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A CHARACTERISTIC OCCURRENCE OF EARTHQUAKE-SWARMS AT THE VOLCANO ASO CALDERA-RIM

By

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Abstract

Since the big explosion of October, 1965, at the Volcano Aso, the red-hot bottom in the 1st crater has been observed almost continuously during these several years. At the end of July, 1971, a small pit of 10 m in diameter opened at the bottom of crater and volcanic ash has been ejected intermittently from October, 1971, until now. Under such volcanic conditions, four groups of small earthquakes occurred at the western area of the Aso Caldera during the period from August, 1970, to January, 1972.

The results obtained are as follows: (1) The life of each swarm is shorter than about 40 hours and the foci are restricted to a small region. (2) The epicentral regions of the four swarms lie on a line along the northwestern rim of the caldera and the seismic region appears to be migrated successively from the south to the north. (3) The focal depths are 4～16 km under the Tateno Valley, only a collasped part of the caldera, and 4～8 km under the caldera-rim or the outer side of caldera. (4) The spaces occupied by the swarms occurred under the caldera-rim or the collapsed part, spread vertically while those under the outer side of caldera spread horizontally. (5) The released energy of the swarm under the Tateno Valley amounted to 10^{17} ergs, is smaller than the energies of the others, amounted to $10^{18\sim19}$ ergs. Therefore, it seems to reflect the tectonic state under the collapsed part of the caldera.

1. Introduction

A characteristic feature of recent seismology is the remarkable stimulation of research in the field of seismicity. In other words, it means the contiguity between the geology and the geophysics for the solid earth. Physical volcanology has been seen as a possible branch for connecting both sciences. The expectation, however, might be not yet sufficiently achieved and difficulties seem to be again recognized. An important task in physical volcanology may be related with the study of the seismicity in the volcanic region or zone from the point of view of the new geotectonics. It should be noticed that, in comparison with other fields, the work in this field demands rather higher accuracy and particular technics in observation.

The Aso Volcano on Kyushu Island, the field of the present work, is characterized by the typical and gigantic caldera, and then the tectonic feature of caldera should be elucidated to solve the puzzling question of the origin of the caldera. The typical study of seismicity on the Aso volcanic region was carried out by Sassa [1935, 1936 and 1939], who considered the records of earthquakes occurred there from 1929 to 1938.

He recognized the existence of seismic zone under the western part of the caldera, excepting the seismic zone under the central cones, and stressed the complementary relation between the seismic activity near the caldera and the eruptive activity in the central cone. In fact, his excellent study is the pioneer work in this field, although unavoidably restricted by the level of scientific knowledge at that time. After that, observational researches have been continued by his followers (Tani[1937], Wada et al. [1964 and 1967] and Kamo et al. [1971]). They found several earthquake-swarms and deep earthquake zones near the outer side of the caldera.

From August of 1970 to January of 1972, several earthquake-swarms have been found in the outer region of the caldera. Those will be discussed in this paper. The examples of swarms in the Aso region are as follows: the Oguni swarm from the end of 1928 to January of the next year, the Higo-ōzu swarm in July of 1930 and November of 1933, and the swarm of June of 1941 in the northeastern part of the Volcano Aso. Generally speaking, as Sassa [1939] pointed out in the study of the conspicuously violent stage of volcanic activity, the events near the caldera-rim were restricted to the western part of the caldera.

2. Observation

The seismic stations are shown in Fig. 1, in which LAB, HON, SUN, KIS, TAK and MAK are the abbreviation of the stations, Laboratory, Hondo, Sunasenri, Kishima, Taka-dake and Maki, respectively. As seen in Fig. 1, LAB locates inside of the caldera, SUN, KIS and TAK are around the crater and on the other hand, MAK is placed on the outer side of the caldera. The constants of seismographs set at each station are summarized in Table 1.

The foci were determined mainly by the tripartite net with 580 m span at LAB and the others were also used as auxiliary data to determine the position of foci and

Table 1. Description of instrument set at each station

Station	Seismograph	Component	Magnification
LAB	$T_0=1.0$ sec, $h_0=1.0$ $T_g=0.3$ sec, $h_g=1.0$	3 comps. & V*	3×10^3 & 10^4 *
HON	$T_0=1.0$ sec, $h_0=1.0$ (mechanical)	H	10^2
SUN	$T_0=1.0$ sec, $h_0=1.0$ $T_g=0.3$ sec, $h_g=1.0$	V	3×10^3
KIS	ditto.	3 comps.	ditto.
TAK	ditto.	V	ditto.
MAK	ditto.	ditto.	ditto.

* An automatically seismic recording system (tripartite array)

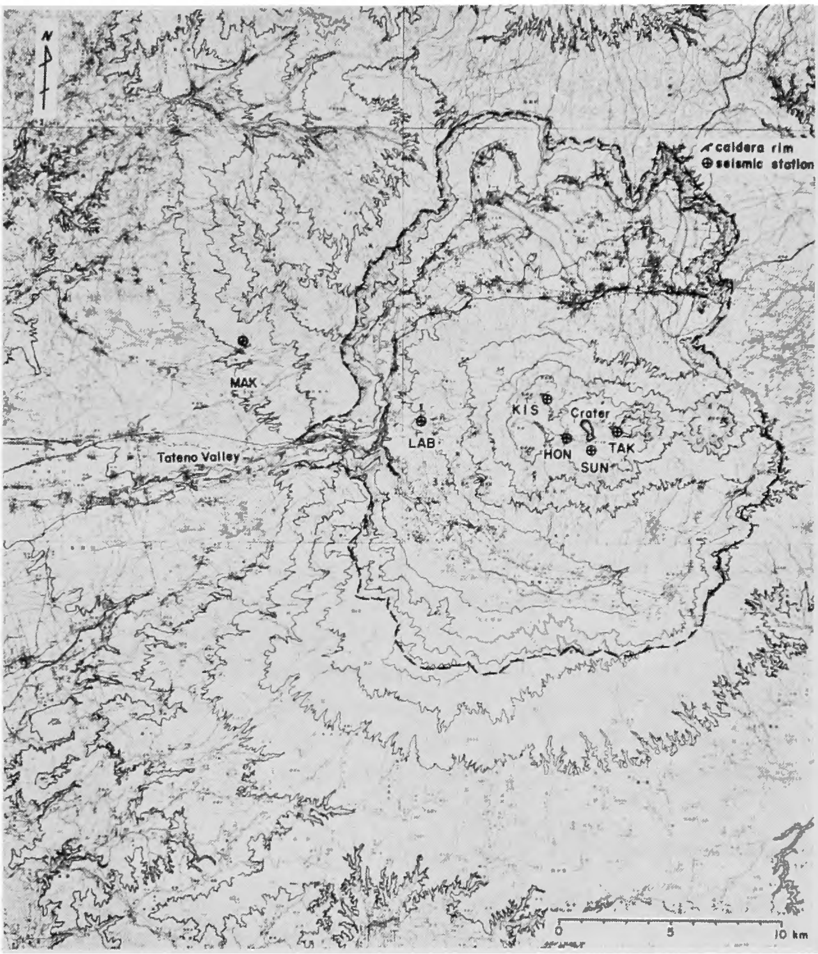

Fig. 1. The Aso Caldera and locations of seismic stations.

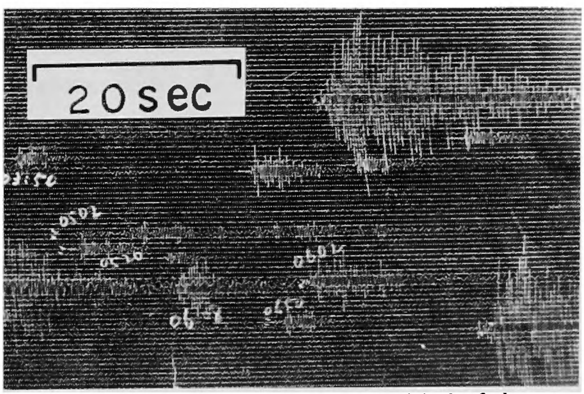

Photo. 1. A portion of seismogram on which the 3rd swarm is recorded by high-sensitivity seismograph on July 6. 1971, at LAB.

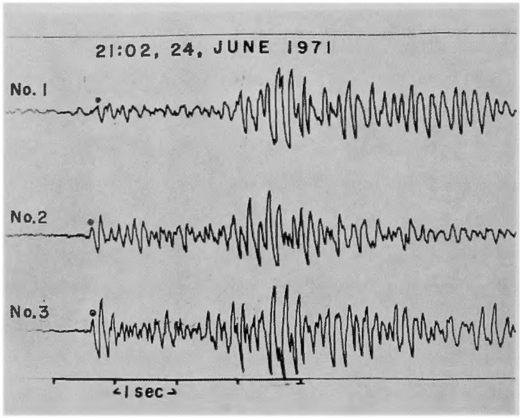

Photo. 2. An example of seismic waves of the swarms on the record reproduced by automatically seismic recording system with magnetic tape.

to evaluate the magnitude of earthquake. In the tripartite observation at LAB, the automatically seismic recording system (Wada and Kamo [1970]) was used. The examples of seismograms are shown in Photo. 1 and Photo. 2.

In determining the positions of foci, the structure under the Aso area assumed by Wada and Kamo [1964] is used. The number of earthquakes of which foci are determinable is about 30 percent of the total number, owing to an essential ambiguity of the initial phase of seismic wave at the volcanic area.

3. Earthquake-swarms

It is well known (Sassa [1936], Wada and Kamo [1964] and Kamo et al. [1971]) that the western part of the caldera is seismically active in comparison with the other

Table 2. List of four earthquake-swarms

Swarm	Date	Total number of earthquakes	Number of earthquakes of which epicenters are determinable.	Number of earthquakes of which *s–p times* are readable.
1st	Aug., 9th, 06:06 ~ Aug., 10th, 07:59 1970	57	13	20
2nd	Jun., 24th, 05:30 ~ Jun., 25th, 12:44 1971	36	11	25
3rd	July, 5th, 20:19 ~ July, 7th, 09:05 1971	132	29	75
4th	Jan., 12th, 22:30 ~ Jan., 13th, 04:46 1972	13	10	12

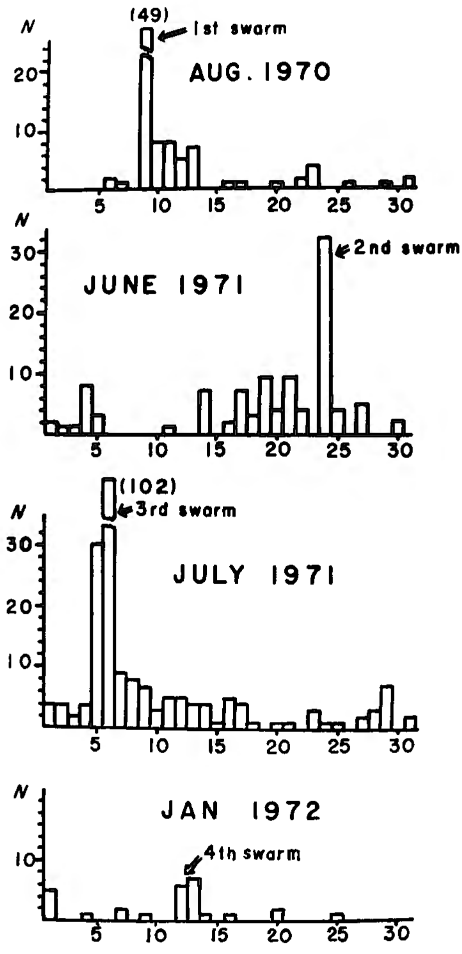

Fig. 2. Daily sums of number of earthquakes recorded at LAB for a month within which the swarm occurred.

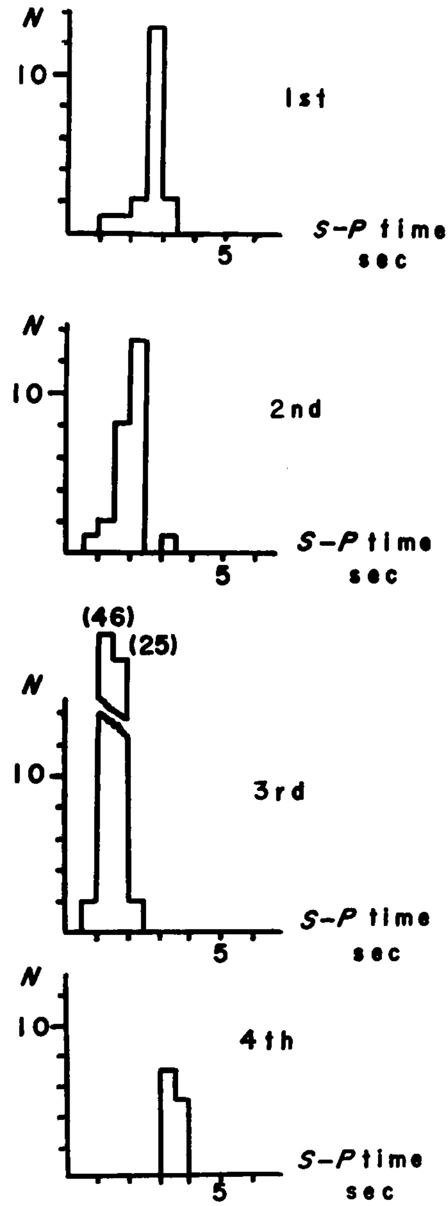

Fig. 3. Number of earthquakes versus *s–p time* observed at LAB for each swarm.

near the caldera. In the western part, one or two events with a magnitude of less than 1, occurred usually each day. Sometimes several events, have been detected. Neverthless, during the four periods, that is, from 9 to 10 of August, 1970, from 24 to 25 of June, 1971, from 5 to 7 of July, 1971 and from 12 to 13 of January, 1972, the events, of which some have the magnitude of 3∼4.5, have been crowded into short period. The dates of occurrence, the total number of earthquakes and the number of earthquakes of which epicenters are determinable and of which *s-p time* are readable for each swarm, are summarized in Table 2. For the sake of simplicity, the swarms will be called successively the 1st, the 2nd, the 3rd and the 4th swarm. To illustrate the character of occurrence, the diagram of the daily example is shown in Fig. 2. It is natural to recognize that the four groups of events are unusual in comparison with the normal condition of seismicity at the western part. To estimate approximately the positions of epicenters, the diagram of the numbers of earthquakes versus *s-p times* for each swarm is shown in Fig. 3. The predominant values of *s-p times* of these swarms are ca. 2.5 sec, ca. 2.0 sec, ca. 1.5 sec and ca. 3.5 sec for the 1st, the 2nd, the 3rd and the 4th swarm, respectively, as seen in Fig. 5. From these figures it may be recognized that the four swarms exist actually, that is, the character of occurrence, both in time and space, of each swarm is particular.

4. Distribution of foci

To illustrate the particularity of the location of each swarm as described in the previous section, the distributional patterns of the epicenters determined are shown in Fig. 4 (a), (b), (c) and (d) for each swarm, respectively. It is easily seen in the figures, that the 1st swarm occurred at the southwest outside the caldera, the 2nd at the Tateno Valley, a collapsed section of the caldera-rim, the 3rd at the western rim of the caldera and the 4th at the northwest outside the caldera. All the topographical positions of foci are shown in Fig. 5 to represent the characteristics of occurrence. It is interesting that each epicentral region lies on the zone parallel to the straight

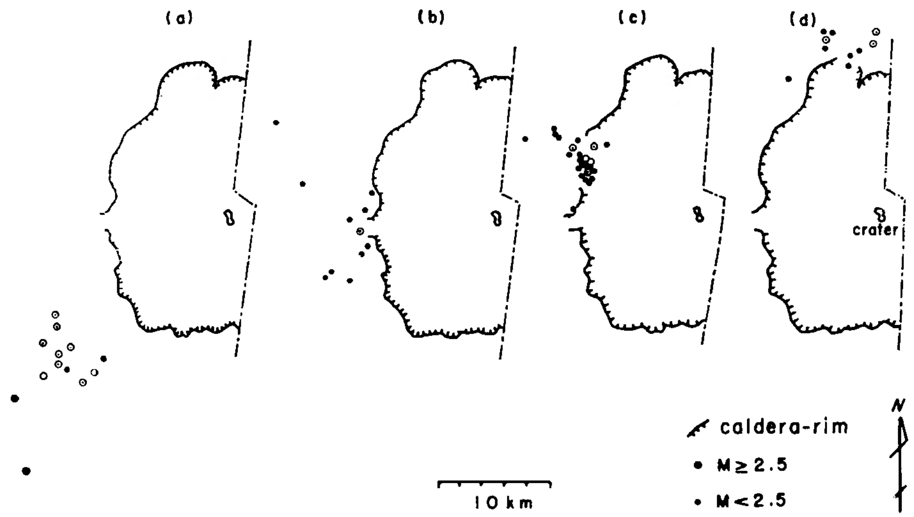

Fig. 4. Distributions of foci for each swarm on the western part of the Aso Caldera. (a) in case of the 1st swarm, (b) of the 2nd, (c) of the 3rd and (d) of the 4th.

line AA′, as seen in the figure, along the western wall of the caldera, and is transferred successively from the south to the north. Considering that small earthquakes occurred in this zone in the past (Sassa [1936 and 1939]), it is evident that the zone is seismically active. Furthermore, it should be noticed that this active zone crosses the tectonic line on which the central cones of the Volcano Aso sit, that is, the so-called *Ōita-Kumamoto tectonic line.*

It is interesting as well as necessary to examine in detail the spacial distribution of foci in relation to the structure of the caldera. Then the depths of foci are projected on a cross section. The distributional pattern on the cross section along the line AA′ is shown in Fig. 6. The spaces occupied by foci of the 1st and the 4th swarms, generally speaking, spread horizontally within the range from ca. 6 km to ca. 8 km and on the other hand, those of the 2nd and the 3rd spread vertically within the ranges from ca. 4 km to ca. 16 km and from ca. 4 km to ca. 8 km, respectively. In other words, the depth of the swarm occurred under the Tateno Valley was deeper than them of the others. The similar result was already pointed out by Sassa [1936 and 1939], according to his experience during ten years since 1929, that is, the foci under the

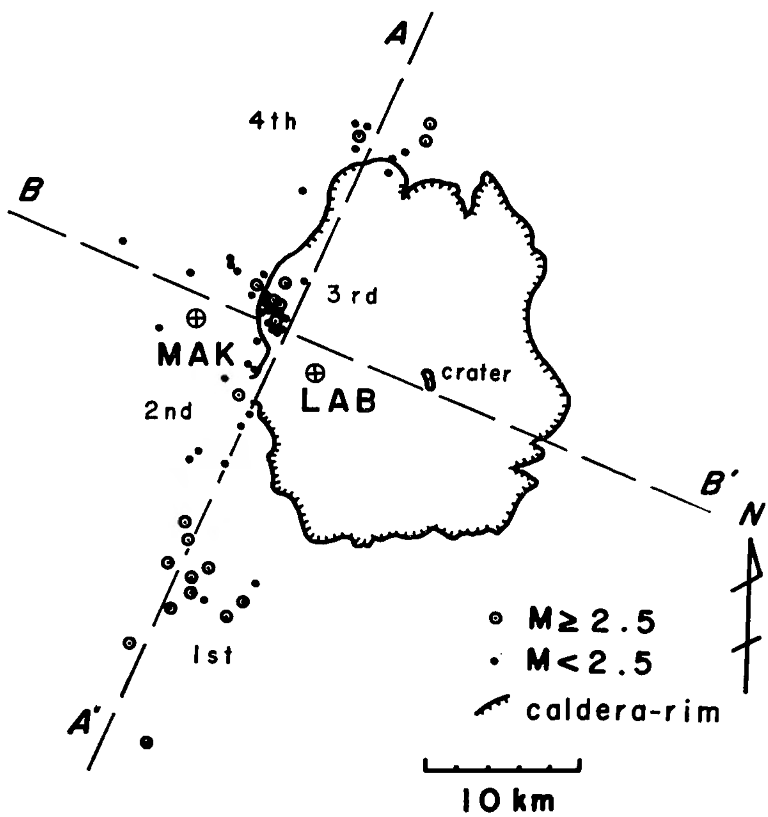

Fig. 5. Distribution of foci for all swarms.

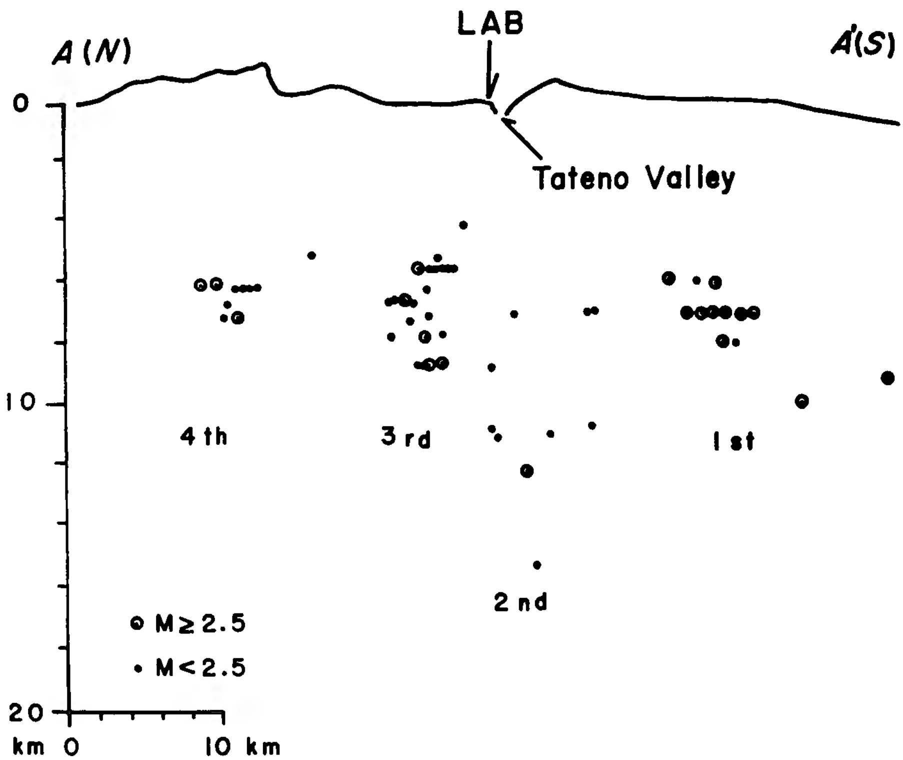

Fig. 6. Distribution of foci on a cross section AA′ in Fig. 5 for all swarms.

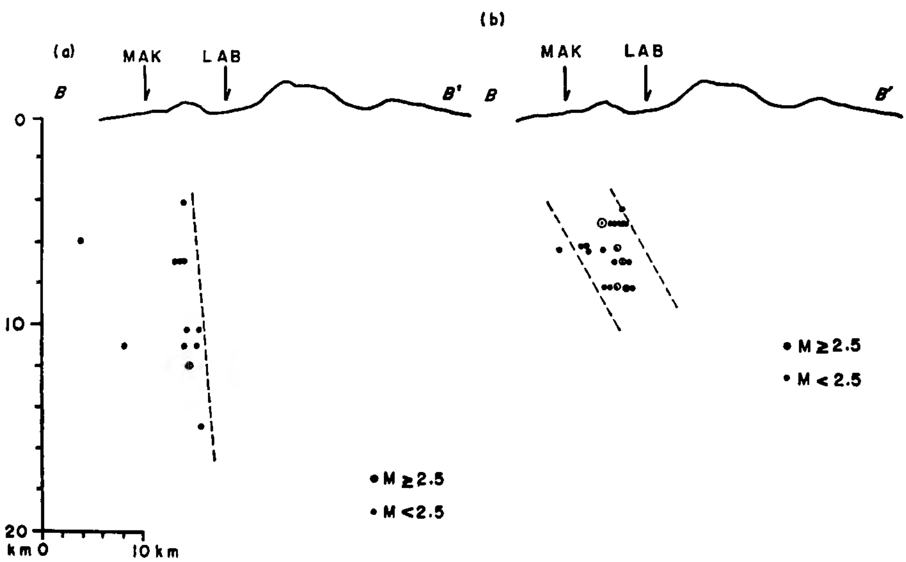

Fig. 7. Distributions of foci on a crooss section BB′ in Fig. 5. (a) in case of the 2nd swarm and (b) of the 3rd.

western wall of caldera is located above 3 km deeper than those under the other parts. This suggests that the region neighbouring the Tateno Valley is a fault zone where the caldera wall is actually collapsed. To illustrate the lengthwise distribution of foci, the depths of the 2nd and the 3rd swarms projected on the cross section along the line BB′, which is perpendicular to the line AA′, are shown in Fig. 7 (a) and (b), respectively. The zone under the Tateno Valley is sloping inward to the caldera at about 60°, and that under the rim at about 90°. As contrasted with them, the zone of the southwestern or the northwestern part under the outer slope of the caldera, seems to be stretched rather more horizontally.

And this gives us some intimations as to the tectonic structure of the caldera related with the model of the Aso Caldera presented by Wada and Nishimura [1971]. In their model, there are two basement blocks under the Aso Caldera divided by the tectonic zone on which the central cones are situated from the east to the west passing through the Tateno Valley. It may be reasonable then to suppose that the tectonic zone AA′ would represent the western edge of the blocks.

5. Push and pull of initial phase

The relative arrangement of the seismic stations, as seen in Fig. 1, is never enough to analyze the focal mechanism of the swarms discussed here. But LAB and MAK are situated almost symmetrically with each other with respect to the line AA′ which is considered as a tectonic line, as mentioned in the previous section. Furthermore, it may be noticed that the dierction of AA′ is coincident with that of a nodal line of the focus at the eastern part of the caldera (Wada et al. [1968]). Then the signs of initial phases observed at LAB and MAK, are summarized into Table 3 in the form

Table 3. Rate of *push and pull* of initial phases at the stations MAK and LAB in percentage

Swarm	Push*	Pull*	Out-phase	In-phase
1st	94	6	47	53
2nd	39	61	50	50
3rd	26	74	70	30
4th	0	100	56	44

* The initial phase observed at MAK.

of percentage. As seen in Table 3, in the cases of the 1st, the 2nd and the 4th swarms the rate of *in-phase* between both statons is almost equal to the rate of *out-phase*. On the other hand, in the case of the 3rd swarm, the rate of *out-phase* is about 70 percent. However, these observational data are not enough to determine any focal mechanism.

6. Tectonic zone deduced from estimation of strained state

In the previous section, the statistical analysis of distribution of initial phases enable us to imagine the existence of a tectonic line. In this section, the energy restricted by strength and strained volume of the space occupied by foci, will be discussed in the relation with the existence of tectonic zone. The total energy*, the volume of space occupied by foci and the strain energy stored in unit volume for each swarm are summarized in Table 4 where the volume is estimated by use of Figs. 5, 6 and 7, and is represented in the unit of 100 km^3, and the strain energies are shown in the form of "total energy/volume".

Table 4. Comparison of strain energies per unit volume stored in the spaces occupied by foci

Swarm	Total energy in ergs	Volume of space in unit of 100 km^3	Strain energy in ergs
1st	10^{19}	2	10^2
2nd	10^{17}	1	10^0
3rd	10^{18}	1	10^1
4th	10^{18}	1	10^1

The strain energies per unit volume of these swarms, as seen in Table 4, are smaller in order than the normal value, $10^{3\sim4}$ ergs (deduced from the formula E/V $=1/2\ \mu x^2$; E: total energy, V: volume, $\mu=5\times10^{11\sim12}$ C. G. S. and $x=1\sim2\times10^{-4}$ C. G. S.). This means a decrease in strength in those region. It is probable that the decrease in strength is due to some structural weakness rather than any variation of physical properties of the constituent material. The 2nd swarm has the lowest strength. To interpret this result, the location may be remembered to be in coincidence with the crossing zone of two tectonic lines, that is, one running from the south to the north, and another from the east to the west, the *Ōita-Kumamoto tectonic line* as it is called by geologists, suggested by Wada and Nishimura [1971], who obtain the underlying structure of the caldera from the analysis of azimuthal direction of initial motion. That is, the superposing of two tectonic lines could decrease the strength.

7. Conclusion

During the period from August of 1970 to January of 1972, four earthquake-swarms occurred at the western part of the Aso Caldera. The swarms have been examined mainly from the viewpoint of the tectonic structure under the caldera. In conclusion, the existence of a tectonic zone extending along the western rim of the caldera is confirmed by the distributions of the foci and of the *push and pull* of the initial phase, and then, the swarm appears to be migrated successively from the south to the north. And by analyzing the strained state of the region occupied by foci, it is founded that the strength of constituent material under the zone decreases

* By applying the formulas $M=1.73 \log \Delta + \log A - 0.83$ and $\log E = 1.5\ M + 11.8$, the magnitude M and the total energy E are evaluated, where Δ and A are epicentral distance and maximum amplitude, respectively.

comparing the expected, and in particular, the existence of superposition of two tectonic lines under the Tateno Valley appears to be related with the tectonic weakness. It is also interesting in relation with the structure and origin of the caldera, that the foci under the outer side of caldera are streched horizontally and on the contrary, those under the western rim of caldera are streched vertically.

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