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(With 21 figures)

On Explosive Activities of Andesitic Volcanoes and Their Forerunning Phenomena.

CONTENTS

1. -- Introduction

That marked topographical deformations accompanied explosive activities were made clear in the case of a number of volcanoes from resurveys by triangulations and precise levellings. For examples, during the activities in the Usu volcano, in 1910 and 1944, Sakura-sima in 1914 and 1946, Komagadake in 1929, Miyake-sima in 1940, and Asama in recent years, large scale subsidences and upheavals in the vicinity of these volcanoes were brought to light. Similar results were noticed by foreign investigators in the cases of Merapi, Central Java, and Kilauea and Mauna-Loa, Hawaii, etc..

Since these topographical deformations appear at a point on the earth's surface as variations in the inclination of the ground, it seems reasonable to expect marked tiltings of the ground in volcanic regions as an usual accompaniment of volcanic activities.

Although these volcanoes do not all show the same characteristics in their eruptions, the marked deformations that accompany them are a common phenomenon. In the case of active volcanoes however, continuous and precise observations of these tilts have not yet been made for a sufficient length of time to yield accurate knowledge with respect to the relation between volcanic activities and variations in the inclination of the ground.

In the Hawaiian Volcano Observatory, T. A. JAGGAR and R. H. FINCH have been continuing tilt observations by means of BOSCH-OMORI seismographs and other instruments since 1913. Although severe eruptions occurred in Kilauea in 1920 and 1932, and Mauna-Loa in 1942 no relation of the activities to the tilt of the ground could be established. Judging from their reports, the instruments used for the purpose were too unduly affected by variations of air temperature to enable study of the ground tilts that accompany volcanic activities.

In the Asama Volcano Observatory, similar observations, by means of silica clinographs, have been made since 1934. In this paper, the writer presents the results of tilt observations made during the last 14 years and some discussions on their correlations with volcanic activities and on the forecast problem of the eruption.

2. — Volcanic Earthquakes of Various Volcanoes

It is doubtless well known that in the case of volcanoes, an earthquake is accompanied with an explosion, which we now call an explosion-earthquake for the convenience of description. Fig. 1, (a) is a seismogram of an explosion-earthquake recorded at a distance of 4.5 km. east of the Asama crater. Studies of these explosion-earthquakes show that the periods of the P and the other kinds of waves, are all 0.5-0.8 second. Whence it may be said that the periods of P and preliminary tremors of explosion-earthquakes are markedly larger than those of ordinary volcanic earthquakes, in contrast to which, the phase of explosion-earthquakes is not recognized so distinctly on their seismograms.

A marked character of an explosion-earthquake is that the surface waves are markedly dominant, its amplitude corresponding to five or ten times that of the P and S waves, the reason for which is that the hypocenter of an explosion-earthquake is very shallow.

On the other hand, in the neighbourhood of the Asama volcano, there occur sometimes other kinds of earthquakes which do not accompany volcanic explosions, being mostly of very small intensity [see Fig. 1, (b)]. The depths of these hypocenters are estimated at about two or three km below the earth's surface. From the wave forms of this kind of earthquake on the seismograms, it is difficult to distinguish it from those of an ordinary tectonic earthquake [Fig. 1 (c)] that is recorded near its epicenter. In other words, the phases of the P and S waves are distinctly recognized on the seismogram, their periods being about 0.2-0.4 second, much shorter than those of the former kind of earthquake. As seen on the seismogram, it is easy to distinguish the one from the other. (see Figs. 1-2).

These two kinds of volcanic earthquakes occur not only in the Asama volcano of the « Vulcanian type » but also in Miyake-sima and Oosima of the « Strombolian type ». An example of these two kinds of earthquakes occurred at Miyake-sima at the time of its explosive activity of July 1940. [Fig. 2, (a), (b)]. According to the seismometric study of Miyake-sima at the time, a number of earthquakes of ordinary type occured at depths of 3 or 4 km below the central part of Miyake-sima island. The explosions of the summit crater in the island at the time, which occurred at short intervals of a few seconds, continued for three weeks — a character common to eruption of the Strombolian type. In this activity of Miyake, explosion-earthquakes occurred with each individual explosive eruption at short intervals of a few seconds, with the result that on seismograms recorded at a distance of 4 km from the origin, these explosion-earthquakes appeared as continuous waves of the pulsation type throughout the whole period of volcanic activity. The amplitudes of seismic waves of the continuous pulsations increased or decreased with changes in the intensity of explosion. The same phenomenon was observed in the explosive activities of Strombolian type volcanoes, namely, Kusatu-Sirane, in 1937 and 1938, Oosima in 1940, Aso in 1932, Sakura-sima in 1946. In addition, at the time of the activities of Volcano Usu, there occurred not only these two kinds of earthquakes but also another type of earthquakes followed by growth of a new lava dome. The earthquakes of this kind have the intermediate character between the ordinary earthquake and the explosion one on their seismograms. Seismograms of these earthquakes of various types shown in Fig. 3 were recorded by the same seismograph, of which the constants were as following;

Magnification	=	400
period	=	1.0 second
Damping ratio	=	10:1

Full discussion of the correlation between the seismic activity near the volcano and its explosive activity is reserved for the forthcoming paragraph.

3. — The Distribution of Volcanic Bombs and the Energy of an Explosion of Asama

The initial velocity of volcanic bombs, lava-blocks and volcanic detritus ejected in the eruptions of volcanoes seeing an important datum in estimating the magnitude of the explosions, the problem has received the attention of a number of investigators.

On the other hand, F. v. WOLFF studied the problem thermodynamically and obtained the pressure at the instant of explosion of Santorin, Mont. Pelée, Lassen Peak and other volcanoes. Asama is the most typical andesitic (acidic) volcano and Aso, Oosima, and Miyake-sima the basaltic (basic) volcanoes.

The outstanding characteristic of Asama's explosions is strong detonation and ejection of much juvenile lava, usually ending in a few minutes and returning to the normal state. Another distinguishing property of this volcano is that, even in very active periods, two or more strong explosions on the same day are very rare, usually, several days intervening until the next explosion.

In contrast to this explosions of Oosima, Aso, Miyake-sima, and other basaltic volcanoes are usually much less violent, the amount of ejecta being also much smaller, although the number of explosions is much larger, continuing without interruption for several hours or for a number of days.

In a violent explosion of Asama, a large quantity of ejecta such as lava blocks, volcanic bombs, lapilli, and ash, with steam and gas, are thrown out at a great velocity from the crater, with smaller fragments, such as ash, with gas and steam, ejected with less velocity for several minutes.

As one method of measuring the intensity of the recent explosion of Asama, the writer studied at the start the velocity of various bombs at the instant of ejection. Usually, the flight of the volcanic bombs is determined by the manner in which they fall on the ground, namely, the angle at the moment of ejection (angle of emission), and the time consumed in the flight, and the angle at which the bomb fell, and other conditions. The initial velocities of various bombs were obtained for thirty explosions during the recent volcanic activity.

For convenience of computing the flight, bombs as nearly spherical as possible were selected, and the mean density of air and the velocity of the wind were taken. Further, it is assumed that the vertical component of air resistance affects only the vertical component of flight and the horizontal resistance of air affects only the horizontal component of the motion.

Since, in the present computation, bombs larger than 50 cm. in diameter being mostly dealt with and the effect of air resistance to bombs of large size being not remarkable, the simplifications and assumptions mentioned above do not seriously affect the result.

1). — The Explosion of April 16, 1937.

The explosion of April 16, 1937, was one of the most remarkable in the recent activities of 1935-1947.

Topographical surveys of the interior of the crater were made on April 13, three days before the explosion, and on April 17, the day following the explosion. As the results of these topographical surveys, changes in the crater floor, both in form and depth, were made clear. After this explosion, the exact positions where the bombs fell and the diameters of these bombs were investigated and the bomb-fall area obtained. The result is given in Fig. 4 with a rough topographical map of the volcano. It should be noted that the bombs shown in the distribution map are only those that fell farthest away from the crater, in all directions those that fell near the crater being excluded.

According to the topographical surveys before and after the explosion, the surface of the pit before the explosion was quite flat, whereas by the explosion, the western part of the pit, with a volume of about 50m×50m×30m, was thrown out in the form of lava blocks, volcanic bombs, and volcanic sand and ash. Although most of this material fell outside the crater, a part of it had either fallen back into the crater or was prevented by the crater-wall from leaving the crater, with the result that it accumulated on the eastern floor of the crater.

At the same time, in the north-eastern part of the volcano, a number of bombs fell in the woods and injured the trees. For this reason, the angle of fall of these bombs were obtained by measuring the scars on the trees and the positions of these bombs on the ground.

The measured angles of fall of the bombs were as follows;

TABLE I.

	D	φ	H	Z
1	90 cm	60°	3450^{m}	-850^{m}
2	75 cm	57°	3320^{m}	-835^{m}
3	60 cm	59°	3000^{m}	-830^{m}

where D: diameter of bomb

H: horizontal distance between the origin of emission and the place of fall

Z: vertical distance

φ : angle of fall

From these data, the initial velocities and the angles of emission were computed, as follows:

	V	θ
1.	178 m/sec.	43°
2.	183 m/sec.	37°
3.	176 m/sec.	42°

where V: initial velocity
θ : angle of emission

The mean initial velocities obtained for these bombs is 179.0 m/sec.

On the other hand, as is seen from Fig. 4, in the distribution of bombs, those on the eastern side travelled a markedly greater distance from the crater than those on the western side, the former distance being almost five times that of the latter. From this fact, and from the manner in which the ejecta had accumulated on the floor of the crater, it may be reasonable to suppose that the range of angle of emission within which it is possible for the bombs to leave the crater, is an important factor in the distribution of the bombs, so that the angle of emission with which the bombs reach the greatest distance from the crater was studied for various diameters of bombs. The angles of emission (α) of bombs that would travel the farthest, if there were no crater-wall, are obtained for all directions of travel from the crater, with results as shown in Fig. 5. Naturally, in these calculations, the effect of air and wind resistance at the time of explosion have been allowed for.

At the same time, the minimum angles (Θ) of emission for all the directions, in which it is possible for the bombs to travel from the origin of the explosion, to points outside the crater were obtained from topographical surveys of the crater.

These two kinds of angle of emission, defined above, namely Θ and α, were then compared with each other for all the corresponding directions, with the result that the angle α

is less than Θ, that is to say, that on account of the crater-wall, it was impossible for bombs thrown out with angle of emission α in whatever direction to fall outside the crater (Fig. 5). Consequently, it is concluded that the angles of emission with which the bombs travelled the farthest are the minimum angles of emission Θ with which it is possible for the bomb to leave the crater.

By assuming that these bombs reached the most distant places, travelling with the angle (Θ) of emission for each direction, the initial velocities of these bombs for every direction were obtained. In the present case, of the many bombs that fell in the same direction, the one that gave the largest velocity was selected for our purpose.

As the result of calculation, the initial velocities of the bombs for all directions are almost 160 m/sec.-170 m/sec., the mean value being 166.3 m/sec., which nearly coincides with the former result obtained by angles of fall.

In contrast to this, when a bomb, 50 cm in diameter, is ejected with an initial velocity of 166.3 m/sec., and with the angles of emission for all the corresponding directions from the crater into which they flew, the distances travelled by the bombs were computated for every direction.

On the map, Fig. 4, the result of calculation is shown by the closed curve I. Besides, the wind, which had a mean velocity of 10 m/sec., and which was blowing in the eastern direction at the time of the explosion, was allowed for in calculating the distances travelled by these bombs. The result is also shown by the closed curve II, on the same map. As is seen from Fig. 4 although these two curves pass through almost the outer margin of the bomb-fall area, closed curve II is closer to the bomb-fall area than is closed curve I.

Summarizing these results, it is concluded that all these bombs from the explosion on April 16, 1937, were ejected with almost the same velocity of 166 m/sec. the bombs that travelled farthest from the crater leaving it with the minimum angle of emission for their respective directions. At the same time, the phenomenon is interpreted from stand-point that the form of the bomb-fall area is a shadow of the edge of the crater-wall, assuming the western corner of the crater-floor to be the origin of the ejection.

2). — **The Explosion of April 20, 1935.**

In this outburst the center of explosion on the crater-floor, that is, the point on the pit, whence the lava was ejected, was nearly its center. Accordingly, the outer edge of the bomb-area is nearly of the same distance from the crater. As the result of the same study as the former case, it was made clear that the initial velocities of the bombs that fell on the edge of the bomb-fall area lies in the range between 151 m/sec. and 140 m/sec., and that the mean velocity is 144.5 m/sec. On the basis of the topographical survey of the pit in the crater, and the distribution of ejecta, the total mass of ejecta in this explosion was estimated at 2.3×10^5 tons.

3). — **The Explosion of June, 1938.**

In the present explosion, the unusually large lava blocks were ejected. One of them, which fell 300 m south-east of the crater, has a diameter of 7.5 m and weighs about 3.4×10^5 kg. (Fig. 6). Bombs almost 100 cm in diameter flew over Ko-Asama, a parasitic cone on the eastern slope of the volcano and at a distance of 3.5 km from the crater, and fell near our Volcano Observatory, 4.5 km from the crater. The mean initial velocity of these lava-blocks and incandescent bombs and the total mass of ejecta of this explosion were estimated at 212 m/sec. and 3.8×10^5 tons respectively.

4). — **The Explosion of February 2, 1936.**

This explosion was not so violent as the three already described. Explosions of this severity were fairly frequent during 1935-1947. In this explosion, the times taken by the bombs in their flight and the distances travelled by them were measured, and their initial velocities were estimated at nearly 130 m/sec. in the mean and its total mass of ejecta were about 8×10^4 tons.

The various results described above may be summarized as follows;

a) From the various elements for determining the flight of bombs, their initial velocities were obtained.

b) These initial velocities at the moment of ejection by same explosion are nearly the same.

c) From topographic survey of the crater-floor made both before and immediately following the explosion, and from investigations of bomb-fall areas, the mass ejected by each explosion was determined.

On the basis of these results, the kinetic energy necessary for importing the initial velocity to the ejecta is found to be

$$E = \frac{1}{2} MV^2$$

where M: mass of ejecta
V: mean velocity of ejecta at the instant of ejection.

On the other hand, T. MATUZAWA, who is of the opinion that BERNOULLI'S law practically holds in the pressure and the velocity of ejecta at the instant of explosion, gives the pressure at the time of explosion by the relation.

$$P = \frac{1}{2} \rho V^2$$

where ρ : mean density of ejecta
V: initial velocity of ejecta

The following kinetic energy and pressure at the instant of explosion were obtained for these four explosions described above.

Date of explosion	M	E	P
Apr. 20, 1935.	2.2×10^5 tons	2.3×10^{19} ergs	260 atm. pres
Feb. 2, 1936.	0.8×10^5 »	0.7×10^{19} »	210 »
Apr. 16, 1937.	3.0×10^5 »	4.2×10^{19} »	336 »
June 7, 1938.	3.8×10^5 »	1.7×10^{20} »	563 »

4. — The Intensity Scale of the Explosion of Asama

In the activity of Asama, every explosion occurred with an interval of several hours, at least, and in most cases several days, it is easy to identify on the seismograms the corresponding earthquakes that accompanied the explosive eruption. Reviewing the volcanic activities of Asama during the last fifteen years, it will be found that, although no explosion occurred in the years 1933, 1934 at all, a number of severe and moderate explosions occurred during the periods 1935-1943 and 1947, in which there were several tens of times of ebb and flow in the activity.

At all events the volcano was generally active throughout the period just mentioned, the number of violent and moderate explosions totalling six hundreds. From this large number, sixteen explosions were selected for which the individual kinetic energies were estimated from studies of the mass of the ejecta and of the motions of flight of the ejecta, as described in the preceding paragraph.

According to these results, the severest explosion that occurred in this period had an energy of 1.7×10^{20} ergs and 567 atmospheric pressure at the instant of explosion, while explosions of such intensity as 10^{19} ergs occurred now and then in the active periods.

In volcano Asama, which is of typical Vulcanian type, the energy of an explosion reached 10^2 or 10^3 times that of Miyake, in 1940, or that of Oo-sima, 1940, both of which are typical Strombolian.

Seismic observations were continuously made throughout the period with two kinds of horizontal seismographs at a distance of 4.5 km east of the crater, and all the explosion earthquakes were recorded. These numerous explosion earthquakes were thus recorded at the same station by the same seismographs. Since these explosions occurred in the vent of the central crater of the volcano, their hypocentres and the medium through which the seismic waves are propagated are nearly the same. A comparison of the seismograms of these explosions earthquakes shows that their wave forms markedly resemble one another, and that the amplitudes of the seismic waves, specially in the surface waves, depend on the intensity of the explosion, from all which it may be reasonably supposed that these explosion earthquakes occurred by means of almost the same mechanism, although their intensities differed.

In order to obtain an intensity scale of explosion, the kinetic energies of the sixteen explosions just mentioned and the maximum amplitudes of the surface waves of the corresponding explosion earthquakes are taken, as the result of which these two quatities are found to be connected by a simple relation as expressed by the formula

$$E = [0.03 + 4.50\ A + 0.70\ A^2 + 0.08] \times 10^{19}\ \text{ergs.} \quad (1)$$

where E : energy of explosion
A : maximum horizontal amplitude of surface waves (mm in unit).

The constant term in the formula (1) is due to the solid friction of the various points in the seismographs and the dissipation of the seismic waves in the medium on their course from the origin to the station.

TABLE II.

Maximum amplitude of the surface waves and explosion energy.

Date		A	E	
1935				
Apr.	20	0.440 mm	2.30 ×	10^{19} ergs.
May	16	0.227	1.20	»
»	22	0.092	0.50	»
»	27	0.212	1.00	»
Sept.	16	0.148	0.70	»
1936				
Feb.	7	0.140	0.70	»
Mar.	7	0.260	1.20	»
July	22	0.113	0.50	»
Oct.	15	0.307	1.50	»
1937				
Mar.	25	0.255	1.10	»
Apr.	6	0.136	0.69	»
»	16	0.552	4.20	»
Sept.	3	0.243	1.10	»
»	10	0.074	0.40	»
»	26	0.223	1.00	»
Nov.	6	0.137	0.60	»

In Table II, are shown the kinetic energies of the explosions and the maximum amplitude of the surface waves of the corresponding earthquakes, by means of which relation (1) was determined.

The energy scale of the explosion being obtained, with its aid the energies of all the explosions that have occurred during the last fifteen years were determined from the results of seismic observations.

Naturally, explosion earthquakes of smaller intensity than 3×10^{17} erg. were not recorded by our seismographs, although rough estimates of the energies of these small explosions were frequently made by investigating the mass of ejecta, of which volcanic ash is the largest constituent, and of the height of the smoke of explosion. According to these investigations, the total energy of these small explosions which are impossible to obtain by scale (1), is only 20 per cent of the total energy of all the explosions that occurred. Although the explosions stronger than 3×10^{19} erg. occurred within the last fifteen years, the energies of these very strong explosions were obtained directly by investigations of the mass of ejecta and their motion of flight, consequently, the energies of explosions obtained with the aid of formula (1) are those ranging in intensity from 3×10^{17} erg. to 3×10^{19} erg.

However, the intensity scale given by (1) contributed almost all the energy of the explosions that occurred.

Needless to say, it is possible enlarge the range of the energy-scale (1) by using seismographs of high sensibility, or by making the observations at a closer distance from the crater.

5. — Tilt Observations at Volcano Asama.

A pair of silica clinographs is placed in a cave of massive natural lava at a distance of 4.2 km E and 6.0 km N of the crater, namely, the Nakanosawa and the Oniosidasi stations respectively. Continuous observations were begun in 1933 at the former station and in 1936 at the latter. As the air temperature in these observation-rooms has a small range of only $0^\circ \pm 1^\circ$C. throughout the year, the unfavourable effects of air temperature on the instruments are greatly reduced. The records of tilts are obtained on bromide paper. The sensibility of the instruments are so adjusted that 1 cm on the bromide paper represents one second of arc of tilt. A small portion of the results of tilt observations at the Nakanosawa station, is represented by the two components (E-W), (N-S) of the tilt. (Fig. 7).

Judging from the structure of the ground, the Oniosidasi station is not so favourable situated for the present purpose as the one at Nakanosawa. Besides, the Oniosidasi station lies at such an inconvenient place for the observers to reach that some parts of the observations were missed. For the reason, the result at Nakanosawa forms the major part of the subject of the present study.

A glance at the variation curves of the tilt at Nakanosawa, shows that the variations in 1934, in which no explosion occurred, are much smaller than those in other years, in which the volcano frequently showed explosive activities. However, during the quiescent period of 1934, small variations of 3 or 4 seconds of arc appeared in the winter season; and upon reviewing also carefully the original records for active periods we find the same kind of small variations in tilts during the winter season. Moreover, the annual variation in tilt in 1934 was also about 5.0 seconds of arc, so that notwithstanding the very quiescent period of the volcano such seasonal and annual variations were observed.

Since, on the other hand, the marked variations in tilt observed during 1935-1939, in 1941 and 1942 amounted to 20-60 seconds of arc, are an outstanding feature compared with the seasonal and annual variations. As will be seen from Fig. 7 as well, the explosions occurred as a swarm of several or several ten explosions within one or several months. Looking backward on the progress of the two phenomena, we find that marked variations in tilt appeared associated with every one of these explosion-swarms.

In comparing the times of occurrence of these two phenomena, we find the very marked fact that the 1st explosion of an explosion-swarm occurred one or one-and-half months after the appearance of an abnormal tilt. In some cases, tilt began as an upheaval in the direction of the crater and returned to the original level within one or three months. But, the directions of these tilts in question are not always in the same sense as those just mentioned. What generally characterized them is that, within one or three months, the tilt curves mostly resume their original state, scarcely remaining as secular variation.

6. — Character Number of Tilt.

A comparison of the tilt curves with the occurrence of explosion swarms, suggests remarkable correlation of these phenomena. In order to enable quantitative treatment of the problem and ascertain the relation more precisely, the degree of variability of tilt is defined in the following manner.

From the original records of tilt the reading of (θ'_n) at 12h every day is taken, in which the zero position of tilt is taken the reading of January 1, 1934, at zero, but since the daily variation in tilt is less than 0.2 second of arc, just enough of the effect is nullified to render attainment of the object by taking of the readings at the same hour every day, and then, the mean value (θ_n) of the readings for three successive days are adopted.

Readings at 12h $\theta'_1, \theta'_2, \theta'_3, \cdots\cdots\cdots \theta'_n$.

The mean values for three successive days are,

$$\theta_2 = \frac{1}{3}(\theta'_1 + \theta'_2 + \theta'_3),$$
$$\vdots$$
$$\theta_{3n-1} = \frac{1}{3}(\theta'_{3n-2} + \theta'_{3n-1} + \theta'_{3n}).$$

Moreover, the differences of the every other mean values are taken. Such as

$$\Delta\theta_5 = \theta_8 - \theta_2,$$
$$\Delta\theta_{11} = \theta_{14} - \theta_8,$$
$$\vdots$$
$$\Delta\theta_{6n-1} = \theta_{6n+2} - \theta_{6n-4}.$$

By this procedure, small variations of the tilt of which the periods are one or two days, due to the rainfall and other causes, were reduced from the last result. Since these small variations in tilts are undoubtly only a few seconds of arc, that is, only a few per cent of those that appear during volcanic activities, the final result is hardly affected by the procedure just mentioned, which last is done with the E-W and S-N components of the tilt. Neglecting the direction of tilt, the magnitude of variation alone of the tilt is considered in the following discussion.

By the foregoing procedure, the following quantities are determined:

$$\Delta\Theta_1 = (\Delta\theta^2_{1,EW} + \Delta\theta^2_{1,NS})^{\frac{1}{2}},$$

$$\vdots$$

$$\Delta\Theta_m = (\Delta\theta^2_{m,EW} + \Delta\theta^2_{m,NS})^{\frac{1}{2}}.$$

Although by this procedure, the effects of small variations in tilt that appear during such short intervals as 2 or 3 days were mostly reduced, the effects of long periods, such as the annual and seasonal variations, is contained more or less in the last value ($\Delta\Theta_m$). For the foregoing discussion, moreover, it is desirable to bring out as clearly as possible only the tilts that are related to volcanic activity.

For this purpose, the variations in tilt during periods of volcanic quiescence are subtracted from those that occur during periods of volcanic activity, and the ratio of the residuals and the variation in tilt during periods of volcanic calm is taken.

That is,

$$K = \frac{[\Delta\Theta_m]_a - [\Delta\Theta_n]_c}{[\Delta\Theta_n]_c}$$

$[\Delta\Theta_m]_a$; value of active period,

$[\Delta\Theta_n]_c$; » » calm period. (1934)

The quantity K defined above is a kind of character number representing the degree of variation in the tilt at the time of volcanic activity. These character numbers were obtained for every month (K_1), every half month (K_2), and every six days (K_3), from which results, the maximum values of the character numbers of a month, half a month, and six days, during the period of 1934-1946, are 25.5, 32.0 and 56.6, respectively.

In Figs. 9 and 10, it will be found these values defined above, namely, K_2 (semi-monthly character number of tilt) and E_2 the total explosion energy for every semi-month. By reviewing the figures of K and E, the correlation between the occurrence of the explosion-swarm and the tilts of the earth's surface is made clearer than by comparing with the tilt curves themselves. That is, although the peaks of the energy of explosion swarms that correspond to every peak of the character numbers appear, the former do so one or two months later. In order to make everything certain, as done in the statistical investigations of the occurrence of earthquakes and other phenomena, the following investigation from the standpoint of probability is made with respect to the occurrence of these two phenomena. The sum of the explosion energy E for every month and the character number K for every month, showed the relations of their occurrences to the variations in the increase and decrease with respect to time.

In all the peaks of the energy curve and that of the character number, the relation of their appearance to the time were examined and found to be

a) The total number of peaks in E-curve = 18

b) » » » K-curve = 19

c) The number of peaks of E, that appeared one month, or two months later than that of the K-curve 19, that is, the E peaks lagged behind the K peaks.

d) The number of peaks of E, which did not appear in the foregoing relation = 1.

Now if the occurrences of the peaks in the K-curve are independent of the occurrences of the peaks in the E-curve, in other words, if the former is distributed at random with respect to the latter, then the probability p of a peak of K appearing one or two months before the occurrence of a peak of E is

$$p = 2 \frac{18}{11 \times 12} = \frac{3}{11}, \text{ (11 years, 1934 - 1945).}$$

and the probability q of the former not appearing in such a relation to the latter is

$$q = 1 - p \times \frac{8}{11}$$

The probability that out of the number of m peaks will occur in a favourable case is

$$P = \frac{m\,!}{(m-r)\,! \times r\,!}\, p^{r} q^{m-r} = 3.4 \times 10^{-9}$$

which is for $m = 18$, $r = 17$

The probability that more than r peaks will occur in a favourable case is

$$P' = \sum_{m=r}^{m} \frac{m\,!}{(m-r)\,!\, r\,!}\, p^{r} q^{m-r} = 3.5 \times 10^{-9}$$

which is for $m = 18$, $r = 17$

From calculations, the probability for the time distribution of peaks of the two kinds of curves is very small, provided they are regarded as being distributed in an entirely haphazard manner. In other words, it is natural to conclude that the time distributions of these two phenomena have a causal relation.

7. — Forecast Function for the Volcanic Activity of Asama.

As just mentioned, it was made clear that corresponding to a remarkable tilt of the earth's surface, an explosion swarm occurred one or two months after the occurrence of the former phenomenon, and in addition, that the energy of a swarm is roughly proportional to the character number K of the corresponding tilt.

In order to investigate these two phenomena more precisely, the writer applied TSUBOI's method in solving the problem.

C. TSUBOI showed that when two arbitrary kinds of quantities are given in time or space, the function for determining the relation of phase and magnitude between these two quantities is given by two kinds of FOURIER's coefficients, which are determined by these quantities.

At first, the series of these quantities (K and E), which are given with respect to the same time interval, are expanded in FOURIER's series, that is,

$$K\ (t) = \sum_{m=o}^{m} [a\ \ \cos mt + b_m \sin mt],$$

$$E\ (t) = \sum_{m=o}^{m} [A_m \cos mt + B_m \sin mt].$$

The correlation function $\varphi(\alpha)$, which determined the relation of these two kinds of quantities is expressed by the series.

$$\varphi\ (\alpha) = \frac{1}{\pi}\left[\frac{1}{2}\frac{A_o}{a_o} + \sum_{m=o}^{m}\frac{a_m A_m + b_m B_m}{a^2_m + b^2_m} + \right. \\ \left. + \sum_{m=o}^{m}\frac{b_m A_m - a_m B_m}{a_m{}^2 + b_m{}^2}\right],$$

The function $\varphi(\alpha)$ in the present investigation is obtained from two time intervals, the one, 12 months from January to December 1935, and the other, 18 months from July 1940 to December 1941. In these two time intervals, the character numbers of the tilt and the sum of the energies are both taken for every half month, as shown in Figs. 9 and 10.

In these two correlation functions (φ_1, φ_2) in these two periods, the former covers the case in which the tilt that occurred one month prior to the occurrence of the explosion is mostly affected, and the latter in which the tilt that occurred two months ago most affects the explosion. Now, in order to render adaptable the correlation fuction in these two extreme cases, we use the mean value of φ_1 and φ_2.

The correlation function $\varphi(\alpha)$ is shown in Fig. 11 and Table III.

Since the correlation function has an effective value only in that domain within two and half months prior to the occurrence of explosion, the correlation function above defined, is, in other words, a forecast function for the volcanic activity of the Asama volcano.

TABLE III. Forecast function

months α	$\varphi(\alpha)$
0	-0.65×10^{17} ergs
—0.5	3.35 »
—1.0	5.00 »
—1.5	3.85 »
—2.0	2.15 »
—2 5	0.75 »
—3.0	—0.30 »
—3.5	—0.15 »
—4.0	0.90 »
—4.5	0.70 »
—5.0	—0.10 »

It is possible to forecast the occurrence of explosions, one after the other, by means of the forecast function (φ) which was determined in 1941, and by continuous observations of tilts, the coming occurrence of the explosion being given by the integration.

$$E(t_0) = \int_{-2\pi}^{0} K(t_0+\alpha)\, \varphi'(\alpha) d\alpha \, .$$

As an example, the forecast function is applied to the occurrence of explosions of Asama for the period from January to August, 1942.

Since the forecast function $\varphi(\alpha)$ has an effective value only in that domain within two and half months prior to the time t_0, and vanishes in the domain prior to more than 3 months, it is possible almost to write the integration in the form of the following summation,

$$E(t_0) = \sum_{\alpha=-2.5}^{-0.5} K(t_0+\alpha)\, \varphi'(\alpha)\, \Delta\alpha \, , \qquad (2)$$

$$\varphi'(\alpha)\, \Delta\alpha = \varphi(\alpha) \, ,$$

where

E (t_0); sum of expecting explosion energy for the coming half month.

Since all the quantities given on the right hand of (2) are known half a month prior to time t_0, E (t_0), the sum of the explosion energy for the coming half month is determined.

In this manner, by means of the half month character number of the interval from October 1941 to August 1942, an outline of the explosion-energy distribution for the period from January to August 1942 is calculated.

Since, unfortunately, the clinograph of the E-W component at the Nakanosawa station was destroyed in May, 1942, observations of the tilt of that component were missed during May-July, 1942, the character number during these months being obtained by assuming that the magnitudes of the variations in the tilts of the E-W component were the same as those of the N-S component. Judging from the tilt observations for a number of years, this assumption may not seriously affect the results.

Fig. 12 shows the marked variations in the inclination of the earth's surface at Nakanosawa during the period from April to July, 1942; photographs of the original records of the tilts for the period are shown in Fig. 8.

It is interesting to compare the explosion energy calculated foregoing method with the volcanic activity which actually occurred in the period. These two results, the one calculated and the other actually occurred, are shown together in Fig. 13.

As will be seen from Fig. 13, these two results, in their outline at least, satisfactorily agree. Upon examining these two results in detail, it will be found that the maximum value of the energy forecasted occurs half a month later than actual occurrence.

One cause of this is that it depends on the time interval taken for the summation of explosion energy. On the other hand, as already mentioned, the differences in the appearance of the E and K peaks with respect to time are mostly one and a half month, but one month in some cases and two months in others. The forecast function is determined by taking the mean value of φ_1, and φ_2, of which φ_1, corresponds to the former case and φ_2 to the latter.

In other words, the forecast function is determined for a domain large enough to contain these two extreme cases together. On the other hand, in the other volcanic activity calculated by function $\varphi(\alpha)$ is less in some cases and larger in others than that of the volcanic activity which occurred, so that it may be necessary to take two kinds of safety factors, according to the purposes in view, namely,

$$E_0 = C \times E_c = C \Sigma K (t_0 + \alpha) \varphi (\alpha)$$

where C; safety factor,

$$C = 3 \text{ for one of the purposes,}$$
$$C = \frac{1}{3} \text{ for the other,}$$

E_0 ; actual explosion energy as occurred.
Ec ; explosion energy expected by forecast function.

At any rate, it is possible to give the maximum and minimum range of explosion energy for a period half a month or two months before its occurrence.

Although, in the present investigation, the character numbers of the tilts were derived from the observations at only one station; and it may also be necessary to determine more precisely the seasonal and annual variations and other small fluctuations of the tilts that appear even during the calm period of the volcano.

8. — Forecast of the Explosive Activity of Volcano Asama during July and August, 1947.

During two years beginning the autumn of 1944, Volcano Asama had been inactive; neither an explosion, nor a remarkable tilt of the earth's surface occurred. But, it began to show signs of the volcanic activity in the beginning of June, 1947. At last, a moderate explosion on July 6 and a very violent one, on August 14, 1947, which broke out at the eastern corner of the crater-floor and on these explosions, new lava of 5×10^4 tons for the first one and $3\text{-}4 \times 10^5$ tons for the latter were thrown out in the form of incandescent lava-blocks, bombs, lapilli and ash. These lava-blocks and bombs were estimated at about 1000° C. in temperature at the instant of explosion and not so much less than 1000° C. when they fell on the ground. Because of the high temperature of numerous lava-blocks, fires were started on the western side of the volcano. Some of the lava-blocks fell on the old Volcano Observatory which was located 2.5 km S-W from the crater and the wooden cottages were totally destroyed by fire (Fig. 14).

On the other hand, there appeared not only a marked tilt related to the volcanic activity after May, 1947, but also a number of micro-earthquakes after April, 1947.

In order to prevent any disasters due to the coming volcanic explosions, the writer warned the people at the foot of the volcano.

Since the tilt did not stop in July, he roported at the monthly meeting of Earthquake Research Institute, on July 18, 1947, that violent explosions would probably occur within the coming August, and their total explosion energy should be in the range 10^{19}-10^{20} ergs, on the basis of the forecast function (φ). At the same time, for the purpose of the precise study of the coming activity, the seismometric and other observations were begun on August 7, only a week before the violent explosion. According to our advice, the Tokyo Broad-Casting Station prepared to record the detonation of explosion of Asama four days prior to August 14, when the violent explosion occurred.

At all events, we could sufficiently forecast the occurrence of the present activity and it's total energy, on the basis of the tilt observation and forecast which had been obtained in 1941.

Fig. 15 shows the marked tilts of the earth's surface at Nakanosawa during the period June-July, 1947.

In order to compare the explosion energy expected with the actual explosion energy as occurred, these two kinds of energies are shown in Fig. 16 with the semi-monthly character number of tilts in this period

9. — Volcanic Activities and Seismic Activities in the Volcanic Regions.

Since the earthquakes in the volcanic regions were sometimes followed by violent eruptions, the phenomenon attracted the attention of many volcanologists and the people at the foot of the volcanoes. Indeed, there are many cases of volcanic activities which occurred after the seismic activities near the volcano, lasting several hours or several months.

The eruptions of Volcano Usu, andesitic volcano, in 1853 and 1910, were preceded by three days of the seismic activity for the former, and by four days of that for the latter which caused the slight damage at the foot of the volcano. The following Table shows the daily frequencies of the volcanic earthquakes in the Usu activities mentioned above.

TABLE IV.

Daily frequencies of volcanic earthquakes prior to the Usu eruptions in 1853 and 1910.

Date	Daily freq.
1853	
Jan. 16	3
» 17	44
» 18	75
» 19 (a. m.)	100
» 19 (p. m.)	1st explo.
1910	
July 21	Several
» 22	25
» 23	110
» 24	351
» 25	162
» 25 22h	1st explo.

In the marked activity of the Usu volcano in 1944-1945, numerous earthquakes took place at the skirt of the volcano during the period about six months prior to the outburst.

The large scale explosion of Sakura-sima in 1914, was preceded by a number of severe earthquakes during 34 hours prior to the occurrence of the 1st explosion on January, 12. Table V gives frequencies of these earthquakes for every six hours.

TABLE V.

Every six hours frequencies of earthquakes followed by explosive activity, 1914.

Date	Freq.
Jan. 11	
0h—6h	3
6h—12h	27
12h—18h	71
18h—24h	100
Jan. 12.	
0h—6h	110
6h—12h	117
10h	1st explosion.
12h—18h	45
18h—24h	5

It is reported that, in the furious activity of Mont. Pelée in 1902, and Krakatau in 1883, the earthquakes originated at these volcanoes frightened the peoples at the skirt of the volcanoes during several days before the catastrophic eruptions.

In the recent explosive activities of Volcano Asama earthquakes strong enough to be sensible to the peoples at the foot of the volcano did not take place, but a large number of micro-earthquakes appeared during the period 2-4 months prior to every explosive activities.

Fig. 17 and Fig. 18 show the frequencies of micro-earthquakes of every ten days during January-August, 1935 and January-September, 1947. Reviewing the results of the seismic and tilt observations it is marked that, corresponding to a number of micro-earthquakes and a remarkable tilt of the earth's surface, an explosion-swarm, that is, a number of explosions occurred two-four months after the occurrence of the former phenomenon and one-two months after the appearence of the latter phenomenon.

Accordingly we can conduct the forecast function on the basis of the seismometric observation, as well as is done in the case of tilt.

In any case, it is marked that all those volcanoes as described above, which were preceded by numerous volcanic earthquakes prior to the occurrence of outburst, are andesitic and not basaltic.

As to the topographical deformation, that is, tilt, upheaval and subsidence, before the volcanic activities, we have not such abundant observations at various volcanoes, as the former phenomenon.

However, on the occasion of the marked activity of Volcano Usu during 1944-1945, the remarkable upheaval at the eastern foot of the volcano, which was caused by intrusion of lava, appeared with numerous earthquakes of small depth during the period December, 1943-June 1944, prior to the first outburst on June 23, 1944 (see Figs. 19-21).

With respect to the marked tilts at the Asama volcano, full discussion was already made in the foregoing paragraphs.

It is remarked that Volcanoes Usu and Asama both are typical andesitic.

On the other hand, the viscosity of fresh lava were estimated in the various volcanoes, on the basis of flowing velocity of lava-flow. According to these estimations, viscosities of fresh lava at nearly 1000° C. are 10^4-10^5 c. g. s. for the basalt lava, such as of Hawaiian volcanoes, 10^6-10^7 c. g. s. for the andesitic-basalt lava, such as of Miyake-sima, Oo-sima etc., and larger than 10^9 c. g. s. for the andesite one, such as Asama, Sakura-sima, Usu etc.

It is well known that characteristics of eruption depend on the kinds of lava, that is, either basaltic or andesitic.

In other words, it may be said that the viscosity of juvenile lava has serious effects not only on the characters of outburst, but also on appearence of the topographical deformation and occurrence of volcanic earthquakes followed by the eruption.

Consequently, these phenomena described above are reasonably explained by the following idea.

At the time of intrusion or extrusion of juvenile lava toward the vent passing through narrow fissures below the volcano, the more viscous the lava is, the higher pressure may inevitably act on the earth's crust. As the result of the marked pressure acting on the upper crust near the andesitic volcano, the topographical deformations and numerous earthquakes will naturally occur prior to ejection of that lava. On the contrary, out-flow of lower viscous lava, such as basaltic, is easy made without the action of such high pressure as the former case.

Therefore, it may be said that the forecast of outburst of the basaltic volcano is not so easy, but not impossible, as that of the andesitic one. For the purpose of forecasting the eruption of the basaltic volcanoes, it is desirable that, in addition to the seismometric observations by means of high sensibility, the continous observations of the earth-current and the magnetic field, will be made at these basaltic volcanoes.

10. — Conclusion and Résumé

The writer described at first in this paper that, since large scale upheaval and subsidence in the volcanic regions appear at a point on the earth's surface as variations in the inclination of the ground, it is reasonable to expect marked tilting of the ground near the volcano.

But, it may be pointed out that secular variations in the tilt at Asama and Usu do not harmonize sufficiently with the topographical deformations given by the precise levellings done in 1935 and 1939 for the former volcano, and in 1944-1945 for the latter one, from which it will be seen that these volcanoes are formed of numbers of very small blocks, and that when the volcanoes are active, these blocks move at random according to their underground structure.

Seeing that the tilt on the limited area, which is the differential coefficient of the topographical deformations at a point in the regions consisting of a large number of small blocks, the discrepancy shown by the topographical surveys may be only natural. Since marked tilts in the volcanic regions are caused by variations in the pressure of lava inside or below the volcano, it may be said that the tilts of the earth's surface are an indicator representing the inside activity of the volcano.

The foregoing results summarized are

a) In the recent explosive activities of Volcano Asama, the total mass of ejecta and the velocity at the moment ef ejection were estimated for sixteen strong and moderate explosions, from which result, the kinetic energies of these explosions were determined.

The relation between these kinetic energies and the maximum amplitudes of the surface waves caused by the corresponding explosion was determined, by the use of which relation, all the explosions that occurred during the period from 1935 to 1942 are expressed by their energies.

b) Brief descriptions of volcanic earthquakes of various types and characteristics of activities of basaltic and andesitic volcanoes are given.

c) From tilt observations made at the foot of the volcano, the extent of the variations in the tilt were expressed by character numbers.

d) The relation with respect to time between the occurrence of the explosions and marked changes in the tilt of the earth's surface are examined from the standpoint of probability.

e) The correlation between these phenomena was quantitatively studied with the aid of the weight function. As the result of that, the forecast function of the Asama activity was obtained.

f) For the interval from January to August, 1942, the volcanic activity expected by the forecast function, was compared with actual phenomena, as the result of which, light was thrown on the possibility of forecasting volcanic activities.

g) We could practically forecast the occurrence of the violent activity on July and August, 1947, on the basis of this forecast function. As the result, the damages due to these explosions were remarkably reduced.

h) The explosive activities of Volcanoes Usu, Sakurasima, Asama etc. which are all andesitic, preceded by not only remarkable topographical deformation or tilt of the ground, but also by numerous earthquakes. On the contrary, such phenomena in the case of the basaltic volcano are not so conspicuous as in the former.

i) Characteristics of eruption and forerunning phenomena, namely, topographical deformations and volcanic earthquakes depend mainly on the viscosity of the juvenile lava.

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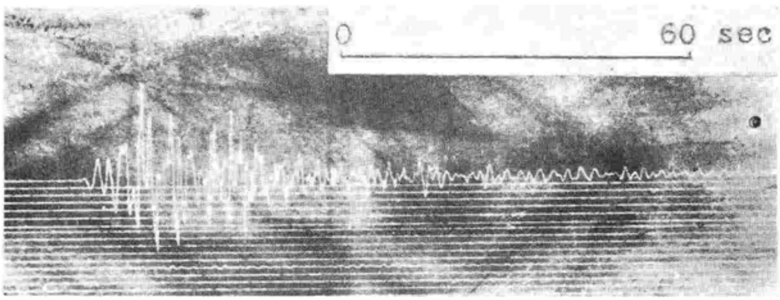
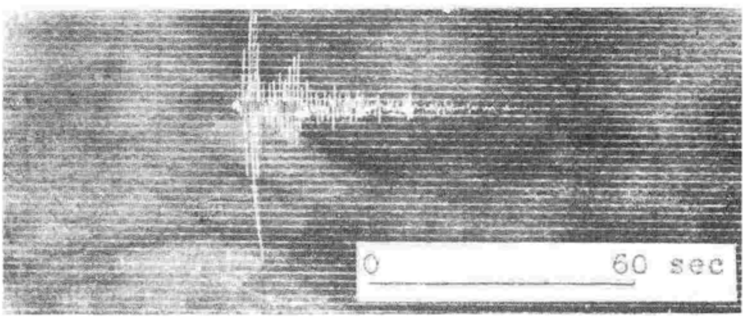
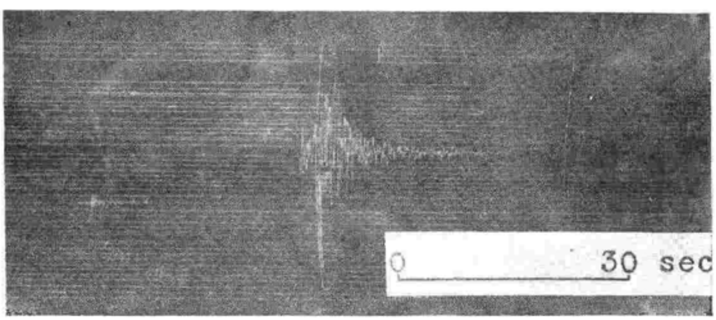


(a)

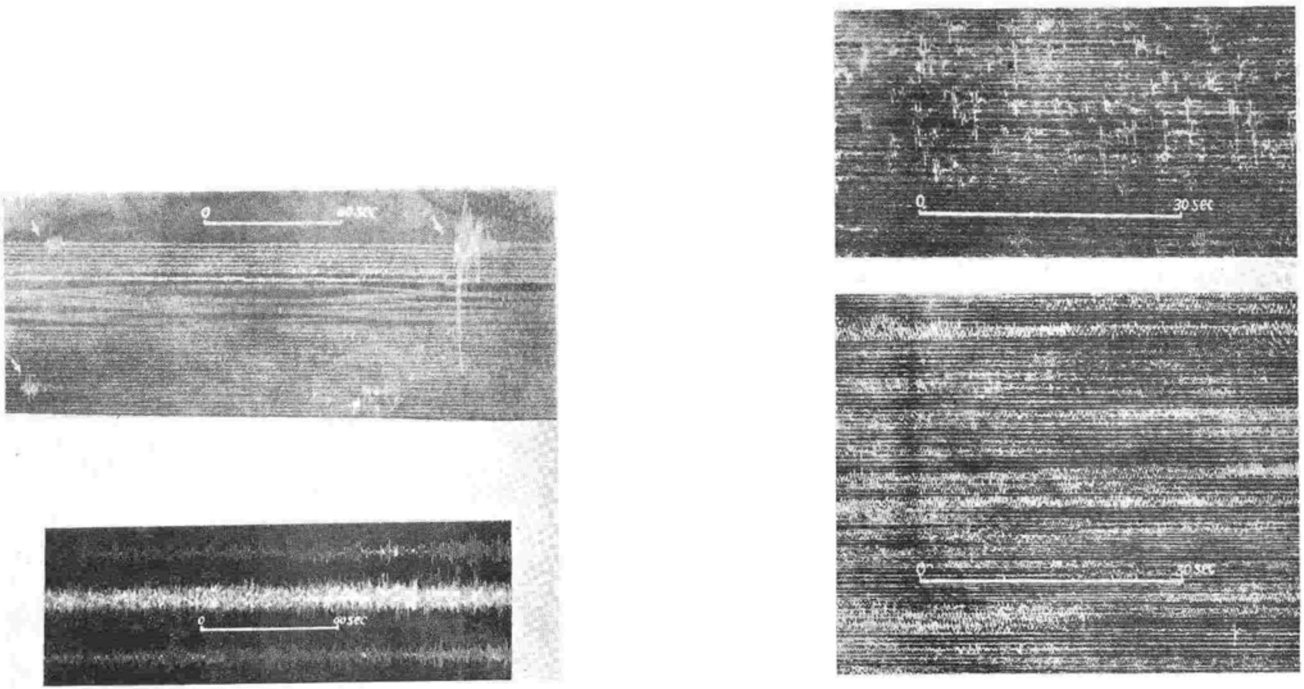


(b)



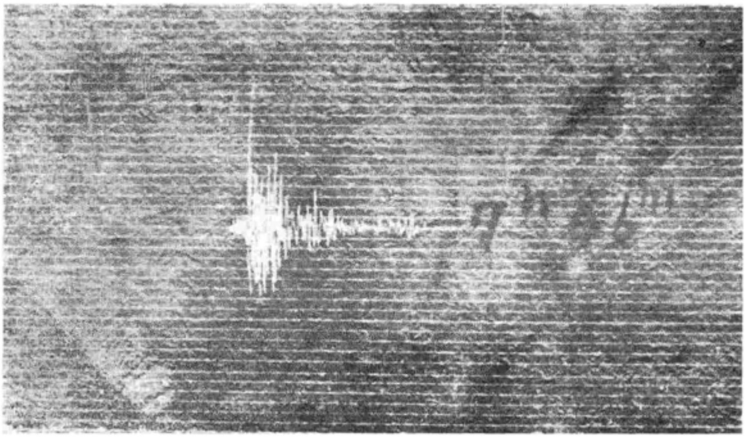
(c)

Fig. 1. - Seismograms of various volcanic earthquakes.
a) An explosion earthquake of Asama Volcano.
b) A volcanic earthquake of ordinary type of Asama.
c) An earthquake of the tectonic origin.
(An after-shock of the Tottori earthquake of Sept. 1943).



(a) (b)

Fig. 2. - Seismograms of the various volcanic earthquakes.
a) The volcanic earthquakes of the ordinary type, at the activity of Miyake-sima and the volcanic pulsations caused by the Strombolian type eruption of Miyake-sima during July - Aug 1940.
b) The volcanic earthquakes and pulsations caused by the mud-eruptions of Volcano Kasatu-sirane, 1938.



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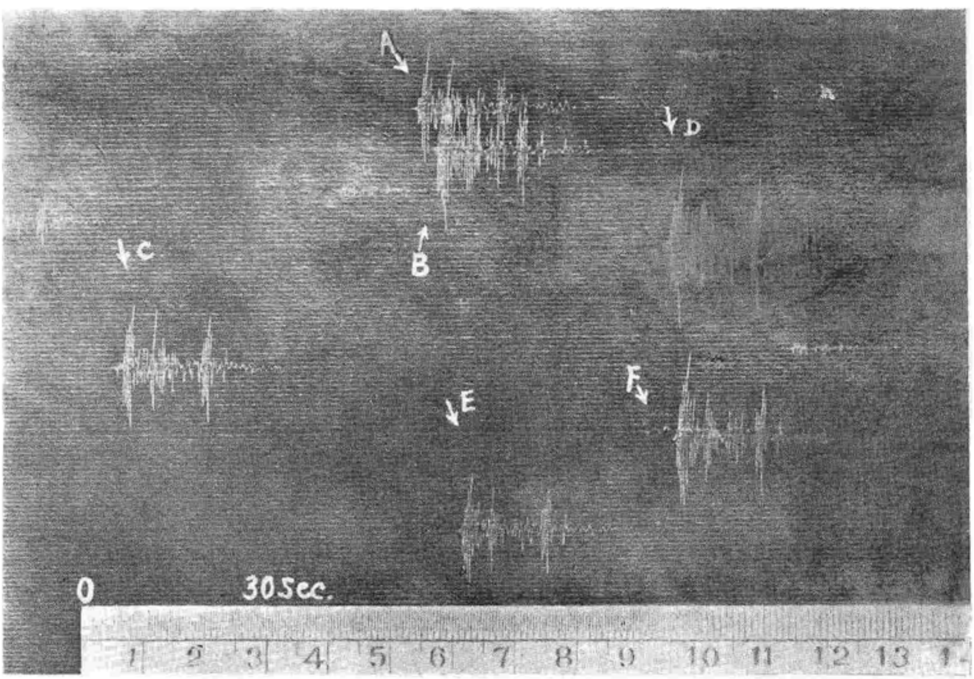

(b)

Fig 3. - Seismograms of the various volcanic earthquakes.

a) A volcanic earthquake of the ordinary type occurred at the large scale activity of Usu during 1944-1945.

b) The earthquakes of peculiar form caused by growth of the new lava dome of Usu during Dec. 1944 - July 1945.

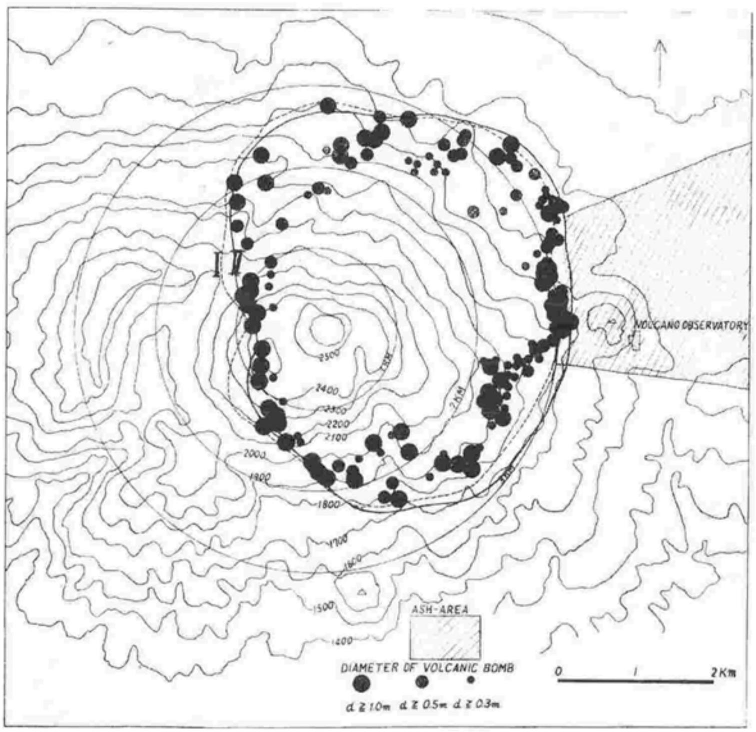

Fig. 4. - Geographical distribution of volcanic bombs in the explosion on April 16, 1937.

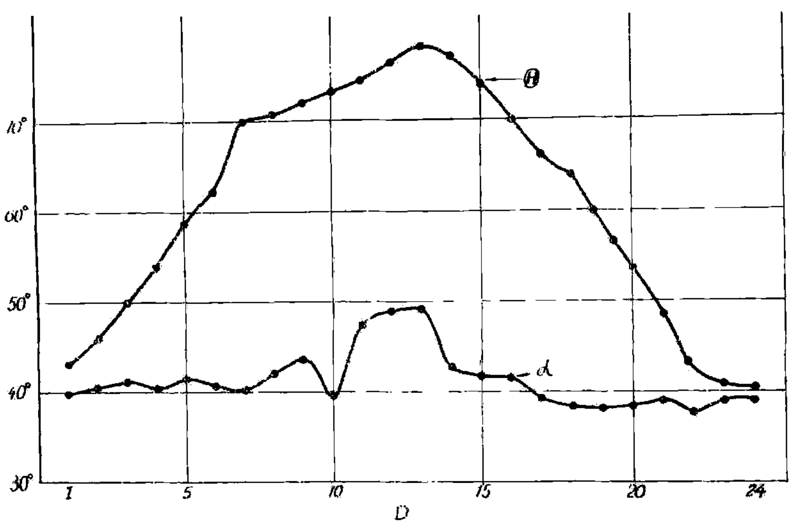

Fig. 5. - Angles of emission of bombs in the explosion on April 16, 1937.

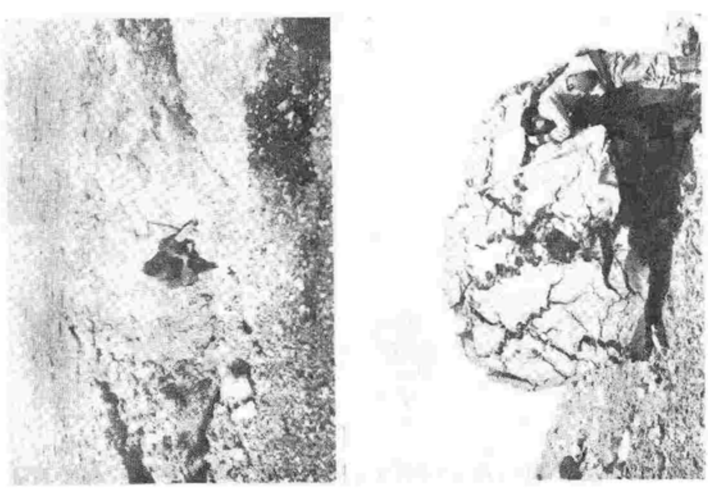

Fig. 6. a) Large lava-blocks ejected at the explosion on April 16, 1937.

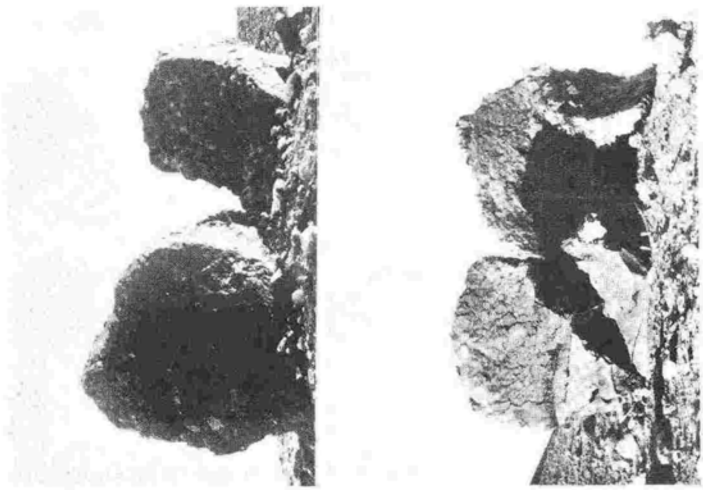

Fig. 6. b) Large lava-blocks ejected at the explosion on June 7, 1938.

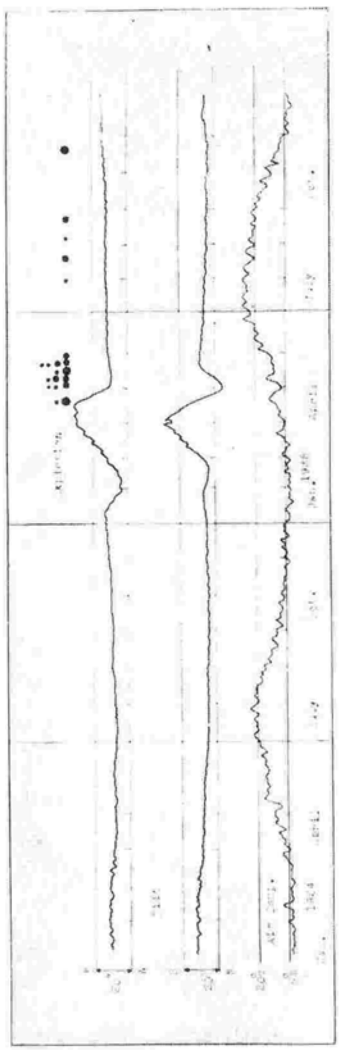

Fig. 7. - Tilt at the Nakanosawa station and explosions during 1934-1935.
(Air temperature outside the observation room.).

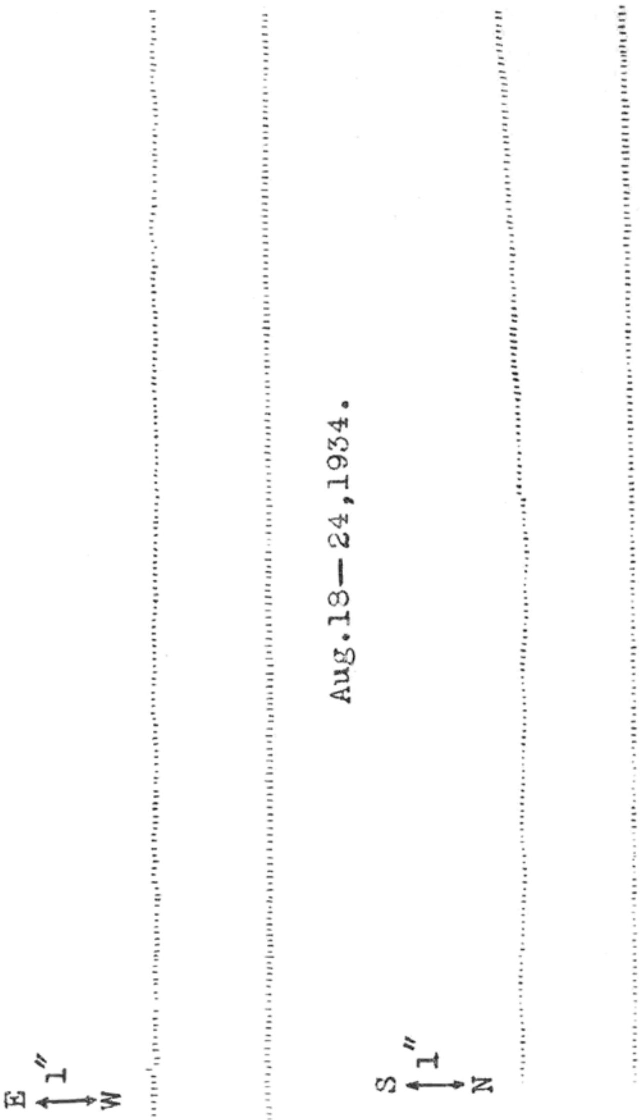

Fig. 8 a) - Records of tilt at the calm period.

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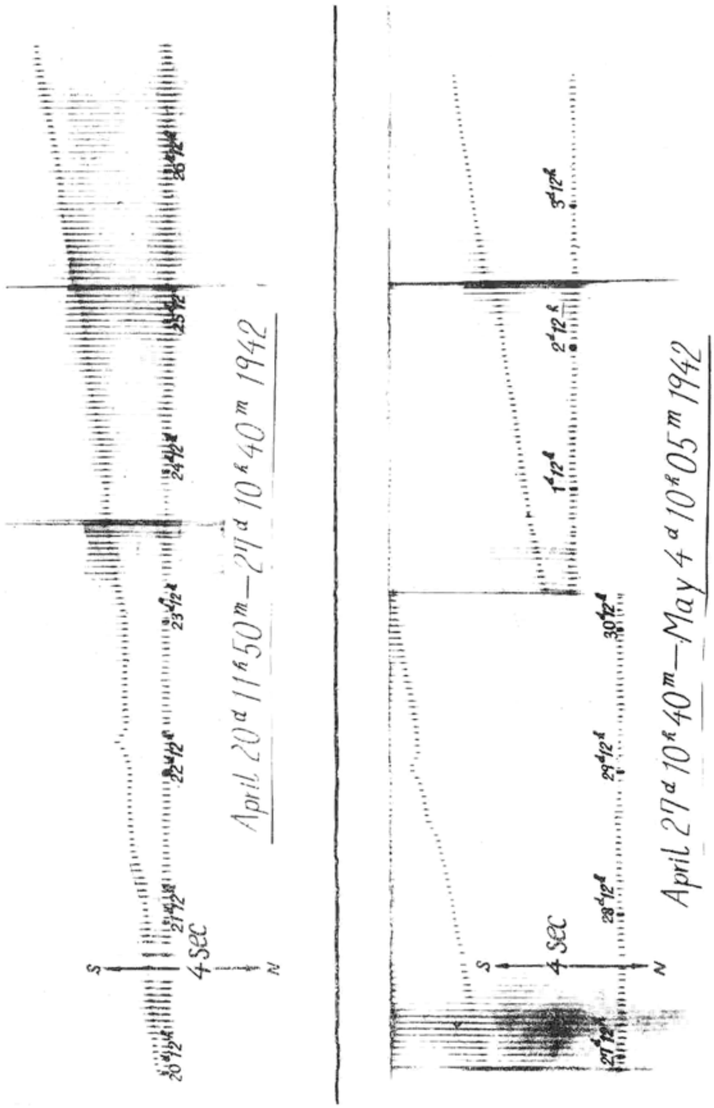

Fig. 8 b) - Records of marked tilt related to the volcanic activity.

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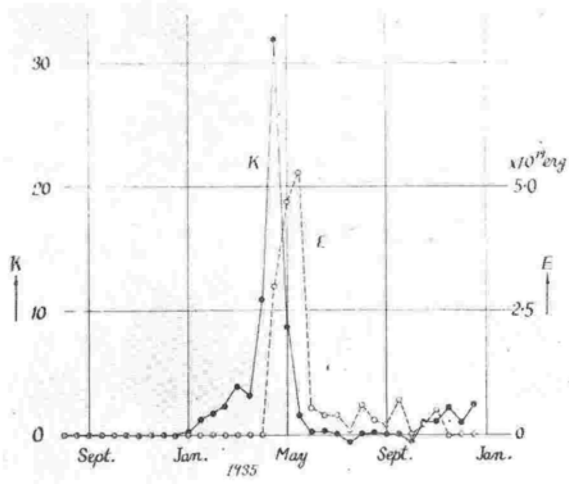


Fig. 9. - The time distribution of the explosion energies of every half month and semi-monthly character numbers during Jan. - Dec. 1935.

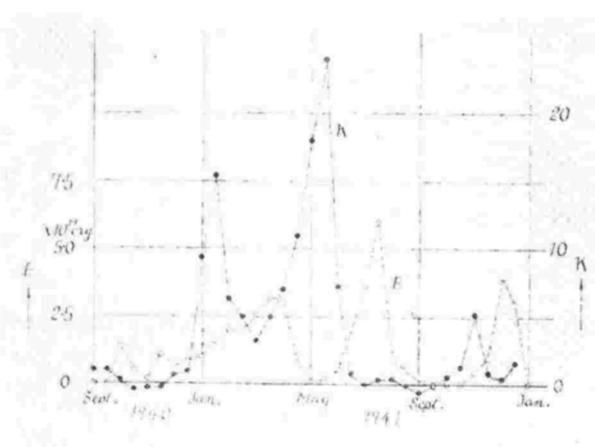


Fig. 10. - The time distribution of the explosion energies of every half month and the semi-monthly character numbers during July 1940 - Dec., 1941.

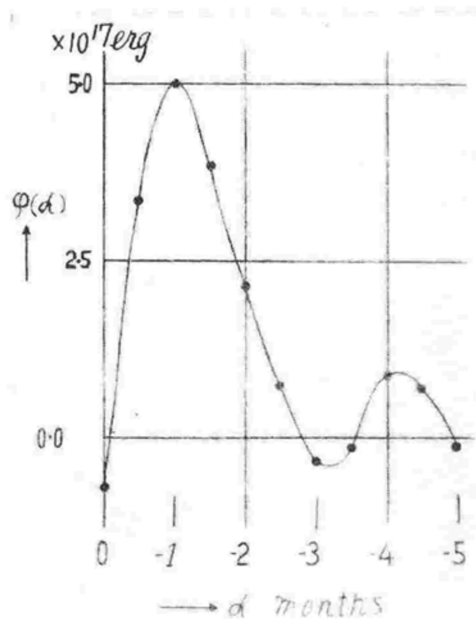


Fig. 11. - The forecast function.

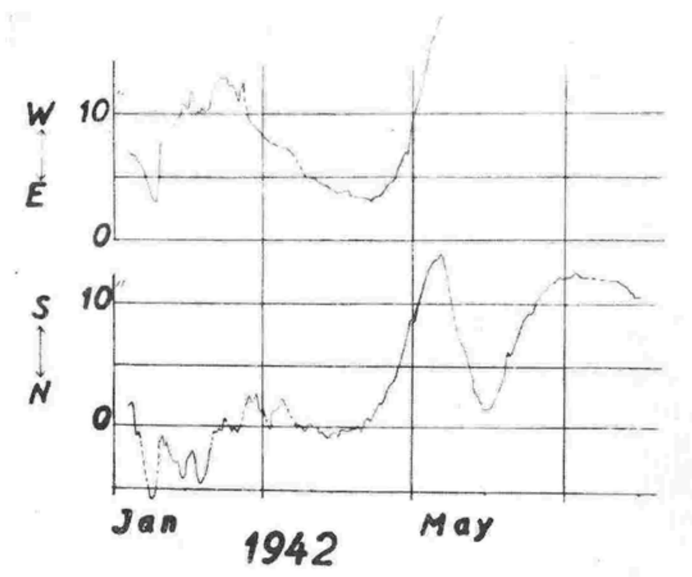


Fig. 12 - Marked tilt appeared during the period Jan. - July, 1942.

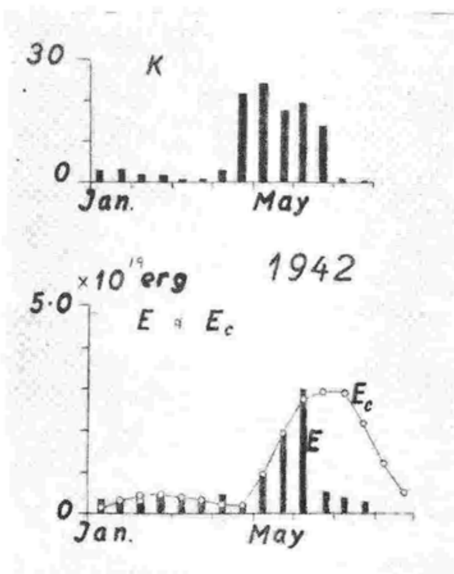
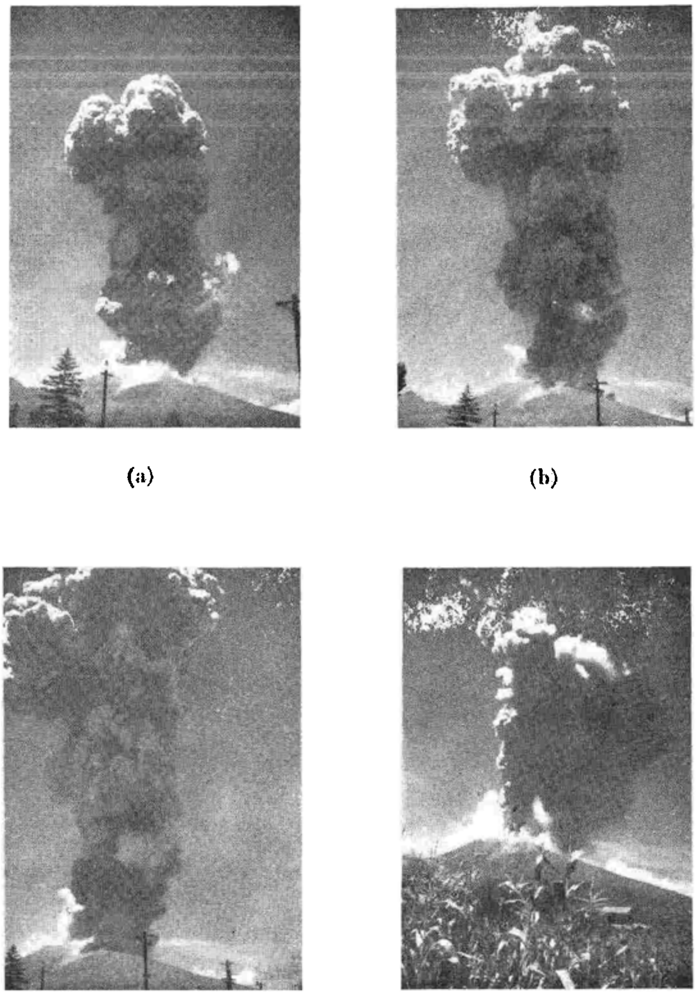


Fig. 13. - The comparison of two kinds of explosion energies, the one calculated and the other occurred actually.
Ec : explosion energy expected by the forecast function.
E : explosion energy occurred actually.

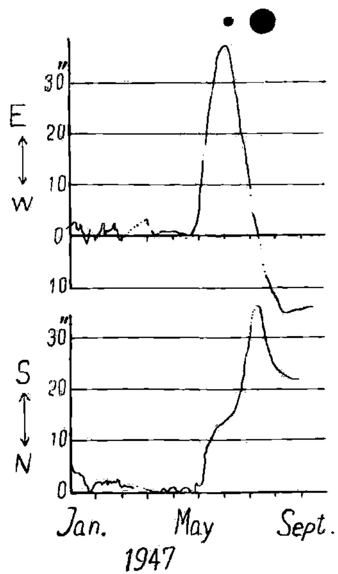


(a) (b)

(c) (d)

Fig. 14. - The violent explosion of Volcano Asama on Aug. 14, 1947.
Four stages of the explosion.

a) 30 seconds after the occurrence of the explosion.
b) 40 » »
c) 60 » »
d) 100 » »



g. 15. - Marked tilt appeared during the period from June to July, 1947.
(Black circles indicate explosions).

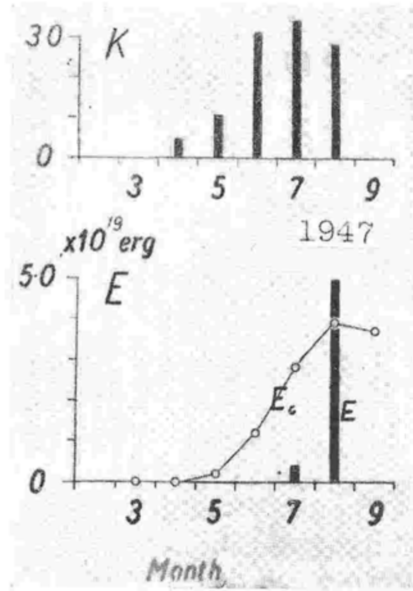


Fig. 16. - The comparison of explosion energies, the one forecast and the other occurred actually.
Ec : explosion energy expected by the forecast function.
E : explosion energy occurred actually.

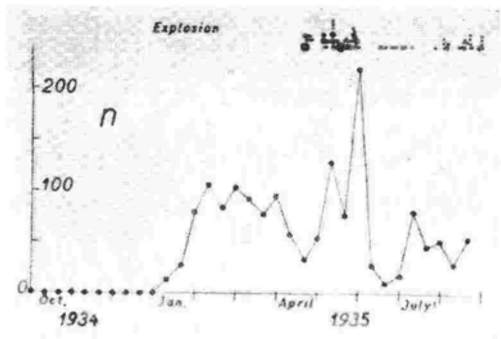


Fig. 17. - The time relation between numerous micro-earthquakes and explosions of the Asama volcano, in the period 1934-1935.

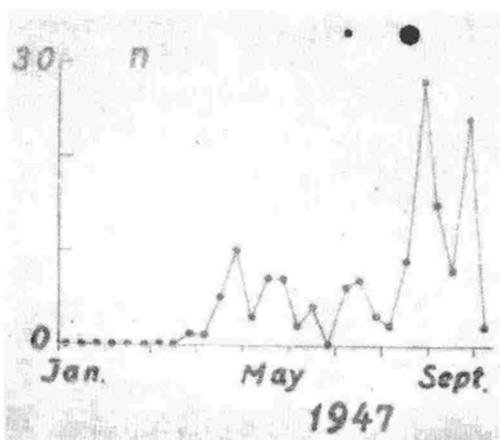


Fig. 18. - Numerous micro-earthquakes occurred prior to the explosions on July 6 and August 14, 1947.
(Black circles indicate these explosions).

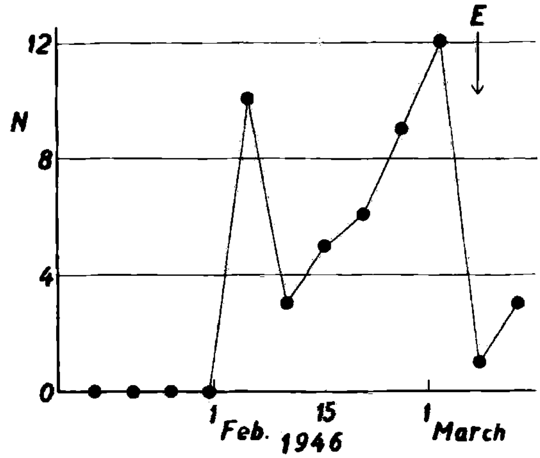


Fig. 19. - Swarms of small earthquakes occurred near Sakura-sima volcano in 1946, prior to its outburst.
N ; Number of earthquakes every five days. E; First outburst.

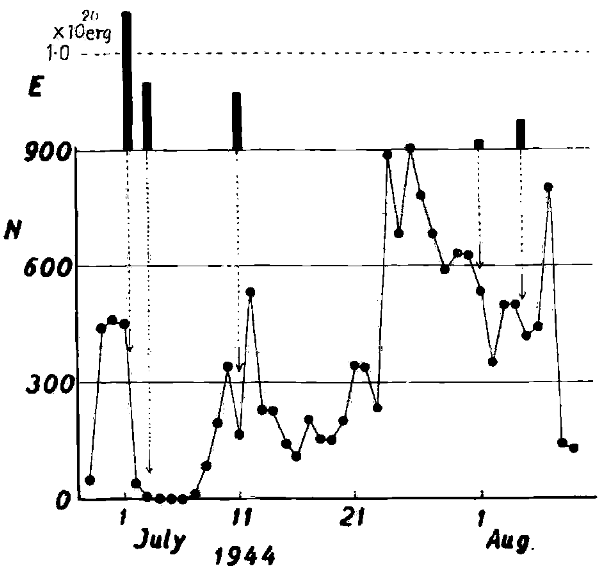


Fig. 20. - Frequency curve of earthquakes predominated during several days prior to the remarkable eruptions of Volcano Usu.
N ; Daily number of earthquakes. E : Remarkable explosion.

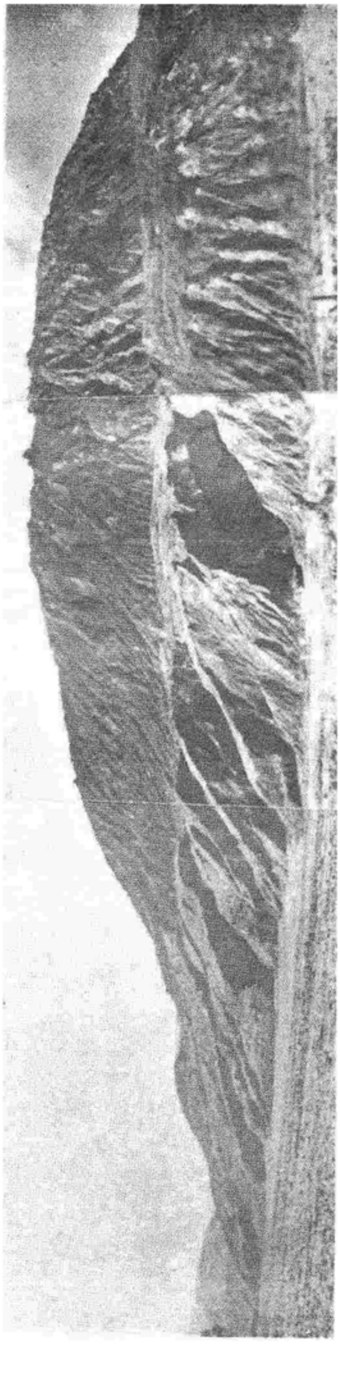


Fig. 21. - New volcano appeared during Jan. 1944 - Oct. 1945 at the eastern foot of Volcano Usu. This new volcano was caused by upheaval of the earth ground, not by accumulation of ejecta.