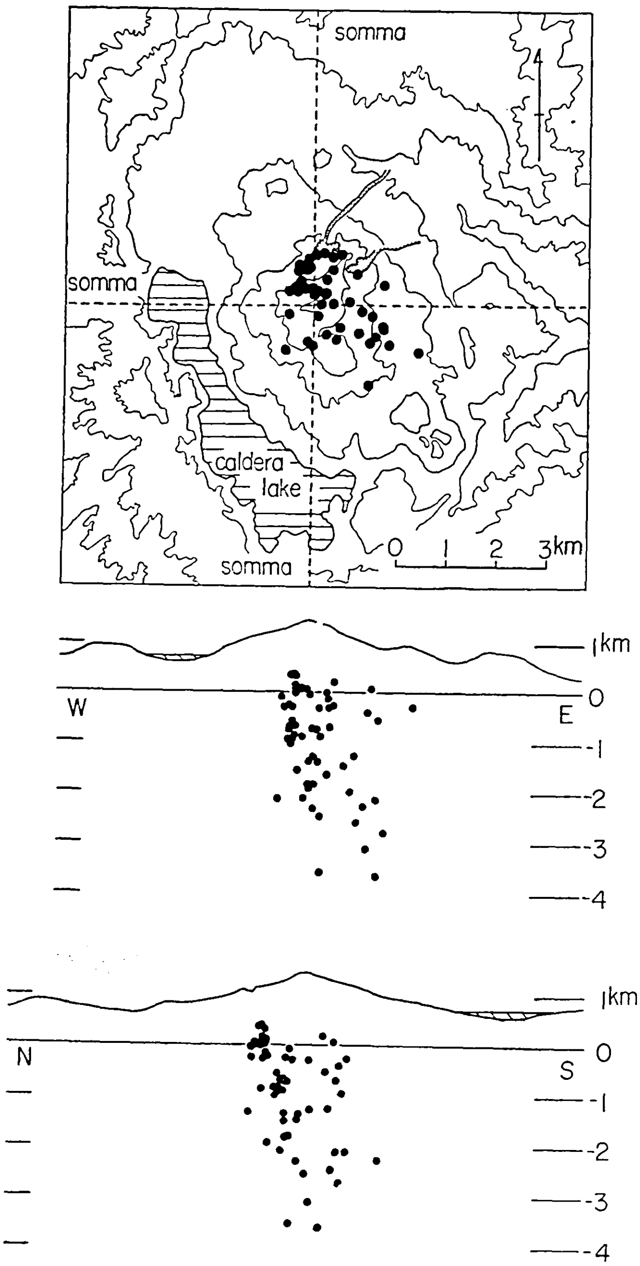


Fig. 20. Hypocentral distribution of the 1960 Hakone earthquake swarm.

felt uneasy about the possibility of impending eruption. Taking the historical activity of the Hakone volcano into account, however, the eruption of lava is almost inconceivable, but eruptive activity having a character of phreatic explosion, i. e., activity that destroys a mountain body as a result of an increase of steam pressure in the interior of the mountain as was seen in the explosion of Bandai-san of 1888 is not always improbable. Thereupon, in order to confirm whether or not the earthquake swarm will develop into such a disaster, the writer attempted to determine the hypocentres, and in particular the depths of hypocentres, as accurately as possible, and the possibility of the hypocentre migrating from the deep to a shallow part.

As a result of the seismometrical observations, as represented in Fig. 20, it was disclosed that all the epicentres of the earthquakes are distributed in a narrow area 1.5 km in radius having the summit of Kami-yama as the centre, and, as far as the focal depths are concerned the shallowest are 0.8 km. in depth, the deepest 5 km. and mostly 1–2 km. In view of the character of the earthquake-motions, these are A-type volcanic earthquakes manifesting distincty the P-phase and the S-phase, and no B-type volcanic earthquake has been recorded at all.

As mentioned above, eruption begins after the occurrence of A-type volcanic earthquakes, B-type volcanic earthquakes, or volcanic tremors corresponding to B-type volcanic earthquakes; or sometimes eruptive activities commence without the occurrence of A-type volcanic earthquakes but after the occurrence of B-type volcanic earthquakes or volcanic tremors. In the earthquake swarm in the Hakone volcano, A-type volcanic earthquakes alone occurred and no B-type volcanic earthquakes or volcanic tremors took place. This probably indicates that seismic activity did not migrate to a depths within 1 km from the earth's surface.

10. The relation between B-type volcanic earthquakes and volcanic eruptions

Physical volcanology aims at disclosing volcanic phenomena by representing quantitatively the physical quantities of volcanic phenomena and by studying the mutual relations among the physical quantities. Hence, it is required to represent numerically the magnitude and intensity of eruptive phenomena.

Volcanic eruptions or eruptive phenomena are the phenomena of extruding solids including viscous fluids to the earth's surface. Therefore, the most available method is to represent the magnitude of the eruptions with the total mass of the extruded solids. One method is to represent the calories of the extruded materials with the total calories of volcanic ejecta mainly consisting of solids and vapour emitted to the ground-surface. The measurement, however, of the emitted gas, such as the vapour, being extremely difficult, reliable results have not been obtained from any volcano. Another method is to represent the magnitude of explosive eruptions of the Vulcanian type with the kinetic energy ($E=\frac{1}{2}MV^2$) of the eruption determined by the initial velocity (V) of ejecta at the time of eruption and the amount (M) of lava blocks, volcanic bombs, volcanic ash, etc., which was ejected by an individual eruption. On the other hand, as there is simple relationship between the maximum amplitudes of the explosion earthquake that accompanied the eruption and the kinetic energy, if the relationship between both is determined, the energy of the eruption can be ascertained from the results of seismometrical observation.

The largest explosive eruption of Asama-yama in the last 25 years was the explosion of June 7, 1938. On that occasion the extruded amount was 3.8×10^8 kg, the initial velocity 212.5 m/sec. and the kinetic energy 1.7×10^{20} ergs respectively. Moreover, in volcanic eruptions from 5×10^{17} ergs to 5×10^{19} ergs in kinetic energy, as reported before, there exists the following relationship between the maximum amplitude of the horizontal motion ($A=\sqrt{A_{E-W}^2+A_{N-S}^2}$) of explosion earthquake and the eruptive energy (E).

$$E=[0.03+4.5A+0.75A^2\pm0.08]\times10^{19}\ \text{ergs},$$

or

$$E=[0.06+5.9A_{E-W}\pm0.11]\times10^{19}\ \text{ergs},$$

or

$$E=[-0.01+7.5A_{N-S}\pm0.19]\times10^{19}\ \text{ergs},$$

(where the unit of A is mm)

Representing eruptive activity by energy and earthquakes originating from volcanoes by their respective frequencies, the relationship between the above two phenomena in Mt. Asama was investigated. As mentioned above, the greater part of earthquakes originating from Asama-yama are classed into B-type volcanic earthquakes. Based on the results of observations over the period 1934–1951, the energy of the eruptions is represented with the monthly sum and the frequency of the earthquakes with the ten-days sum in Fig. 21. The frequency of earthquakes in this figure was recorded with a seismograph of low

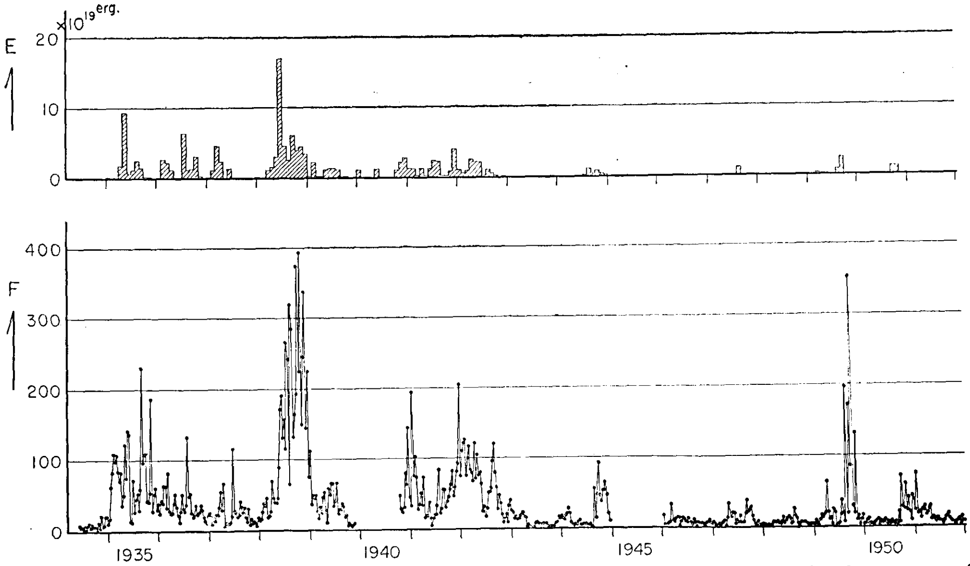


Fig. 21. Relation between the explosive eruption of Mt. Asama and the frequency of the B-type earthquake originating from the volcano.

E: Monthly kinetic energy of eruption.

F: Ten days frequency of earthquakes which were observed by seismograph of low magnification at Asama Volcano Observatory.

magnification (350 times) at a position 4.2 km distant from the crater. That is, these earthquakes are B-type volcanic earthquakes that originated from a shallow part very near the crater. As the earthquakes were recorded at a position about 4 km distant from area where they occurred, however, only some of the B-type earthquakes were recorded. The subsequent observations with seismographs of high magnification installed near the epicentres will be described later. It is noted that the energy of eruption and the frequency of B-type volcanic earthquakes represented in Fig. 21, vary somewhat in parallel. In other words, when eruptive activity is remarkable, B-type volcanic earthquakes occur frequently. On careful examination it is found, however, that in many cases the frequency of earthquakes increases a month or two before a swarm occurrence of eruptions. This fact has been confirmed also by statistical investigations.

The above-mentioned relation that has been clearly defined from the results of observations with a seismograph of high magnification tele-recording apparatus connected with transducers installed in many places on the volcano in recent years. The number of earthquakes recorded with seismographs of 4,000 times at positions 0.9 km., 2.5 km.,

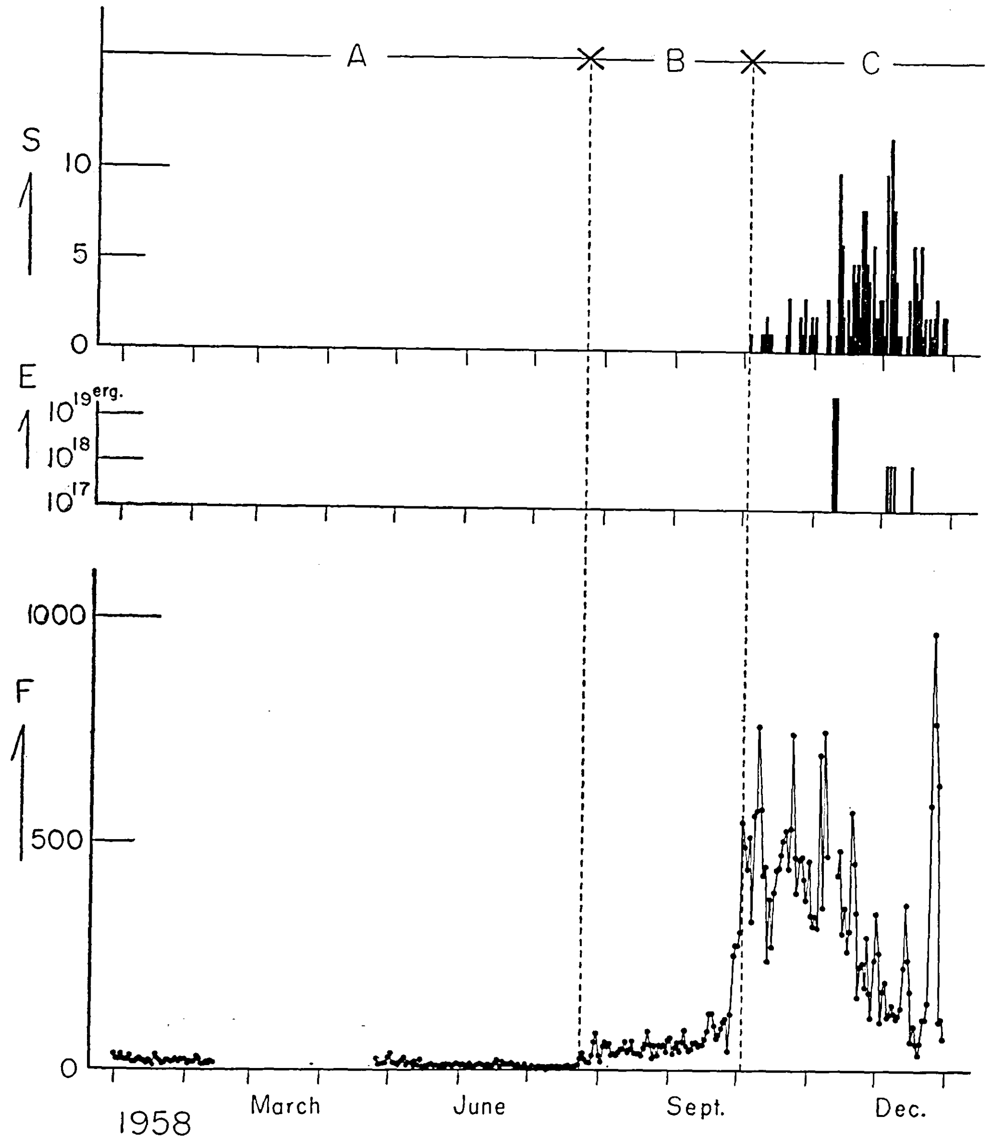


Fig. 22. Relation between eruptions and shallow earthquakes (B-type) of Asama.
A: Calm stage of the volcano, *B*: Pre-volcanic or pre-eruptive stage,
C: Stage of explosive eruption, *S*: Daily frequency of eruption,
E: Kinetic energy of strong eruption, *F*: Daily frequency of shallow earthquake.

and 4.0 km distant from the crater of the Asama volcano is on a daily average, 20, 16, and 6 respectively during calm periods. An increase of several times over is indicated from about two months before the commencement of eruptive activity, and as much as twenty times several days before an eruption. In Fig. 22 the daily frequency of B-type volcanic earthquakes associated with the remarkable eruptions from October to December, 1958, is represented. This is an example in which premonitory phenomena preparatory to eruption were clearly represented in the remarkable increase in the frequency of B-type volcanic earthquakes.

11. Vulnerability rates on the occurrence of eruptions viewed from the frequency of B-type volcanic earthquakes

As mentioned above, it has been known that the occurrence of B-type volcanic earthquakes increases, preceding volcanic outbursts. Therefore, it becomes possible to forecast outbursts of volcanoes by calculating the frequency of B-type volcanic earthquakes, i. e., by the following method, which is the most simple method conceivable to us.

The method is to infer, on the basis of a five day calculation (N) of the daily frequency (n) of B-type volcanic earthquakes, the probability, or in other words, the vulnerability rates of eruption for the next five days.

$$n_1+n_2+n_3+n_4+n_5=N_5$$
$$n_2+n_3+n_4+n_5+n_6=N_6$$
$$n_3+n_4+n_5+n_6+n_7=N_7$$
$$\cdots\cdots\cdots$$

First, taking all values of N under observation the values are divided into the following groups: 0–100, 101–200, 201–300, ……, and the frequency distribution (F) of each group is examined. Next, taking N from the day before the eruption to five days before (this is called by N'), the distribution of frequency (F') is examined. If both distributions are clarified, the distribution of F'/F for N gives grounds to infer the vulnerability rates of eruption. Table 3 which represents the vulnerability rates based on the eruptions of 1954–55 and 1958 indicates that there is no remarkable difference in the general tendency of both rates. It is considered that this method can be applied effectively to future outbursts of the Asama volcano.

In the above description restricting the problem to the frequency of B-type volcanic earthquakes, shallow earthquakes originating from the vicinity of the crater were treated uniformly under the name of

Table 3. Vulnerability rates for an explosive eruption of Asama based on the frequency of the B-type earthquakes.
F_0, F_0'; observed value, F_c, F_c'; calculated value from Polyà-Eggenberger's function.

N	F_0'/F_0	F_c'/F_c
0— 50	0	0.013
50—100	0.018	0.044
100—150	0.139	0.092
150—200	0.216	0.154
200—250	0.264	0.226
250—300	0.243	0.305
300—350	0.489	0.388
350—400	0.542	0.468
400—450	0.389	0.549
450—500	0.722	0.622
500—550	0.800	0.691
550—600	0.500	0.752
600—650	0.900	0.811
650—700	0.500	0.843
700—750	1.000	0.874

B-type volcanic earthquakes. However, judging from the nature of the earthquake-motions, B-type volcanic earthquakes are not always of the same character. Some of them originate nearer the crater bottom as compared with others and the surface waves more clearly predominate. Some of them are of the shock type. It seems that there are also some difference in the depth of the hypocentres. From the above fact, it is understood that the relationship between B-type volcanic earthquakes and outbursts is not the same for every B-type volcanic earthquake. The relationship seems to be direct in some B-type earthquakes and indirect in other B-type earthquakes. As an example, in B-type volcanic earthquakes observed simultaneously with seismographs of the same type and the same magnification, the writer examined the difference in the amplitude of the earthquakes at different epicentral distance.

Comparing the maximum amplitude of each B-type volcanic earthquake observed at the two points (Fig. 23), the maximum amplitude of earthquakes observed at the point near the crater was always found to be the greater. This fact indicates that the epicentres of B-type volcanic earthquakes are centered at the crater. In this respect B-type earthquakes are always the same. On comparing the maximum amplitude of each B-type earthquake, however, it has been revealed that the ratio of the maximum amplitudes at different epicentral distance differs with the periods of volcanic activity. Moreover, it seems that the amplitude ratio differs according to the conditions of volcanic activity at different times, i. e., in the early stage of eruptive activity, the later stage, and the calm period. In Fig. 23, of numerous earthquakes observed on the day before a great eruption, the maximum amplitude of earthquakes observed at the two points was plotted in the ordinates and abscissa according to the respective points, and the maximum amplitude of earthquakes that occurred after the eruption was also plotted in the graph with other symbol. Thereby it is evident that the ratio of the maximum amplitude observed in the periods is different, i.e., immediately before a great eruption, earthquake-motion are attenuated remarkably and the mean ratio of the amplitudes is 1:0.1, while the mean amplitude ratio after the eruption is 1:0.5. In short, such a remarkable difference in the attenuation of earthquake-motions is considered to be a result of the fact that immediately before an eruption the hypocentres of B-type volcanic earthquakes are extremely shallow, the vibrations are of the shock type, and are of short period while the hypocentres of earthquakes that took place after the eruption are rather deep and the periods of vibrations are lengthy. As described above, there are B-type volcanic earthquakes different in character and focal depth, and, on the other hand, there are also different volcanic phenomena with relation to the difference in B-type volcanic earthquakes. Therefore, by classifying B-type volcanic earthquakes into types according to their characteristics and by studying the relation between each type and eruption, it is expected

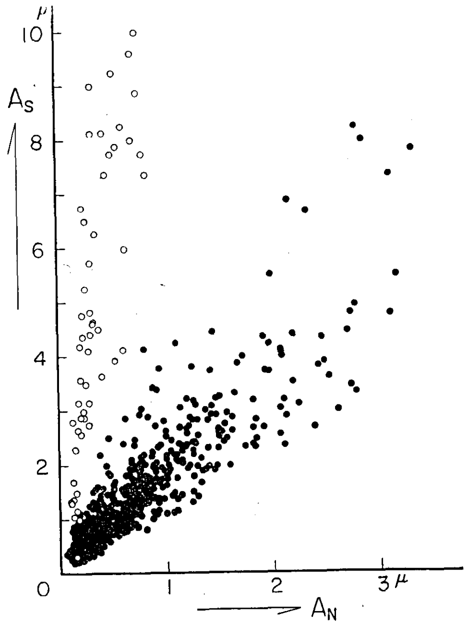


Fig. 23. Comparison of the maximum amplitude of the B-type earthquake-motions at the stations, Sannotorii and Nakanosawa, before and after the strong explosive eruption.
opened circle: earthquakes before the strong explosion on Nov. 10, 1958.
closed circle: earthquake after the strong explosions from Nov. to Dec., 1958.

that the relationship between the above two phenomena will be revealed more distinctly.

12. On the magnitude and frequency of earthquakes originating from volcanoes

It has been known for many years that, in general, the smaller the magnitude of the earthquake the more frequent become the occurrences of earthquakes. M. Ishimoto and K. Iida[73] conducted seismological observations in Tokyo about 20 years ago, making use of a seismograph which is 350 times in magnification and 1 sec. in period, and, on examining the seismograms, they found in 1939 that there exists the following relation:

$$NA^m = c,$$

or

$$\sum_{A=\infty}^{A} N = c[(1-m)A^{1-m}]_{\infty}^{A}.$$

Where N represents frequency of earthquake, A the maximum trace amplitude and m, c both constant. The value of m at this time was 1.8.

It must be added here that C. Richter[74] studied the same problem and proposed in 1935 a scale of magnitude of earthquakes based on their maximum amplitude.

Subsequently, this problem was studied by numerous investigators[75)-83)], and, as a result, it has been confirmed that Ishimoto-Iida's formula has been established almost irrespective of the place of observation, the magnification of the seismographs, etc., and the value of m is 1.8 to 2.2 in general earthquakes and after-shocks. From the fact that the relation between the magnitude and frequency of earthquakes in various places is always the same, it is concluded that the magnitude and fre-

73) M. ISHIMOTO and K. IIDA, *Bull. Earthq. Res. Inst.*, **17** (1939), 443.
74) C. F. RICHTER, *Bull Seism. Soc. Amer.*, **25** (1935), 1.
75) K. IIDA, *Bull. Earthq. Res. Inst.*, **18** (1940), 575.
76) T. MATSUZAWA, *Bull. Earthq. Res. Inst.*, **19** (1941), 411.
77) H. KAWASUMI, *Bull. Earthq. Res. Inst.*, **30** (1952), 319.
78) C. TSUBOI, *Jour. Phy. Earth.*, **1** (1952), 47.
79) Z. SUZUKI and T. ASADA, *Geophys.* Notes 1, 2, (1947, 1949).
80) T. ASADA, Z. SUZUKI and Y. TOMODA, *Bull. Earthq. Res. Inst.*, **29** (1951), 289.
81) Z. SUZUKI, *Sci. Rep. Tohoku Univ.*, [V], Geophys., **5** (1953), 177.
82) S. SAKUMA, *Geophys. Bull Hokkaido Univ.*, **6** (1958), 1.
83) Y. TOMODA, *Zisin*, [ii], **7** (1954), 155. etc.

quency of earthquake at the hypocentres are also in the same relation.

Here, the above relation in respect to earthquakes originating from volcanoes will be outlined. To make clear the problem it is necessary to investigate each kind of earthquake, i. e., the A-type, the B-type, and the explosion earthquakes.

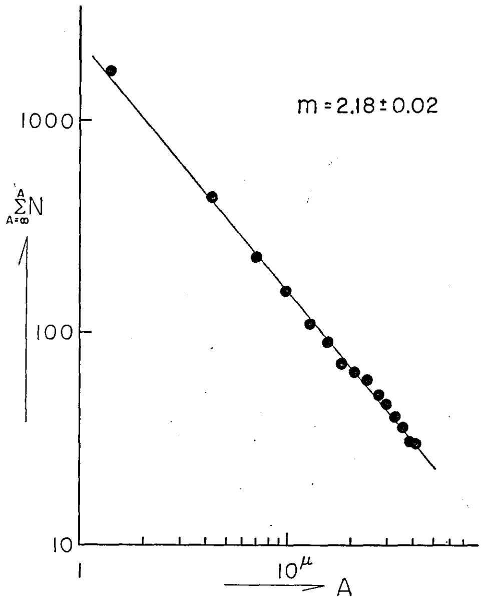


Fig. 24. Magnitude and frequency of the Hukui after-shocks.

A-type volcanic earthquakes originating from Hawaii Is. and Aso-san have been investigated, and the results obtained in each case indicate that the A-type volcanic earthquakes are not different from general earthquakes. The hypocentres of these A-type volcanic earthquakes in Hawaii Is. are 2 km, to several tens of kilometers in depth, those in Aso-san are 1–8 km, in depth, and the value of m is 1.8–1.9 in both cases. However, observation data on A-type volcanic earthquakes is not always sufficient. Therefore, it seems necessary to investigate this problem again in the future together with an accurate determination of the hypocentres.

As to B-type volcanic earthquakes, the results of investigation based on a great deal of observation data in Asama-yama indicate large values of m, 2.8–4.5, which are vastly different from the values in general earthquakes. As regards B-type volcanic earthquakes associated with the activities of Minami-dake in Sakura-zima and Usu-san, the value of m is 4.0–4.1 in the former and 3.1–3.8 in the latter. These values are almost similar to those in Asama. In B-type volcanic earthquakes in Asama, sometimes there are cases where the value of m obtained from the observations conducted at points 2–3 km. distant from the crater appears as a function of the amplitude, and the relationship pointed out by Ishimoto and Iida is not established apparently. This phenomenon, however, is ascribable to the following reason: The vibration-period of the maximum amplitude of earthquake-motions, is short, at least statistically, in the case of the lesser amplitude, and, in the case of the amplitude greater than a certain degree, the vibration-period is almost constant. Therefore, the attenuation associated with the propagation of seismic waves is not constant, and the attenuation of seismic waves of small amplitude is prominent. In such a case, if, taking

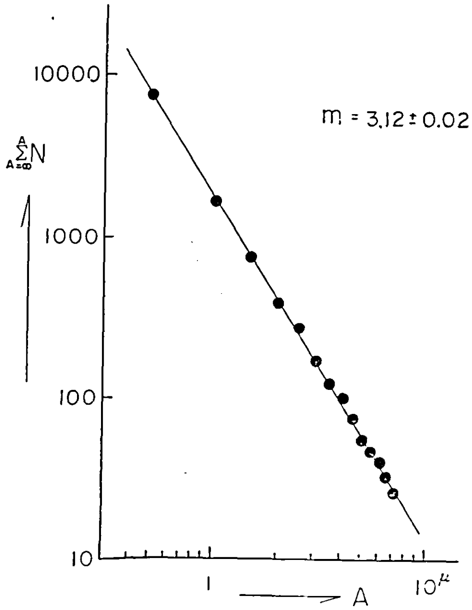


Fig. 25. Magnitude and frequency of B-type volcanic earthquakes originating from Asama.

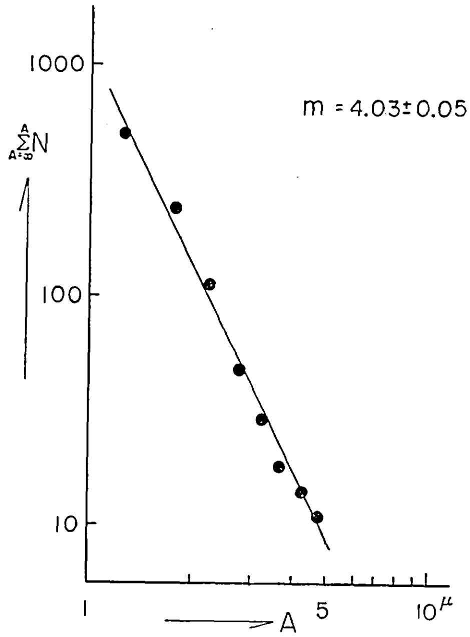


Fig. 26. Magnitude and frequency of the B-type earthquakes originating from Minami-dake, Sakura-zima.

the attenuation into account, the amplitude is reduced to that at the hypocentre (the crater in this case) and the relationship between the magnitude and frequency is reduced to that at the hypocentre, then the value of m becomes constant almost irrespective of the amplitude, and the values 2.8–4.5 are obtained.

In short, the attenuation associated with the propagation of seismic waves is represented by

$$A_{(\varDelta)} = A_0 e^{-k\varDelta} \varDelta^{-n}$$

where $A_{(\varDelta)}$ is the amplitude of earthquake-motion observed at distance ($\varDelta$) from the epicentre (crater), A_0 is the amplitude at the epicentre, n

1 or 1/2 in accordance with the body waves or surface waves, and k the attenuation coefficient. The value of k in this formula is a function of the amplitude and not constant, therefore, the relationship between the magnitude of amplitude A and the frequency observed at Δ does not represent the relationship between the magnitude of amplitude A and the frequency at the hypocentre unless a correction is made.

Next, the relationship between the magnitude and frequency in cases of explosion earthquakes will be discussed taking explosion earthquakes in Asama and Minami-dake in Sakura-zima as examples. As regards the magnitude and frequency of explosion earthquakes in the above two volcanoes, the relationship has been established to be that pointed out by Ishimoto and Iida and the value of coefficient m is 2.7–3.5 in the former and 3.9–4.0 in the latter, which is extremely large when compared with that of general earthquakes and is of almost the same value as those in B-type volcanic earthquakes.

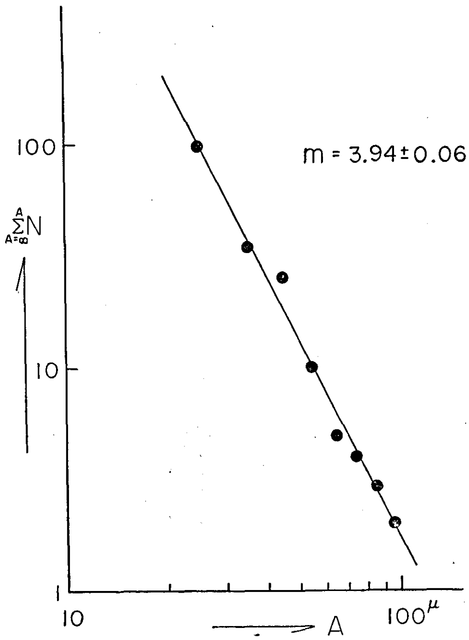


Fig. 27. Magnitude and frequency of the explosion earthquakes originating from Minami-dake, Sakura-zima.

It is noticeable that the relationship between the magnitude and frequency of explosion earthquakes in Mt. Asama and Sakura-zima, i. e., the value of Ishimoto-Iida's coefficient (m), coincides with the value of m in B-type volcanic earthquakes originating from each of the above volcanoes.

On the other hand, the magnitude of explosion earthquakes and B-type volcanic earthquakes was compared. The upper limit of the magnitude of B-type volcanic earthquake in Asama-yama is about 5μ at a distance of 4 km from the crater (or the epicentre), and about 20μ at a distance of 2.5 km from the crater, where few earthquakes of larger magnitude occur. It has also been discovered that the lower limit of the magnitude of explosion earthquakes is about 5μ at the former point and 20μ at the latter point. Thus the upper and lower limits of the maximum amplitude of earthquake-motions of both kinds almost agree with each other.

As described before, the hypocentres of these two types of earthquakes are distributed over an area of several hundred metres under the bottom of an active crater, that is to say, these two kinds of earthquakes agree also with each other in the positions of the hypocentres. They resemble each other in the nature of the earthquake motions and no remarkable difference can be found except in their amplitudes. Consequently, unless a magnification of seismograph is taken into account, there are many cases where the two kinds of earthquakes cannot be distinguished by examining the seismograms alone.

In many cases earthquake-vibrations associated with the explosive eruptions of volcanoes are accompanied by explosion sounds or detonations. In the case of a strong explosion sometimes window-panes facing the crater are destroyed over the whole foot of the volcano. The explosion of Asama on Nov. 10, 1958, is a remarkable example. At Asama explosion earthquakes and explosion sounds are recorded with seismographs and at the same time the explosion sounds are recorded on a magnetic tape. Thus the arrival times of explosion earthquakes and explosion sound waves are accurately measured by the recording of every second mark from the same clock. Making use of the difference between the arrival times of both earthquake-vibrations and sound waves and, under the assumption that the explosion sound occurred simultaneously with the eruption at the crater bottom, it has been disclosed that explosion earthquakes took place in area several hundred meters under the crater bottom a second or two before the commencement of eruption.

Previously the writer defined explosion earthquake as earthquake accompanying explosive eruption. From the above observation, however, explosion earthquake should be defined as earthquake accompanied by explosive eruptions. That is, from the occurrence times of both phenomena, it is reasonable to conclude that the earthquake is the cause, and the explosive eruption takes place as a result of the earthquake.

The geographic distribution of the initial motions of earthquake offers a key to the force that causes earthquake. The initial motions of explosion earthquakes indicate 'push' in every direction irrespective of which directions is taken from the epicentre and no initial motions of 'pull' appear. This has been disclosed as far as explosion earthquakes of Asama are concerned. Earthquakes accompanied by explosive eruptions at Minami-dake in Sakura-zima are also considered similar, though the observations carried out there are not sufficient. Whether or not the initial motions of B-type volcanic earthquakes are the same as those of explosion earthquakes is an important clue for clarifying the mechanism not only of B-type earthquake but also of the explosion earthquake and volcanic eruption. This has not yet been confirmed however, owing mainly to the insufficiency of observation. It is also one reason why, as described above, the magnitude of B-type volcanic earthquakes is small. This problem must be solved as soon as possible.

In the previous paragraph, based on observations and measurements of explosion earthquakes and B-type volcanic earthquakes, the characteristic and the relationship between these two kinds of earthquake hitherto revealed, were described. From these facts the problem naturally arises whether or not explosion earthquakes are a special type of B-type volcanic earthquake, i. e., whether or not, though the cause of both earthquakes is the same, when a B-type volcanic earthquake larger than a certain degree takes place, the solidified lava surface of the crater bottom is destroyed causing eruptions. As to the cause of why of B-type volcanic earthquakes occur, it is conceivable that magma rises near the crater bottom and the strain is newly produced by the separation of the gas contained in the magma and its expansion in volume.

Thus the remarkable increase in the frequency of B-type volcanic earthquakes previous to and during eruptions indicates a high probability that when numerous earthquakes occur, as seen in the relationship expressed by Ishimoto and Iida's formula, earthquakes larger than a certain degree are also liable to occur, or in other words, the remarkable increase in the occurrence of B-type volcanic earthquakes indicates a highly probable occurrence of B-type volcanic earthquakes strong enough to cause an explosive eruption. Herein lies the reason why the relationship between the frequency of B-type volcanic earthquakes and the occurrenc of eruptions is represented in the form of the above-mentioned relationship based on probability.

13. General earthquakes and earthquakes originating from volcanoes

It was described that general earthquakes and earthquakes originating from volcanoes differ in the area where the earthquakes take place, and that this difference is particularly apparent in the depths of the hypocentre.

As to the cause of the earthquake-generating force by which these earthquakes of different hypocentral depths are caused, there is no confirmed elucidation. Some consider that, with regard to general earthquakes originating from depths of several tens of kilometers and earthquakes originating from greater depths, strain is produced by the change in volume brought forth by the partial solution of solid substance crystallized in the interior of the earth's crust, or in other words the change from a solid phase to a liquid phase. Some are of the opinion that magma produced by melting rises to the upper part because of a local increase in the pressure through the separation of the gas in the magma together with the decrease in outside pressure, resulting in the production of strain which causes earthquakes before the magma reaches the ground surface.

In shallow earthquakes originating from dormant or extinct volcanoes like the Hakone volcano in or directly under which the existence of magma is inconceivable, the earthquake-generating force might be the stress in the volcanic bodies resulting from gas of a high temperature separated from the magma, or in other words breaking of an unstable equilibrium accompanying the changes in pressure and temperature of liquid phases and gaseous phases.

The relation between the magnitude and frequency of general earthquakes, i. e., Ishimoto-Iida's coefficient m ranges from 1.8 to 2.2 for general earthquakes and from 2.7 to 4.0 for B-type volcanic earthquakes and explosion earthquakes. This value differs greatly from the former value. Is this difference ascribable to the mechanism of earthquake occurrence or the complex and heterogeneous structure of volcanoes or should it simply be attributed to the difference in the depth of the hypocentre?—this is a vital problem that must be solved.

The effective method by which the difference in the mechanism of earthquake occurrence can be investigated is by clarifying the geographic distribution of the initial motions of earthquake-vibrations. In the cases of general earthquakes, the 'push' and 'pull' of the initial motions are always apparent and the push region and the pull region are sometimes set out in a quadrant formation and sometimes both regions are separated by a conical curve.

However, as far as explosion earthquakes are concerned, 'push' alone appears and 'pull' does not appear in the distribution of initial motions. This problem has not yet been confirmed for B-type volcanic earthquakes, but, judging from the distribution of the initial motions in the case of explosion earthquakes and general earthquakes, both earthquakes are considered to be different in the mechanism of their occurrence. Hence one may suspect that the difference in the relationship between the magnitude and the frequency of earthquakes is caused by the difference in the mechanism of their occurrence. Therefore, it becomes impossible to conclude that the above difference is attributable to the depths of the hypocentre alone. The only way to solve this problem is by determining accurately the distribution of the initial motions, the Ishimoto-Iida coefficient m, and the depths of the hypocentre of A-type volcanic earthquakes originating from volcanoes and having intermediate characteristics between general earthquakes and B-type volcanic earthquakes including explosion earthquakes.

Fortunately, from observations of the earthquake swarms carried out on the Hakone volcano from September 1959 to April 1960, useful data concerning the problem was obtained. Needless to say, the earthquakes that originated in swarms from the Hakone volcano belong to A-type volcanic earthquakes and the hypocentre was determined within a probable error of 200 m–300 m. On the other hand, the value of Ishimoto-Iida's coefficient m as the acceleration amplitude and the displacement amplitude observed with an acceleration seismograph and a displacement seismograph respectively is as follows:

Acceleration amplitude $m_A = 2.64 \pm 0.02$
Displacement amplitude $m_D = 2.60 \pm 0.02$

That is, both amplitudes show the value 2.6. The value is larger than that of general earthquakes and somewhat smaller than that of B-type and explosion earthquakes which is 2.7–4.0.

As described above, the depths of the swarm earthquakes in Hakone were situated between 0.8 km and 5.0 km under the ground surface, and most of them were between 1.0 km and 2.0 km in depth. Consequently the depths of the hypocentres also are shallower than those of general earthquakes and deeper than those of B-type and explosive earthquakes.

Next, the distribution of the initial motions will be mentioned. As a result of an investigation of about 100 earthquakes belonging to the earthquake swarm in Hakone, it was confirmed that in most earthquakes both 'push' and 'pull' appeared and were formed in quadrants. That is, in spite of being different from explosion earthquakes in the mechanism of occurrence as viewed from the distribution of the initial motions, the coefficient m shows a value close to that of explosion earthquakes and B-type volcanic earthquakes and, the value is larger than m of general earthquakes which have the same distribution of initial motion. In short, it may be concluded that the difference in the value of the coefficient m is not a result of the difference in the mechanism concerning the production of seismic waves but of the difference in the depth of the hypocentre alone. Needless to say, for a solution to this problem, further study is necessary, on A-type volcanic earthquakes of other volcanoes.

The shallower the hypocentre, the larger is the value of coefficient m. This means that, in the case of a shallow hypocentre, major earthquakes are not apt to occur, minor earthquakes taking the place of major ones. Based on this fact one can consider an example with an upper limit on the magnitude of earthquakes originating from a certain depth (h). Earthquakes exceeding the limit cannot take place. That is, in the shallow section, the volume of the hypocentral domain is more controlled than in the deep part, and the uppermost limit for the accumulation of the strain that causes earthquake-vibrations is low. Accordingly, the upper limit (A) of earthquakes that originate from a certain depth (h) is, for example, represented by

$$A = ch^x ,$$

where x is, for example, 2–3 and c is a constant related to the destructive strength and the elasticity of materials constituting the earth's crust. Therefore, c also has a relationship with the depths of the hypocentre.

Therefore, the above formula will be written as follows:

$$A = c'h^y h^x = c'h^{x+y}$$

where c' is a constant relating to material only and y is generally positive.

Thus, major earthquakes are not apt to occur in the area near the earth's surface, and on the other hand, when a strain is produced in the earth's crust with the rise of magma or gas of a high temperature near the earth's surface, numerous minor earthquakes take place accompanied by numerous small destructions through which the strain is released.

Besides the reasons mentioned above, it must be added that the large value of the coefficient (m) for the extremely shallow earthquakes from volcanoes depends on the complex and heterogeneous structure of volcanoes and on the manner of the concentration of stress in volcanoes, which is given by the heat from the magma.

14. Conclusion

In this paper, the various characteristics of earthquakes originating from volcanoes and crustal deformations associated with eruptive phenomena were discussed in comparison with general (or tectonic) earthquakes and crustal deformations associated with general earthquakes.

First, general earthquakes and volcanic eathquakes are compared with respect to their hypocentral depths, and volcanic earthquakes are classified in four types according to the position of the hypocentre and the relationships with the volcanic eruption.

With respect to crustal deformations, remarkable differences between those relating to the phenomena are shown as represented in several examples.

It is the writer's main purpose to elucidate how earthquakes and crustal deformations from volcanoes are connected with the rising movements of the magma from the earth's interior to the earth's surface and what are their special features compared with those not originating from volcanoes.

Besides the differencees in depth of the hypocentral position, there is a remarkable difference in the relationship between the magnitude and the frequency of the volcanic and the general earthquakes.

After investigating the relationship between the magnitude and the frequency of various kinds of volcanic earthquakes, the writer arrived at the conclusion that the explosion earthquake is a special type of the B-type earthquake. In other words, B-type earthquakes exceeding a certain degree in magnitude are followed by an explosive eruption.

In general, explosive eruptions in andesite and dacite volcanoes are preceded by a marked increase in B-type earthquakes. It is reasonable to say that the relationship between explosive eruptions and the frequency of B-type earthquakes, or the relation between explosive eruptions and the frequency of B-type earthquakes, or the relationship available for predicting volcanic eruptions of the Vulcanian type, based on the frequency of B-type earthquakes, is provided by a relationship of probability as infered from the Ishimoto-Iida formula. The reason is that the more frequently B-type earthquakes occur, the stronger is the probability that B-type earthquakes of big magnitude will occur.

31. 噴火予知に関する基礎的研究 (I)

火山活動に関連する地震と地殼変動

地震研究所　水　上　武

地下数十粁以上の深さに岩漿が生成し，上昇して，やがて地表に噴出する現象が火山の噴火であるが，岩漿の生成，上昇に伴つてどのような現象が現われるであろうか．

1) ここでは噴火現象に関係して現われる地震及び地殻変動を一般の地震並にそれに伴つた地殻変動と比較して，それぞれの著しい特徴を述べた．

特に岩漿の上昇に伴つて火山の地震及び地殻変動がいかなる性質を示すかに注目した．

2) 火山に発生する地震をその震源の位置及び噴火現象との関連によつて四種類に分類した．同時に 2, 3 の火山について，震源位置の分布の実例を示した．

3) 安山岩質火山 (浅間山) に発生する B 型火山地震とヴォルカノ式噴火の発生との関係を調べ，B 型火山地震の頻度から噴火発生の危険率を推定することの可能なることを述べた．

4) 各種の火山地震について，その大きさと頻度との関係についての概略を記述した．

5) B 型火山地震と爆発地震について，次の諸点から爆発地震は B 型火山地震の特別な場合であることを結論した．

a) 震源の位置がほぼ一致すること．

b) 石本・飯田の係数 m の値が共に 3～4 を示すこと．

c) B 型火山地震の上限と爆発地震の下限とがほぼ一致すること．

d) 地震動の性質が類似すること．

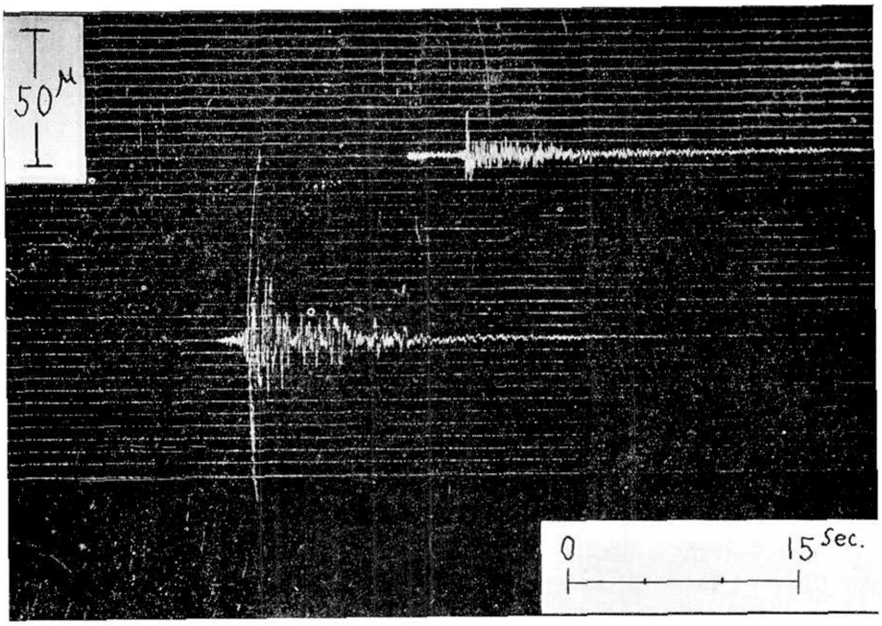
以上の理由で，ある程度以上大きい B 型火山地震の発生によつて爆発的噴火が発生することが推定される．

6) 以上の事から，B 型火山地震の発生頻度が増大すれば．大きい B 型火山地震の発生する確率が増加し，従つて火山の爆発を伴う確率も増大する．

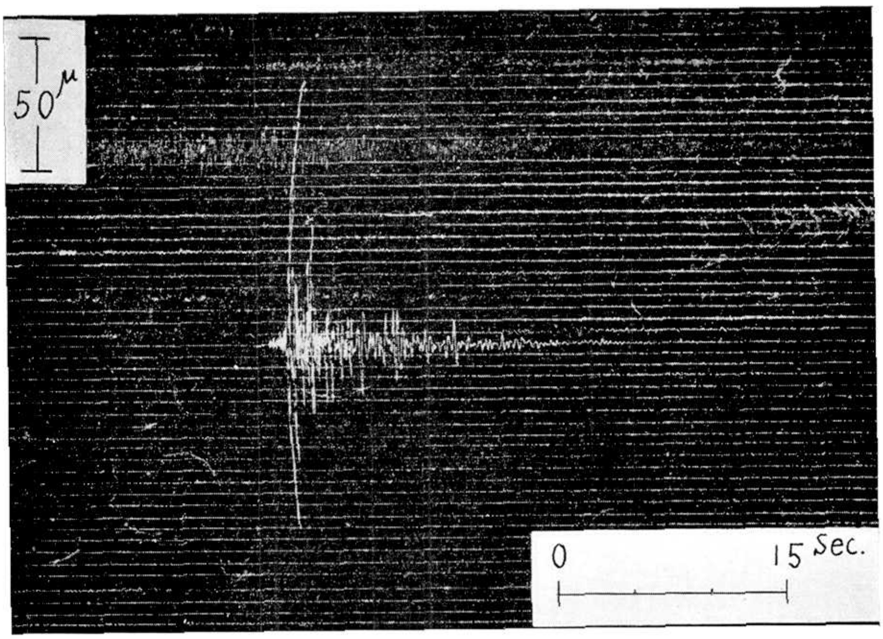
7) 最近の箱根火山の群発地震，つまり A 型火山地震についてその震源位置を精しく調査した結果，その深さの大部分は神山中央火口丘の下 1～2 km の間であること，石本・飯田の係数 m の値が 2.6 を示し，一般の地震と B 型ないし爆発地震との中間の値を示すことが判つた．

8) 石本・飯田の係数 m の値が一般の地震，A 型火山地震，B 型火山地震及び爆発地震について，それぞれ 1.8～2.2, 2.6, 3.0～4.0 の値を示す結果となつた．この事に関して，次のような事が考えられる．震源の深さによつて震源の大きさは制限を受けるが，震源が極端に浅い場合には，特にその影響が著しい．そのために地震の大きさの上限について制約される．また，地震の大きさと頻度は，そこを構成する物質の破壊強度，弾性，不均一性，地質構造等に関係すばかりでなく，火山地震の場合の如く，地表近くの狭い範囲に急激に，しかも過剰に与えられる stress の集中の仕方に関係するものと考えられる．

[本研究の一部は文部省科学研究費によつて行つた.]



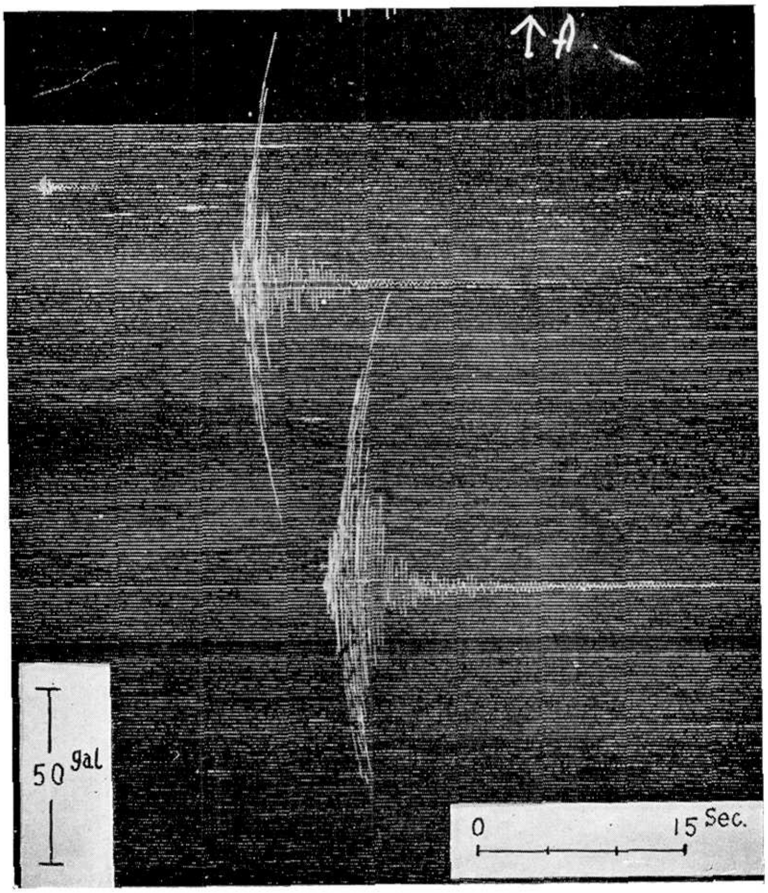
(a)



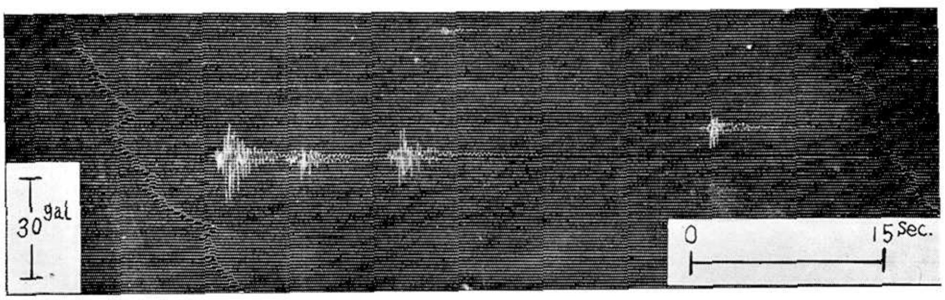
(b)

Fig. 28. The seismogram of the Hukui after-shock (a), and the seismogram of the A-type volcanic earthquake from Usu (b).

(震研彙報 第三十八号 図版 水上)



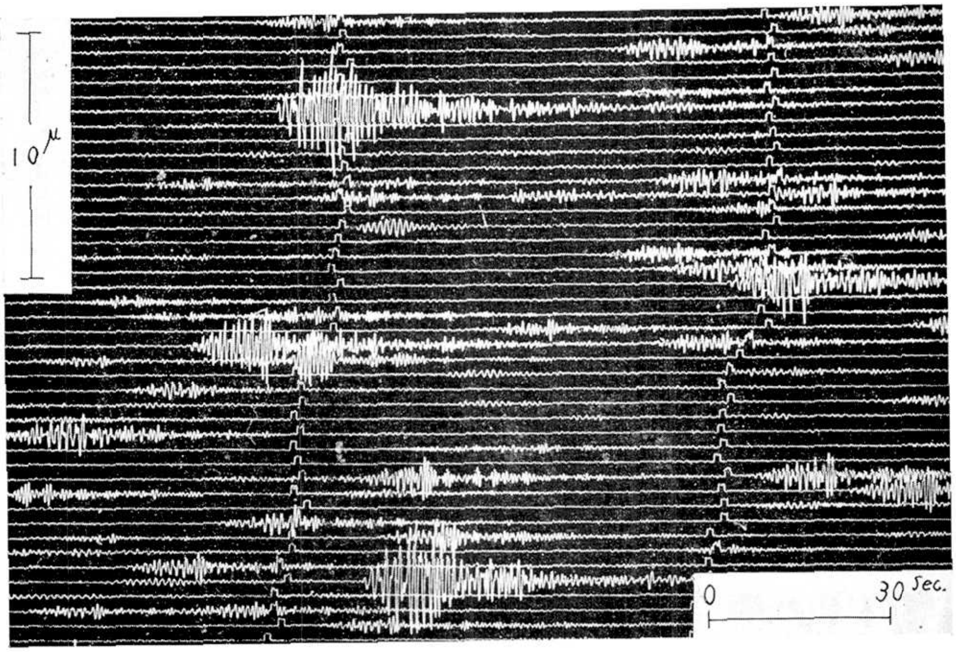
(a)



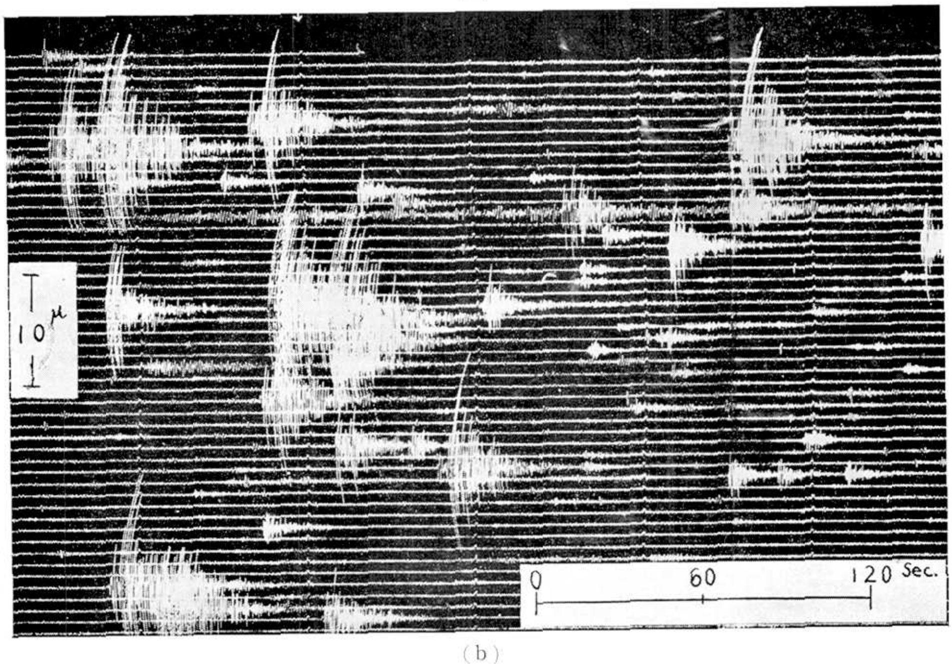
(b)

Fig. 29. The seismograms of the 1960 Hakone earthquake swarm.

(震研彙報 第三十八号 図版 水上)



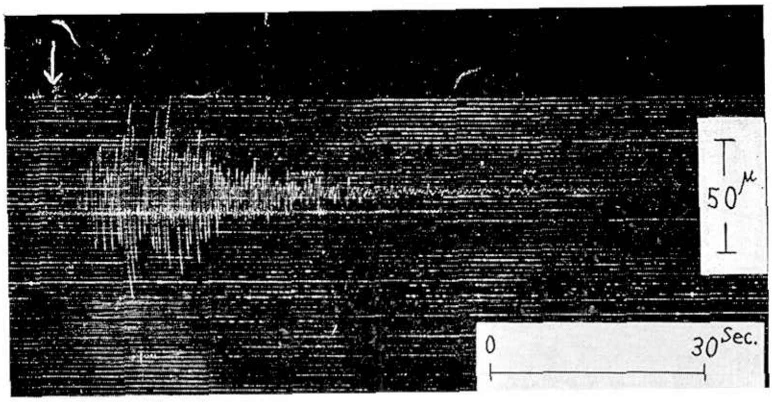
(a)



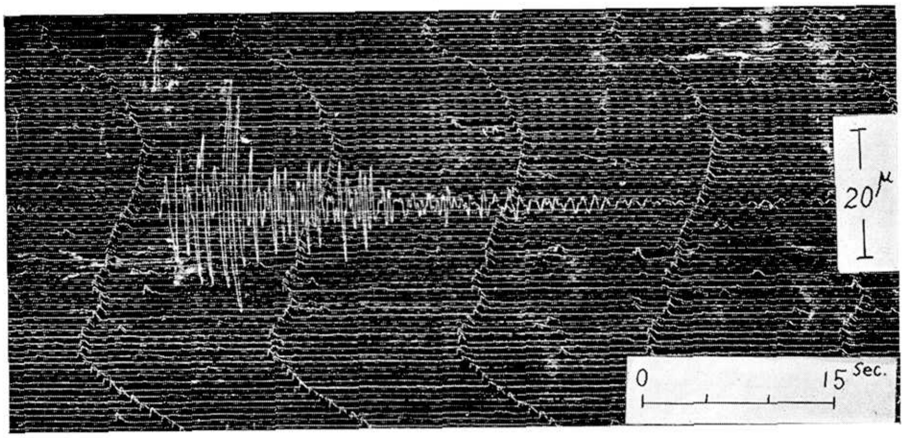
(b)

Fig. 30. The seismogram of the B-type earthquakes which appeared about one month before the 1958 activity of Asama (a).

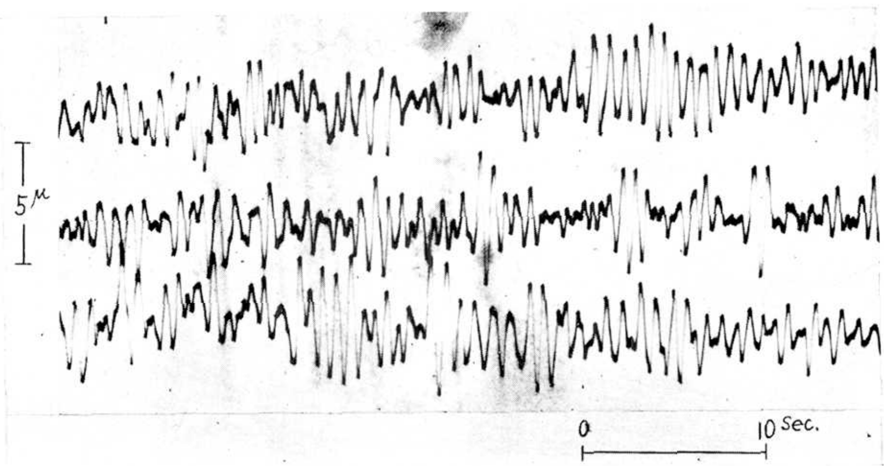
The seismogram of the B-type earthquakes which appeared about 20 hours before the strong explosive eruption of Asama on Nov. 10, 1958 (b).



(a)



(b)



(c)

Fig. 31. The seismogram of the Asama explosion earthquake (a).
The seismogram of the Minami-dake (Sakura-zima) explosion earthquake (b).
The seismogram of the volcanic tremor of Oo-sima (c).