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13. *Ultra Micro-Earthquakes in the Area around Matsushiro.*

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Introduction

An unusual earthquake swarm began to occur around the town of Matsushiro (36°34′ N, 138°13′ E), Nagano Prefecture, in August 1965 and still continues through October 1967, accompanying a certain number of strong shocks and some remarkable crustal movements. The total number of the shocks counted by the USC & GS Standardized Seismograph (Vmax= 100,000) installed at the Matsushiro Seismological Observatory of Japan Meteorological Agency (36°32.5′ N, 138°12.5′ E) reached 660,000 and that of felt shocks exceeded 60,000 throughout the period from August 1965 to October 1967. The largest magnitude of these earthquakes was 5.3, and the total energy released as a seismic wave reached 1.6×10^{21} erg, which corresponds to the energy of a single shock with magnitude of 6.3. In the period up to the present, the evident peaks of the daily number of the shocks appeared in the latter part of November 1965, April and May 1966, August and September 1966. In the year of 1967, the number of the shocks is decreasing as a general tendency but the seismic active area extended greatly southwestwards and northeastwards.

The Earthquake Research Institute worked out a program of field expeditions which included seismometrical observation and other geodetic and geophysical surveys for the Matsushiro swarm earthquakes in and near the town of Matsushiro since October, 1965. Some results of these surveys were already reported in the previous papers.1),2),3),4)

This paper is the study of the ultra micro-earthquakes observed

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1) "Research on the Matsushiro Earthquakes (1)" reprinted from *Bull. Earthq. Res. Inst.*, **44** (1966), 307-445.

2) "Research on the Matsushiro Earthquakes (2)" reprinted from *Bull. Earthq. Res. Inst.*, **44** (1966), 1213-1395.

3) "Research on the Matsushiro Earthquakes (3)" reprinted from *Bull. Earthq. Res. Inst.*, **44** (1966), 1623-1792.

4) "Research on the Matsushiro Earthquakes (4)" reprinted from *Bull. Earthq. Res. Inst.*, **45** (1967), 159-288.

in the area of the Matsushiro earthquakes during the period from October 1965 to May 1967. The activity of ultra micro-eathquakes was also compared with that of felt shocks in this region. Some results of the observation have already been reported in the previous papers.5),6),7),8)

The research of the Matsushiro swarm earthquakes is very important from the standpoint of earthquake prediction research. The study of activity of ultra micro- and micro-earthquakes is one of the important research items proposed by the Japanese Research Group for Earthquake Prediction (1962). Therefore, the author examined carefully the changes in the activity of ultra micro-shocks before and after a large earthquake.

It is said that the enormous amount of data that has been hitherto obtained concerning the Matsushiro swarm earthquakes might correspond to the amount of data that would be obtained in an ordinary ten year period. The data treated here are only a part of the observational data of the ultra micro-earthquakes obtained at our two temporary observational stations, Hoshina and Sanada.

1. Apparatus and observation

The ultra micro-earthquakes were detected by the high sensitivity tripartite observation at Sanada, Hoshina, Asakawa and Kamimuroga around the town of Matsushiro. The location of these stations and the states of the observation are shown in Fig. 1 and Table 1 respectively. As details of the apparatus have been reported in the previous papers,9),10) its description will be abbreviated here. The high sensitivity tripartite observation using the magnetic tape recorder was some times disturbed on account of such accidents as the cutting off of the cable by farmer's works, damage of the instrument by thunderbolt and other instrumental failures, so that completely uniform data were not able to be obtained even in the period when the continuous observation was scheduled. The data of ultramicro-earthquakes analyzed by the usual process were only

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5) K. HAMADA and T. HAGIWARA, "High Sensitivity Tripartite Observation of Matsushiro Earthquakes. Part 1," *Bull. Earthq. Res. Inst.*, **44** (1966), 1213-1238.

6) K. HAMADA and T. HAGIWARA, "High Sensitivity Tripartite Observation of Matsushiro Earthquakes. Part 2," *Bull. Earthq. Res. Inst.*, **44** (1966), 1239-1268.

7) K. HAMADA and T. HAGIWARA, "High Sensitivity Tripartite Observation of Matsushiro Earthquakes. Part 3," *Bull. Earthq. Res. Inst.*, **44** (1966), 1665-1687.

8) K. HAMADA and T. HAGIWARA, "High Sensitivity Tripartite Observation of Matsushiro Earthquakes. Part 4," *Bull. Earthq. Res. Inst.*, **45** (1967), 159-196.

9) K. HAMADA and T. HAGIWARA, *loc. cit.*, 5).

10) K. HAMADA and T. HAGIWARA, *loc. cit.*, 8).

Table 1. List of the stations and the instruments.

Station	Hoshina	Kamimuroga	Sanada	Asakawa
Location	Wakaho town	Kawanishi village	Sanada town	Nagano city
Start of observation	October, 1965	April, 1966	September, 1966	November, 1966
Seismograph V; vertical component H; horizontal component	V; UMP H; PTE	V; UMP H; HS-1	V; HS-10-1 H; HS-10-1	V; UMP H; PTE
Natural frequency (cps)	V; 2.5 H; 3.0	V; 3.5 H; 5.0	V; 1.0 H; 1.0	V; 3.5 H; 1.0
Sensitivity (V/kine)	V; 0.8 H; 4.0	V; 1.5 H; 0.4	V; 0.8 H; 0.8	V; 0.8 H; 4.0
Magnification for 20 cps	500,000	400,000	1,000,000	1,000,000
Recorder	SONY FM 23-S	RHR	SDR-803 S	WR-211
Recording method	magnetic tape & pen-galvanometer	magnetic tape	magnetic tape	pen-galvanometer
Number of channels	3 ch.	6 ch.	6 ch.	6 ch.
Sampling time of analysis	1.5 hours per two days	4 hours every day	2 hours per two days	1.5 hours every day

a part of the total data on account of the large amount of data obtained.

As regards the detection capability of ultra micro-shocks, if we take the Sanada station (magnification = 1,000,000 at 20 cps) as an example, we can expect that the seismic signals with velocity amplitude larger than 30μ kine will be read off, considering the noise level at night. Therefore, using the Muramatsu's diagram[11] which gives the relation between the maximum velocity amplitude and the hypocentral distance, we can expect to detect the earthquakes of hypocentral distance within 50 km when $M=1$ and within 25 km when $M=0$. In the actual observation, if the seismic signals are too large, the hypocenter cannot be determined because the *P-S* time cannot read off on account of saturation of seismic signals. Therefore, considering the attenuation of seismic waves by the use of the Muramatsu's diagram, if we assume that the hypocenter of the shock can be determined for the earthquakes with the maximum velocity amplitude between 30 and 300μ kine, we can expect that the

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[11] I. MURAMATU, *Zisin*, [ii] **17** (1964), 210.

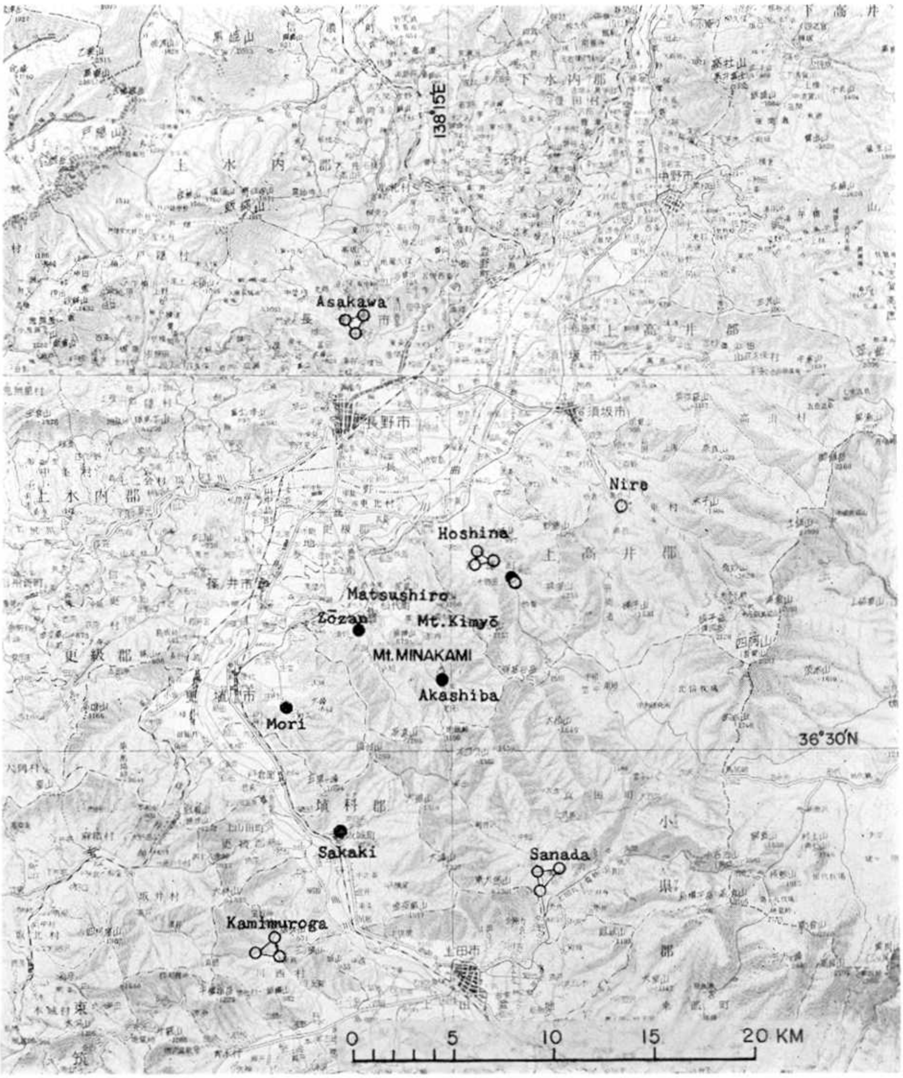

Fig. 1. Location of the observation stations.
∴; tripartite station,
○; HES seismograph station,
●; acceleration seismograph station.

shocks with magnitude $M=-2\sim1$ will be analyzed in the range of hypocentral distance $5\sim30$ km. In this case, however we must pay attention to the fact that the focus of a shock with magnitude of $M=-1$ can be determined when the hypocentral distance of the shock is only within a range $5 \sim 13$ km and in the case of $M=0$ its range is $14 \sim 30$ km, *i.e.*, the magnitude of the shock which can be analyzed mainly depends on the hypocentral distance. In order to eliminate this weak point, we have to analyze all the shocks with amplitude larger than a certain value by using an instrument of lower sensitivity at the same station. However, since no such instrument was available in the present case, we should take into acount the above-mentioned weak point inevitable in high sensitivity observation.

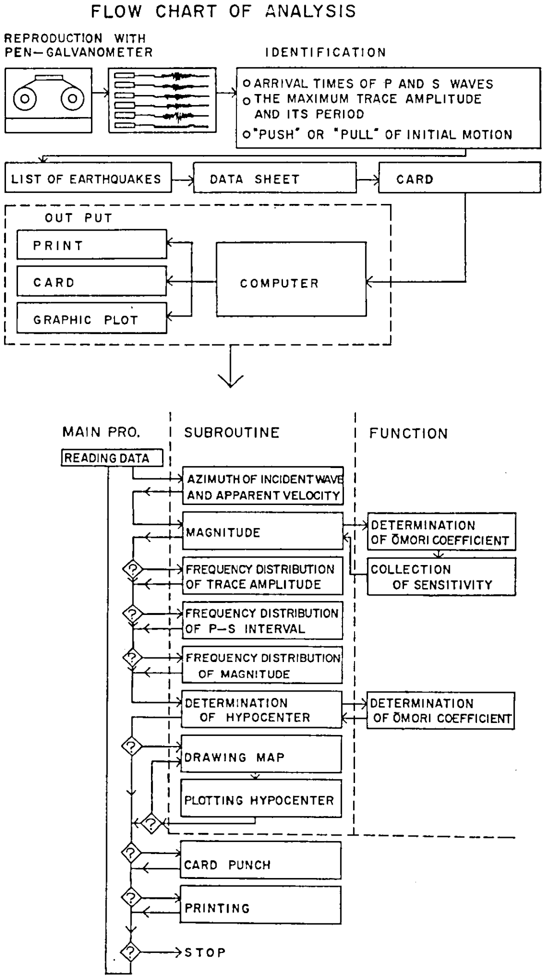

Fig. 2. Flow chart of data processing.

2. Data processing by using an electronic computer

Since the number of the ultra micro-earthquakes observed in the area of Matsushiro swarm earthquakes is enormous, it is very important to consider the economy of time by the use of an automatic data processing system, eliminating careless mistakes. The author felt keenly the

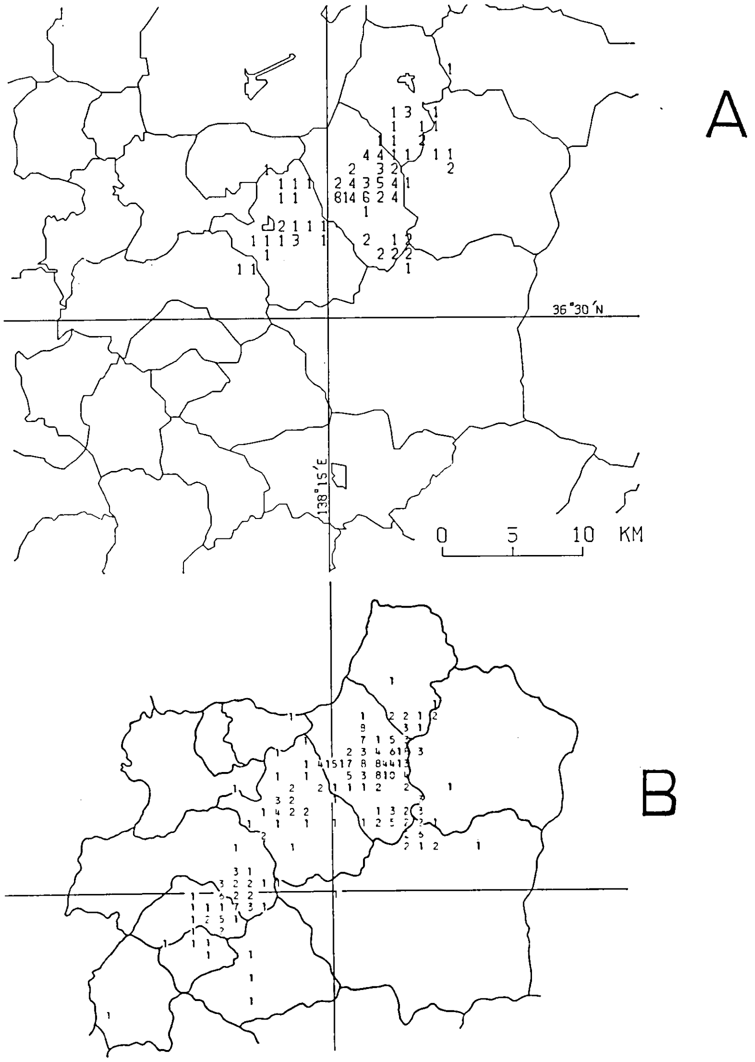

Fig. 3. A; figure drown by the graphic plotter.
B; figure made by the line printer.

necessity of this automatic system from his experience of the hard analytical works involved in processing the enormous number of ultra micro-shocks. Two systems will be considered for data processing, one is the reading-off of the basic data from the seismograms objectively by a standardized judgement, the other the determination of hypocenter, magnitude and other numerals from the basic data, for examples, the arrival times of P and S waves, the amplitude and so on. The automatic reading-off of the basic data from the records cannot be carried out immediately and depends on future study. However we can realize the latter system by using an electronic computer. The author made a program of data processing after reading-off the data from the records. The cards were used as an input, and the output was given by the graphic plotting in addition to the ordinary printing and punching. The flow chart of data processing by using an electronic computer is shown in Fig. 2. The arrival times of P and S waves, "push" or "pull" of initial motion and the maximum amplitude and its period are identified and the data for three shocks are indicated by a punch card. An output card of calculation indicates the result of calculation of three shocks, *i.e.*, the rectangular co-ordinates of the location of the hypocenter, the magnitude, the period of the maximum amplitude and the arrival time. An example of the figure illustrating the sketch map and the location of the foci drawn by the graphic plotter is shown in Fig. 3-A, where the actual map is drawn on a scale of 1/200,000, the planes to which the faci were projected being divided into meshes of 1 km × 1 km and the numbers of the foci being shown by digits at the location of the corresponding meshes on the plane. Except for the sketch map, the straight line and other curves, the location of the hypocenters can be illustrated by the same method by the line printer of the computer. In this case, however, the meshes are taken as 1.015 km long and 0.846 km broad on account of the size of character of the printer. An example of the figure made by the line printer is shown in Fig. 3-B, in which the sketch map is drawn by hand.

3. Frequency of the shocks and division of the period

The frequencies of occurrence of ultra micro-shocks are shown in Fig. 4. For the sake of comparison, the daily number of the shocks counted by the standardized seismograph (Vmax = 100,000) installed at the Matsushiro Seismological Observatory, JMA are shown together.

The frequency of felt earthquakes reported by the same observatory was about 10 percent of the total number of shocks reported by JMA throughout the whole period. The number of ultra micro-shocks observed at the Hoshina station was counted for 90 minutes in the day-time once a day, and at the Sanada station the same work was done for 4 hours at 0∼4 o'clock.

For the sake of convenience, the perid of observation was divided into four stages, *i.e.*, the first stage (October 1965∼February 1966), the second stage (March∼July 1966), the third stage (August∼December 1966), the 4th stage (January∼May 1967). This division was not made by the difference of the actual seismic activity but only for the sake of convenience. However, a peak of seismic activity appears in each stage, *i.e.*, the first

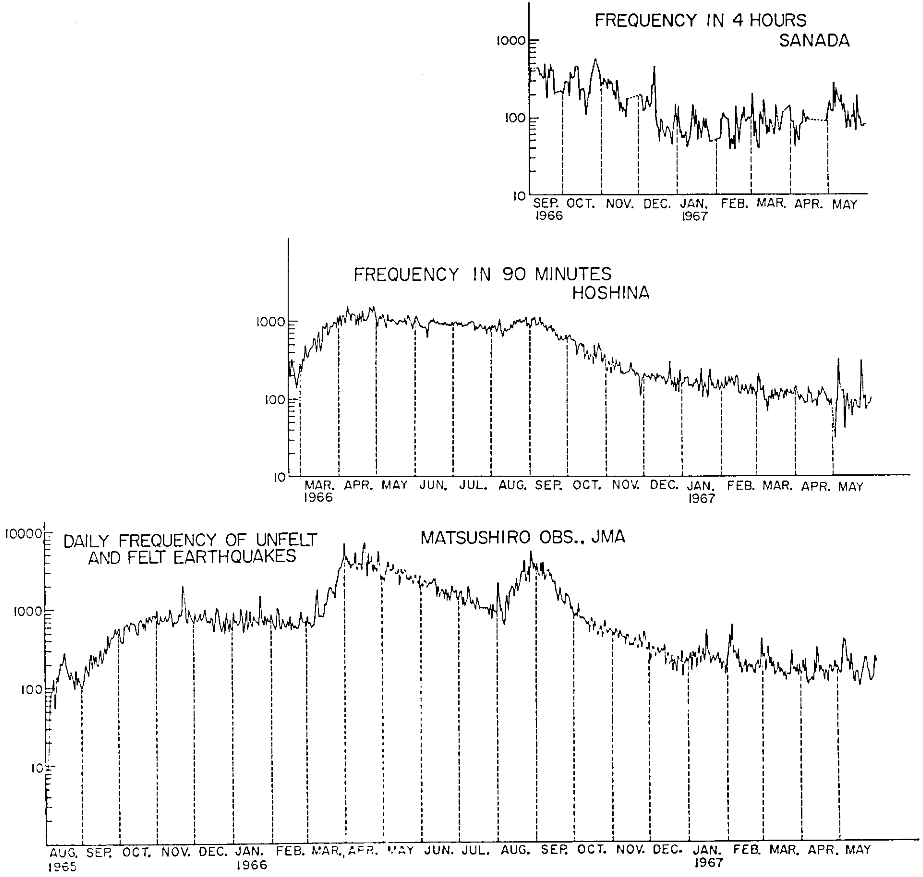

Fig. 4. Frequency of occurrence of earthquakes.

peak in the latter part of November 1965 belongs to the first stage, the second peak in the second stage and the third peak in the third stage.

As details about the frequency of the shocks are illustrated in Fig. 4, their descriptions will be abbreviated here. The decrease in the number of the shocks reported from JMA after the second peak is shown approximately by a straight line on a semi-logarithmical graph, while after the third peak the curve showing the number of the shocks becomes downward convex as shown in the figure. Seismic activity around the village of Sakai became relatively active from the beginning of 1967. Since the numbers of the shocks illustrated in Fig. 4 were obtained at the Matsushiro Seismological Observatory, JMA, Hoshina and Sanada, the number of the shocks that occurred around Sakai may be underestimated compared with other regions. We should pay attention to this fact.

4. Velocity of the seismic wave and the Ōmori coefficient *k* in the region of Matsushiro earthquakes

It is of basic importance to determine the seismic foci from the observational data. It is necessary to know the underground structure in the area of the Matsushiro earthquakes in order to determine the seismic foci correctly. In order to determine the underground structure, the data obtained by explosion are the most valuable but there are as yet no data of explosion. Instead of them, however, there are many observational data of the natural shocks, apparent velocity determined by the tripartite observation, *S* wave's data obtained by the tripartite observation using the seismographs of horizontal component and the Ōmori coefficients obtained at the various stations. In this paper, synthesizing all the above-mentioned observational results, the underground structure will be investigated and the determination of hypocenters will be made.

4-1. Ōmori coefficient *k*

The Ōmori coefficient k called here means the ratio of the hypocentral distance r to the P-S time interval. The stations used to determine k were the acceleration seismographic network, the high sensitivity tripartite stations, and the HES seismograph stations. The locations of these stations are shown in Fig. 1. Since the Ōmori coefficient $k = 6.12 \pm 0.61$ km/sec has been obtained from the acceleration seimographic network. We used this value of k and P-S times when determining the hypocenters from the two different combinations of the stations, Hoshina, Akashiba, Zōzan and Akashiba, Mori, Sakaki. If the location of epicenter of a shock was determined to be inside the triangle composed by the three stations used for determining the hypocenter, the location of this shock is considered to be most reliable. In this case, the accuracy of the depth which is more unreliable than that of horizontal location is estimated to be 1 km. We assumed the above-mentioned case as a correct location of the shock. Using such a location of the shock, we examined the relation between the hypocentral distances and the *P-S* times for other distant stations. The results are shown in Fig. 5, in which the data were obtained during the period from October 1966 to January 1967. The range of the depths of the shocks are 2~5 km, 70

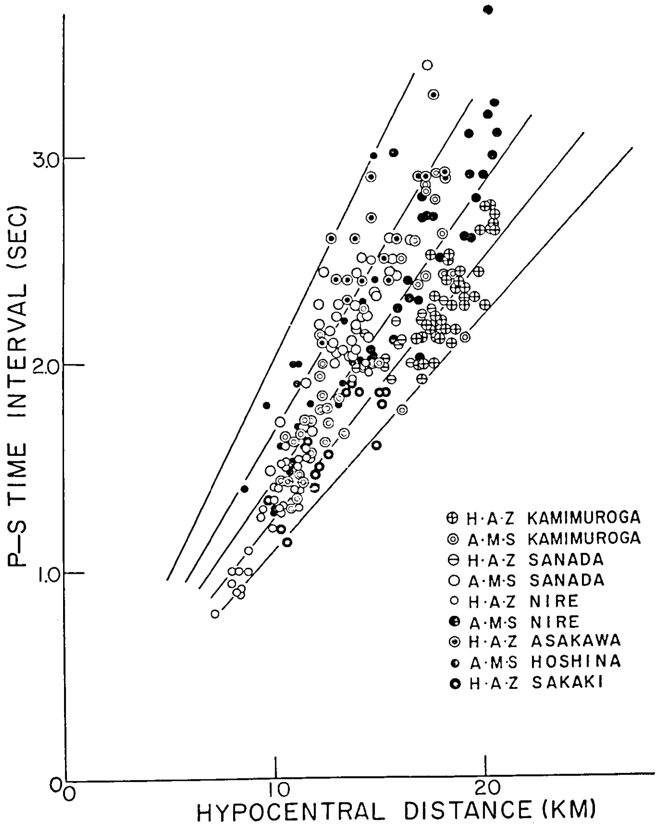

Fig. 5. Relation between the hypocentral distance and the *P-S* time. The straight lines mean the $k=5,6,7,8$ and 9 km/sec in order from the top to the bottom.

percent of them being 3~4 km. Fig. 6 shows the relation between the hypocentral distances and the k derived from the results shown in Fig. 5. From these figures the following were found: 1. The values of k are 6~8 km/sec in the range of r 10~20 km. 2. The fluctuation of k is smaller when the shocks located at a narrow limited region are observed by a single station, the standard deviations of k being less than 0.5 km/sec. 3. The value of k determined at the same station changes considerably if the location of the shocks differs. 4. As a general tendency, when the seismic waves propagate southwestwards, the values of k are larger than when the waves propagate northeastwards. 5. Good correlation between k and hypocentral distance r was not found in the range of r 10~20 km.

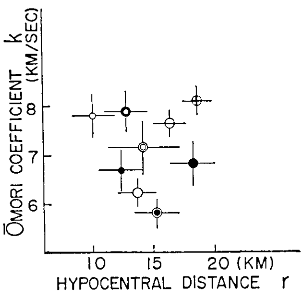

Fig. 6. Relation between the hypocentral distance and the Ōmori coefficient k.

Considering the above-mentioned five facts, we can estimate as follows: The fluctuation of k in each case depends upon the accuracy of P-S times and the locations of the foci, the large fluctuation of the values of k mainly depends upon the underground structure, $k=8.09\pm0.33$ indicates the mean value of k in the region covering a range of 20 km from Hoshina, Akashiba and Zōzan to Kamimuroga, $k=6.82\pm0.45$ shows the mean value in the region covering a range of 20 km from Akashiba, Mori and Sakaki to Nire.

As regards the underground structure, the structure shallower than several kilometers is expected to be fairly irregular place by place judging from the fluctuation of the value of k, but on an average, the velocity of the seismic wave seems to be larger in the southwestern part and smaller in the northeastern part.

The temporary observation of ultra micro- and micro-earthquakes has been carried out around Matsushiro by the research group of Kyōto Univ., Hokkaidō Univ., Gifu Univ. and Akita Univ., the stations being distributed in a circular area of 40 km in diameter with its center at Matsushiro. From this temporary observation, k was determined to be 6.88 ± 0.48 km/sec. For calculating the mean of k, we adopted 258 values of k that gave a deviation less than 0.2 km/sec when the deviation of 0.05 sec was assumed to exist in the reading values of P-S time at each station. This value of k, which can be regarded as a mean value in the area around Matsushiro, is consistent with the values obtained by our observations as shown in Fig. 6.

4-2. Apparent velocity obtained by the tripartite observation

Fig. 7 shows the *apparent* velocity of the P wave propagating along the horizontal earth's surface obtained by the tripartite observation at Hoshina, Sanada and Kamimuroga. The tripartite observation was also carried out at Asakawa, but since the results of the geological survey show that the underground structure in the area on the north side of the Nagano basin is obviously different from the area of Matsushiro,[12] the result obtained at Asakawa was not used here. In the present case, the error of apparent velocity is 300 m/sec for the apparent velocity of 5 km/sec, 400 m/sec for 6 km/sec and 600 m/sec for 7 km/sec when each distance between the transducers of the tripartite station is 1 km. For that reason, the apparent velocity is shown with the division of 500 m/sec in Fig. 7. Since the relation between the apparent velocities and the P-S times was not clear, this relation was abbreviated in the figure. The changes in the apparent velocity with respect to the direction of the incident wave was also not clear excepting the data observed at Sanada. In the case of Sanada, the apparent velocity was the slowest when the seismic wave propagated southeastwards.[13] Such a phenomenon seems to be caused by the underground structure just under the Sanada station but not by the distribution of the hypocenters. Judging from the results shown in Fig. 7 and considering the peculiarity of the Sanada observation, the velocity of P wave was determined to be 5 km/sec from the lower limit of the apparent velocity in the cases of Hoshina and Kamimuroga. The velocity of 6 km/sec is obviously recognized in the case of Kamimuroga on account of the frequent occur-

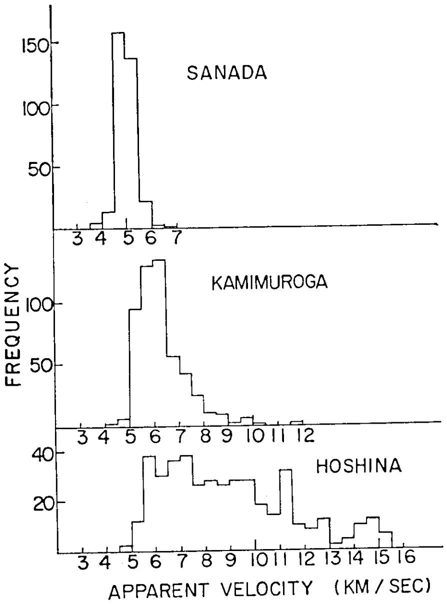

Fig. 7. Apparent velocity determined by the tripartite observation.

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[12] R. Morimoto *et al.*, "Geological Consideration on the Matsushiro Earthquakes-Swarm since 1965 in Central Japan," *Bull. Earthq. Res. Inst.*, **44** (1966), 423.

[13] K. Hamada and T. Hagiwara, *loc. cit.*, 8).

rence of longer P-S time. At the Sanada station, the lower limit of the apparent velocity is 4 km/sec and the maximum frequency of occurrence lies at 5 km/sec. If there were no peculiarity of underground structure just under the Sanada station, it would be expected that the lower limit of 4 km/sec and the peak at 5 km/sec become 5 km/sec and 6 km/sec respectively as shown by the Hoshina and the Kamimuroga observations. The speciality of the underground structure at the Sanada station seems to be caused by the river gravel on which the seismographs were set up.

Consequently 5 km/sec and 6 km/sec were obtained as the velocity of P wave in the area of Matsushiro earthquakes, these values are also reasonable from a common-sense standpoint. As regards the relation between the Ōmori coefficient k and the velocity of P wave, the velocity of P wave of 5 km/sec and 6 km/sec correspond to the values of k of 6.8 km/sec and 8.2 km/sec respectively, if the ratio of P waves's velocity to S waves's velocity is assumed to be $\sqrt{3}$. Therefore, the value of k of 8 km/sec is reasonable but the value of 6 km/sec is too small to be explained under the assumption stated above.

4-3. Observation of S wave by the tripartite method using the seismographs of horizontal component

As stated in the previous section, the velocity of S wave is required to be known in order to verify the fact that the velocity of P wave is 5.0 km/sec and consists with the Ōmori coefficient k which is 6.12. Fortunately, the observation of S wave by means of the tripartite method with the seismographs of horizontal component has been carried out at Hoshina. Although the true velocity of S wave itself cannot be observed directly by the tripartite observation, if both P and S phases are observed, the ratio of the apparent velocity of P wave to that of S wave will be found. This ratio is nothing more than the ratio of the actual velocity of P wave to that of S wave. To explain in detail, if the ratio of the velocity of P wave to that of S wave in each medium of the underground is the same, both the rays run along the same route, and the ratio of the apparent velocity of P wave to that of S wave is represented as follows: we denote

D = distance between the observation stations A and B

Vp_i = velocity of P wave in the i-th layer

Vs_i = velocity of S wave in the i-th layer

AVp = apparent velocity of P wave between the stations A and B

AVs = apparent velocity of S wave between the stations A and B

l_i = length of each ray route in the i-th layer in the case that the wave passes from the seismic focus to the station A

l'_i = length of each ray route in the i-th layer in the case that the wave passes from the seismic focus to the station B

n = the number of the layer that the wave passes from the seismic focus to the station A

n' = the number of the layer that the wave passes from the seismic focus to the station B

c = the ratio Vp_i/Vs_i.

then, the ratio of the apparent velocity of P wave to that of S wave is represented as follows:

$$AVp = D\Big/\left(\sum_{i=1}^{n} l_i/Vp_i - \sum_{i=1}^{n'} l'_i/Vp_i\right)$$

$$AVs = D\Big/\left(\sum_{i=1}^{n} l_i/Vs_i - \sum_{i=1}^{n'} l'_i/Vs_i\right)$$

$$\begin{aligned} AVp/AVs &= \left(\sum_{i=1}^{n} l_i/Vs_i - \sum_{i=1}^{n'} l'_i/Vs_i\right)\Big/\left(\sum_{i=1}^{n} l_i/Vp_i - \sum_{i=1}^{n'} l'_i/Vp_i\right) \\ &= \left(\sum_{i=1}^{n} l_i/Vs_i - \sum_{i=1}^{n'} l'_i/Vs_i\right)\Big/\left(\sum_{i=1}^{n} l_i/cVs_i - \sum_{i=1}^{n'} l'_i/cVs_i\right) \\ &= c \qquad\qquad (\because Vp_i/Vs_i = c) \end{aligned}$$

$$\therefore AVp/AVs = Vp_i/Vs_i$$

The S phase were well identified on the seismographs. Both P and S phases were read off for about 60 shocks during 3 hours of observation time. Examples of the seismographs are shown in Fig. 8. In order to determine the apparent velocities of P and S waves, 17 shocks were adopted, of which the wave forms of both P and S phases were clear at the three observation points, and of which the two incident directions determined by P and S waves were consistent within 10 degrees. As a result, the ratio of the velocity of P wave to that of S wave was determined to be 1.82 as the mean value with the standard deviation ± 0.26.

The velocity of P wave Vp, that of S wave Vs and the Ōmori coefficient k have the relation $k(Vp/Vs-1)=Vp$, if the underground

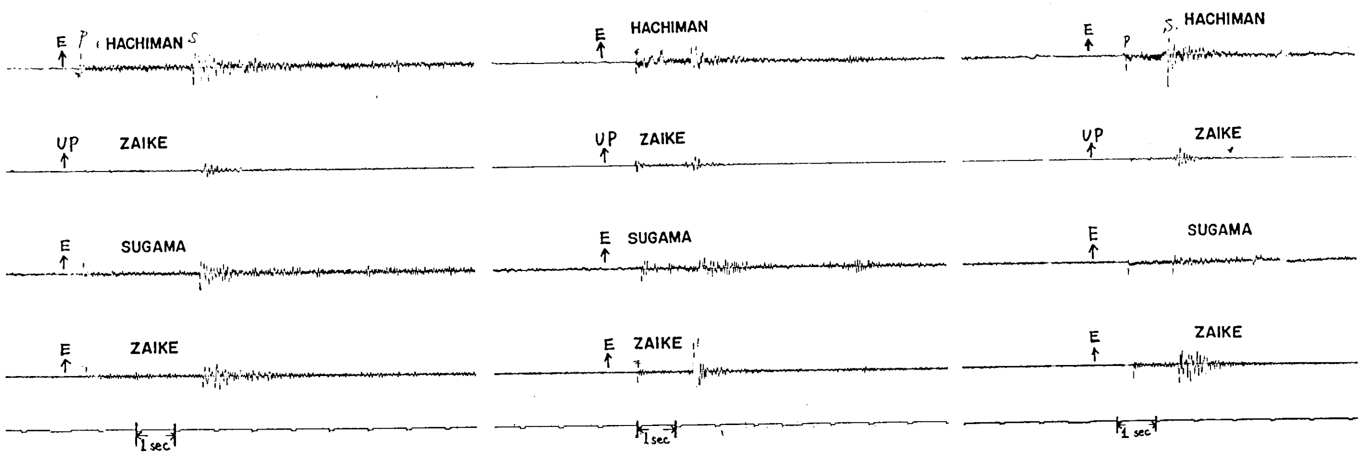

Fig. 8. Horizontal component seismographs obtained at the Hoshina station.

structure is isotropic and homogeneous, the velocities of P and S waves being constant with depth. If we substitute the values of Vp/Vs and k into the left-hand side, we obtain $Vp=5.0$ km/sec, which is equal to the value estimated from the apparent velocity of P wave determined by the tripartite observation. As described in the foregoing, the three values of Vp, Vp/Vs and k determined independently from the observational results coincide with each other, so that these values may be reliable as the values in the region around Matsushiro.

From the results obtained in the foregoing, we will be possible to estimate the underground structure in the area of Matsushiro earthquakes. The underground structure is rather irregular as seen from the fact that the value of k fluctuates between 6 and 8 km/sec. However, as a general aspect, it can be described as follows: There exists an upper layer with the P wave's velocity of 5 km/sec and a lower medium with that of 6 km/sec. The boundary of the upper layer and the lower medium is shallower in the southwestern part, being about at most 1 km at Kamimuroga, and deeper in the northeastern part, being about at least 5 km at Nire. The estimation of the thickness of the upper layer was done in such a way as that the apparent k obtained by numerical calculation satisfies the results determined by the observations at Kamimuroga and Nire respectively. The numerical calculation was done under the assumption that there exists a layer of uniform thickness with the P wave velocity of 5 km/sec over a solid bottom with the P wave velocity of 6 km/sec and the ratio of the velocity of P wave to that of S wave being $\sqrt{3}$. The reason why the 2 cases above-mentioned were chosen is that $k=8.09$ km/sec and $k=6.82$ km/sec can be regarded as the mean values in the region covering a range of 20 km from Hoshina, Akashiba and Zōzan to Kamimuroga and in the region covering a range of 20 km from Akashiba, Mori and Sakaki to Nire respectively.

5. Domain of felt earthquakes and its variation with time

Before examining the activity of ultra micro-earthquakes, with a view to investigating the relation between the activity of ultra micro-shocks and that of felt ones, we shall summarize the activity of felt earthquakes. The division of the period follows after that described in the previous section 3.

The observation of felt earthquakes by the temporary seismographic network has been carried out since October 1965, set up around the town of Matsushiro. The results of this observation have been reported already.[14),15),16)] The hypocentral distributions of felt earthquakes in every five-months are reprinted in Fig. 9 after T. Hagiwara *et al.*[17)]

The first stage (October 1965 ~ February 1966). In this stage, 15 large earthquakes with intensity of IV on the JMA scale occurred, *i.e.*, they occurred 8 times in November, 2 times in December 1965, 3 times in January and 2 times in February 1966. It is noticed that four of them occurred repeatedly in three days from November 22 to 24, 1965. The latter part of November 1965 is called the first climax of the seismic activity. The hypocenters were located mainly in the town of Matsushiro, a part of them were located in Wakaho adjacent to Matsushiro. The epicenters were located in a circular area of 8 km in diameter with its center at Mt. Minakami. The region near Mt. Minakami was densely crowded with the seismic foci around the depth of 3 km. The depths of the hypocenters were in the range 0~8 km.

The second stage (March ~ July 1966). In this stage, the large earthquakes with intensity larger than IV occurred exceedingly 35 times, *i.e.*, occurring 2 times in March, 15 times in April, 11 times in May, 5 times in June, 2 times in July 1966. April and May are called the second climax of the seismic activity, which exceeded extremely the first climax. In the second stage, the hypocentral area spread mainly to Wakaho, some shocks being located in Sanada, Kōshoku, Shinonoi and Kōhoku adjacent to Matsushiro and Wakaho. The shocks were located in a circular area of 13 km in radius with its center at Mt. Kimyō. Although the area near Mt. Minakami was dense with the seismic foci in the first stage, the shocks occurred frequently in the region near Mt. Kimyō in the second stage. The depths of the seismic foci were in the range 0~10 km, most of them being 2~6 km.

The third stage (August ~ December 1966). The 23 large earthquakes with intensity larger than IV took place in this stage, *i.e.*, they occurred 10 times in August, 7 times in September, 5 times in October and once

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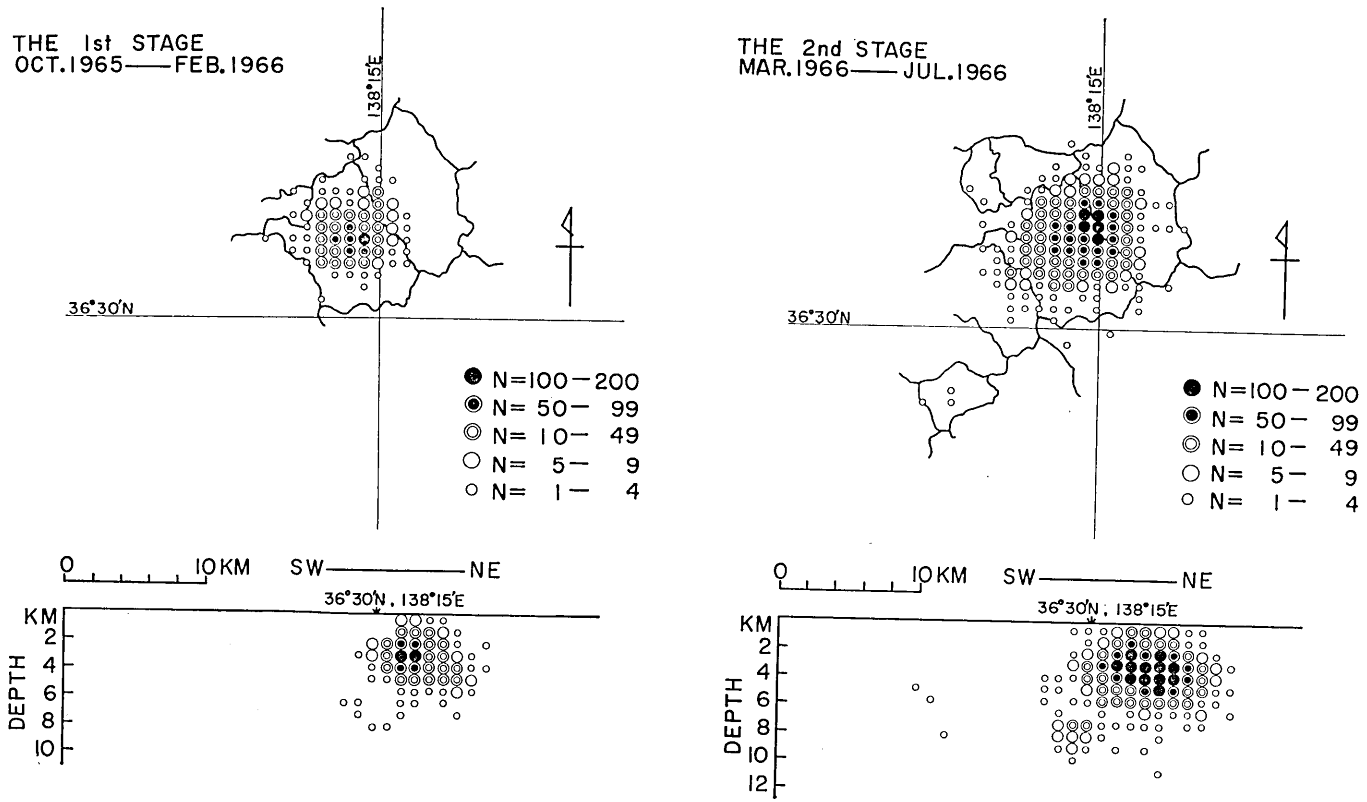
14) THE PARTY for SEISMOGRAPHIC OBSERVATION of MATSUSHIRO EARTHQUAKES and the SEISMOMETRICAL SECTION, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network. Part 1," *Bull. Earthq. Res. Inst.*, **44** (1966), 309.

15) THE PARTY for SEISMOGRAPHIC OBSERVATION of MATSUSHIRO EARTHQUAKES and the SEISMOMETRICAL SECTION, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network. Part 2," *Bull. Earthq. Res. Inst.*, **44** (1966), 1689.

16) THE PARTY for SEISMOGRAPHIC OBSERVATION of MATSUSHIRO EARTHQUAKES and the SEISMOMETRICAL SECTION, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network. Part 3," *Bull. Earthq. Res. Inst.*, **45** (1967), 197.

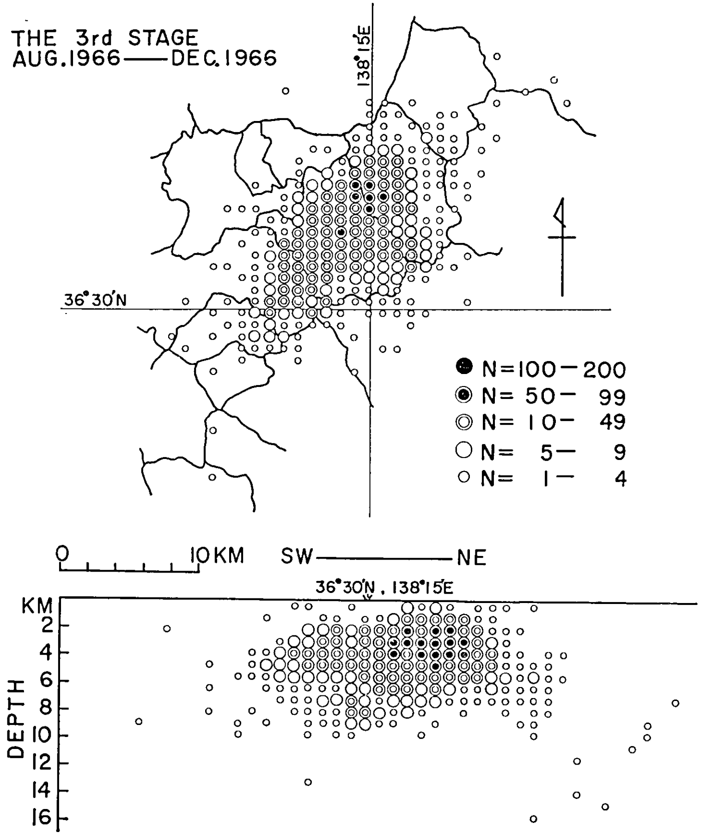
17) T. HAGIWARA, T. IWATA and K. HAMADA, *Personal Communication.*



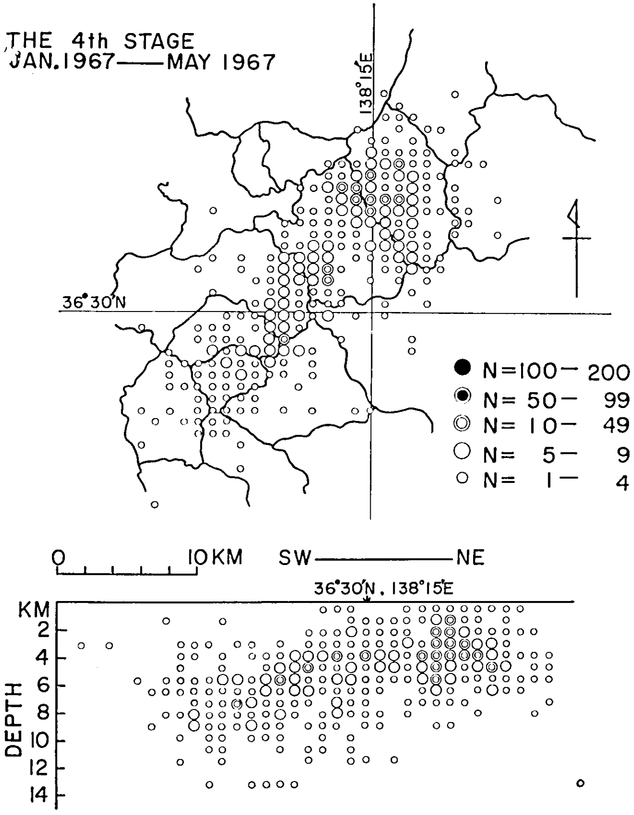
A; the first stage.

B; the second stage.

Fig. 9. Hypocentral distribution of the felt earthquakes, after T. HAGIWARA *et al.* N; the number of the shocks in a mesh (1.015×0.846 km).

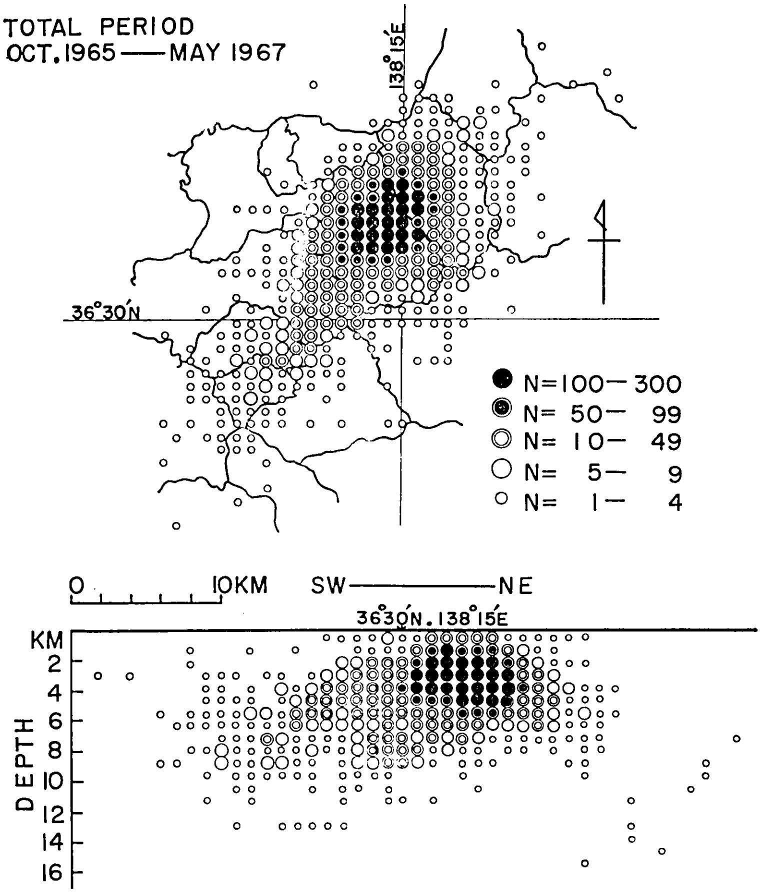


C; the third stage.



D; the 4th stage.

in December 1966. August and September 1966 are called the third climax of the seismic activity. When the third stage began, the hypocentral area further enlarged particularly northeastwards and southwestwards. Azuma, Suzaka, Takayama in the northeastern area and Sakai, Tokura, Kamiyamada in the southwestern area were added to the area of seismic activity. The shocks were mostly located in Matsushiro, Wakaho and Kōshoku, but the area in which the shocks occurred very frequently was on the north side of Mt. Kimyō. The epicenters distributed in an elliptical area 33 km long in the northeast-southwest direction, 15 km long in the northwest-southeast direction with its center at Mt. Kimyō. The depths of the seismic foci were in the range $0\sim10$ km, most of them being $2\sim6$ km.



E; the total period.

The 4th stage (January～May 1967). The 12 large earthquakes with intensity larger than IV occurred in this stage, *i.e.*, 1 in January, 4 in February, 2 in March, 1 in April and 4 in May 1967. There was no climax of the seismic activity in the 4th stage. The hypocentral area extended particularly to the southwestern area, Kamiyamada, Sakaki, Kawanishi and Sakai, after the third stage. On the other hand the number of the shocks decreased as a general tendency. The area on the north side of Mt. Kimyō was densely crowded with the seismic foci following after the third stage. An interesting fact is that the shocks that had occurred frequently in the neighbourhood of Matsushiro since the beginning up to the third stage decreased greatly in number in the 4th stage and the number of the shocks became particularly small in the narrow region on the northeast side of Mt. Minakami where an earthquake fault was created. Examining more precisely, the pattern of hypocentral distribution different from the third stage was recognized after October 1966, while October 1966 was the month when a noticeable phenomenon of the crustal movement was observed in the area of Matsushiro,[18] *i.e.*, the remarkable crustal movement progressing there stopped or showed a reverse movement. Such a phenomenon indicates the close relation between the crustal movement and the seismic activity.

The hypocentral distribution of the felt earthquakes in the total period from October 1965 to May 1967 is shown in Fig. 9-E. Although the number of the shocks in Matsushiro decreased remarkably in the 4th stage, the shocks occurred very frequently in Matsushiro throughout the whole period of observation as shown in the figure.

6. Domain of ultra micro-earthquakes and its variation with time

6-1. Method of determination of the hypocenter by the tripartite observation

The determination of the seismic foci by the tripartite observation has been described in the previous paper,[19] so that, it will be described here briefly. The underground structure was assumed to be isotropic and homogeneous, the velocity of P and S waves being constant with depth. We determined the location of the hypocenter by the use of the

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[18] K. KASAHARA *et al.*, "Electro-Optical Measurement of Horizontal Strains Accumulating in the Swarm Earthquake Area (3)," *Bull. Earthq. Res. Inst.*, **45** (1967), 241.

[19] K. HAMADA and T. HAGIWARA, *loc. cit.*, 5).

arrival times of P wave at three stations and that of S wave at one of these stations, assuming that the seismic waves were propagated as a spherical wave and giving a fixed value to the velocity of P wave and the coefficient k. Such an analytical method of the tripartite observation is different from the usual method, in which seismic waves are assumed to be propagated as a plane wave, and is more accurate when the stations are nearer to the epicenters. The method was very suitable in the first and the second stages because the epicentral distances were small and were in the range of 0∼10 km. However, when the hypocentral area extended in the third and the 4th stages, an undesirable problem occurred. This was that the first arrivals of seismic waves were not direct waves but the head waves or refracted waves. In such cases, the depths of the shocks were apparently determined to be deeper and the epicentral distances shorter than actual values. However our present knowledge concerning the underground structure in the area of Matsushiro earthquakes is so poor that we cannot determine the hypocenters based on a certain layered underground structure. Since we can expect considerable irregularity of the underground structure in this area as shown in the previous section, the accuracy of location of the seismic foci will not be improved, even if we assume a simple underground structure. Therefore we continued to use the same method of determination of the hypocenter hitherto used, bearing in mind that some systematic deviation of the location of the foci would exist for a larger epicentral distance.

When we determine the hypocenter, we assumed that the velocity of P wave was 5.0 km/sec at the Hoshina station and 4.5 km/sec at the Sanada station. The value of k was assumed as follows:

Fig. 10 shows the relation between the values of k and the P-S times derived from the data shown in Fig. 5, in which $k=6.12\pm0.61$[20] obtained by the observation of four stations, Hoshina, Akashiba, Mori and Zōzan, was added. The value of k is expected to be about 8 km/sec for the long P-S time on account of the existence of the lower medium with P wave velocity of 6 km/sec.

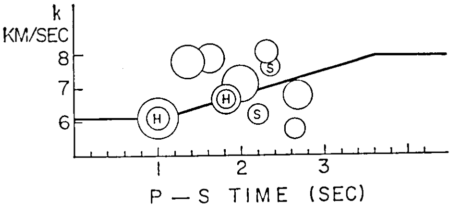

Fig. 10. Relation between the k and the P-S time.
Ⓗ,Ⓢ; data obtained at the Hoshina and Sanada respectively.

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[20] K. HAMADA and T. HAGIWARA, *loc. cit.*, 7).

From the above-mentioned facts, when we determine the hypocenter by the tripartite observation at Hoshina and Sanada, we considered that k was a function of the P-S time as indicated with the broken line in Fig. 10. Finally k was represented as follows:

$$k=\begin{cases} 6.12 & P\text{-}S<1.0 \\ 0.723\times(P\text{-}S)+5.40 & 1.0\leqq P\text{-}S<3.6 \\ 8.00 & P\text{-}S\geqq 3.6 \end{cases}$$

Next, there is a problem of how accurate is the location of the hypocenter determined by the present method. Since, of course, an absolutely accurate location of the shock is unknown, the only way given to us is to compare the location of hypocenter determined by the present method with that of the same shock determined by another method. As the result of such comparison was already reported in my previous paper,[21] only a brief description will be made here. In comparison with the location of the hypocenter determined by the P-S times at the stations of our ordinary seismographic network set up at Matsushiro and Wakaho, there is no systematic deviation of the location of the hypocenter determined by the Hoshina tripartite observation, so far as earthquakes in the neighbourhood of Matsushiro and Wakaho are concerned. However, a systematic inclination was recognized in the case of the Sanada tripartite observation. When determining the hypocenter by the Sanada tripartite observation, the location of the hypocenter was displaced about ten degrees anticlockwise watching from the station and was attracted to the station, *i.e.*, the location of the shock determined by the observation at Sanada was at a distance of $2\sim4$ km southwest and $1.5\sim2$ times deeper compared with the focus of the same shock determined by the Hoshina tripartite observation or by the ordinary seismographic network.

6-2. Hypocentral area of ultramicro-earthquakes and its variation with time

The data treated here were obtained by the tripartite observation at Hoshina during the period from October 1965 to May 1967 and by the same method at Sanada during the period from September 1966 to May 1967. The observation at Hoshina was interrupted in the period from December 19, 1965 to February 19, 1966. After this interruption,

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[21] K. HAMADA and T. HAGIWARA, *loc. cit.*, 8).

the observation was opened again, raising sensitivity of the instruments higher than before. In both cases the ultra micro-earthquakes were observed very frequently so that both the observations were combined together when investigating the ultra micro-earthquake activity in the first stage. The result of the determination of the hypocenter by the Sanada tripartite observation shows a systematic deviation for the shocks which occurred in the area of Matsushiro and Wakaho but we have no such knowledge concerning such systematic deviation for the shocks occurring in other areas, so that the results of analysis were shown in the figure without any correction. The planes to which the foci were projected were divided into 50×50 meshes 1,015 km long and 0.846 km broad for the convenience of the line printer of the computer, and thus a reduced scale became 1/200,000. The number of the shocks was indicated by digits in the location of the corresponding meshes on the plane, and lastly the counter lines were drawn on the projected plane by hand as shown in Fig. 11. In the case when the number of the shocks in a mesh is smaller than 5, the location of the mesh was marked with a small circle. Since the observation of the ultra micro-earthquakes was carried out for the purpose of forewarning of the activity of the Matsushiro earthquakes, the observed data were obliged to be analyzed promptly, the number of the analyzed data exceeded 30,000 in the period from October 1965 to May 1967.

The first stage (*October 1965～February 1966*). In this period, the high sensitivity tripartite observation was carried out at Hoshina at first during the period from October 31 to December 18, 1965, the second observation by the same method being started on February 20, 1966 after an interruption of sixty days. The magnitude of the shocks was in the range $-1.0\sim+0.2$ in the first observation and $-2.0\sim-0.3$ in the second observation due to the difference of sensitivity of the instruments used. Fig. 11-A illustrates the hypocentral distribution of ultra micro-earthquakes observed in the first stage, in which the total number of the shocks analyzed was 1,500 and the total observation time was 70 hours. It was found that the clusters of ultra micro-shocks lay in Matsushiro and Wakaho respectively. Some shocks were located in Azumamura, Sanada, Kōshoku, especially Azmamura and Kōshoku but the shocks occurred most frequently in the region on the northeast side of Mt. Minakami. As regards the activity in the first and the second period of observation, all the shocks lay in the region of Matsushiro and Wakaho in the first period, *i.e.*, from October 31 to December 18, 1965, while the area of ultra micro-earthquake activity extended greatly in the second period, *i.e.*, after February 20, 1966. The depth of the shocks distributed in the range 0～12 km, concentrating 2～6 km. It is a noticeable fact that the region on the northeast side of Mt. Minakami where ultra micro-earthquakes occurred very frequently as shown in the figure became later a fracture zone where many cracks were seen on the ground in echelon and an earthquake fault was estimated to be created in the bed rock.[22] In comparison with the epicentral distribution of felt earthquakes, that of the ultra micro-earthquakes determined by the Hoshina tripartite observation was far wider in its area. The area on the northeast side of Mt. Minakami was densely crowded with felt earthquakes and the ultra micro-earthquakes occurred also very frequently there but there was no cluster of felt shocks in Wakaho in spite of the existence of the cluster of ultra micro-earthquakes near the tripartite station in Wakaho.

The second stage (*March～July 1966*). The second stage contains the second climax of the seismic activity in April and May 1966, the number of the shocks being the largest throughout all the stages. The total number of analyzed shocks was 14,000 and the total time analyzed was 115 hours. The hypocentral distribution of ultra micro-earthquakes in the second stage is shown in Fig. 11-B. As seen in the figure, comparing with the first stage, the area of ultra micro-earthquakes extended to Suzaka, Azumamura, Sanada, Kōshoku, Shinonoi, Kōhoku and Nagano. The area which was densely crowded with the shocks was Matsushiro and Wakaho with its center on the northeastern side of Mt. Kimyō, the two clusters of shocks at Matsushiro and Wakaho which had existed in the first stage disappeared in the second stage. As regards the vertical distribution of the shocks, the depths of the foci were mostly distributed between 0 and 12 km, concentrating at 5 km. Only 9 shocks lay in the depth between 12 and 20 km, five of them having occurred at the beginning of June 1966.

The third stage (*August～December 1966*). The period began with the third climax of the seismic activity of August and September and the number of the shocks in this stage was very large following the second stage. The total number of the ultra micro-earthquakes analyzed was 9,400 and the total analyzed time was 123 hours. The hypocentral distribution of the ultra micro-earthquakes is shown in Figs. 11-C and-F.

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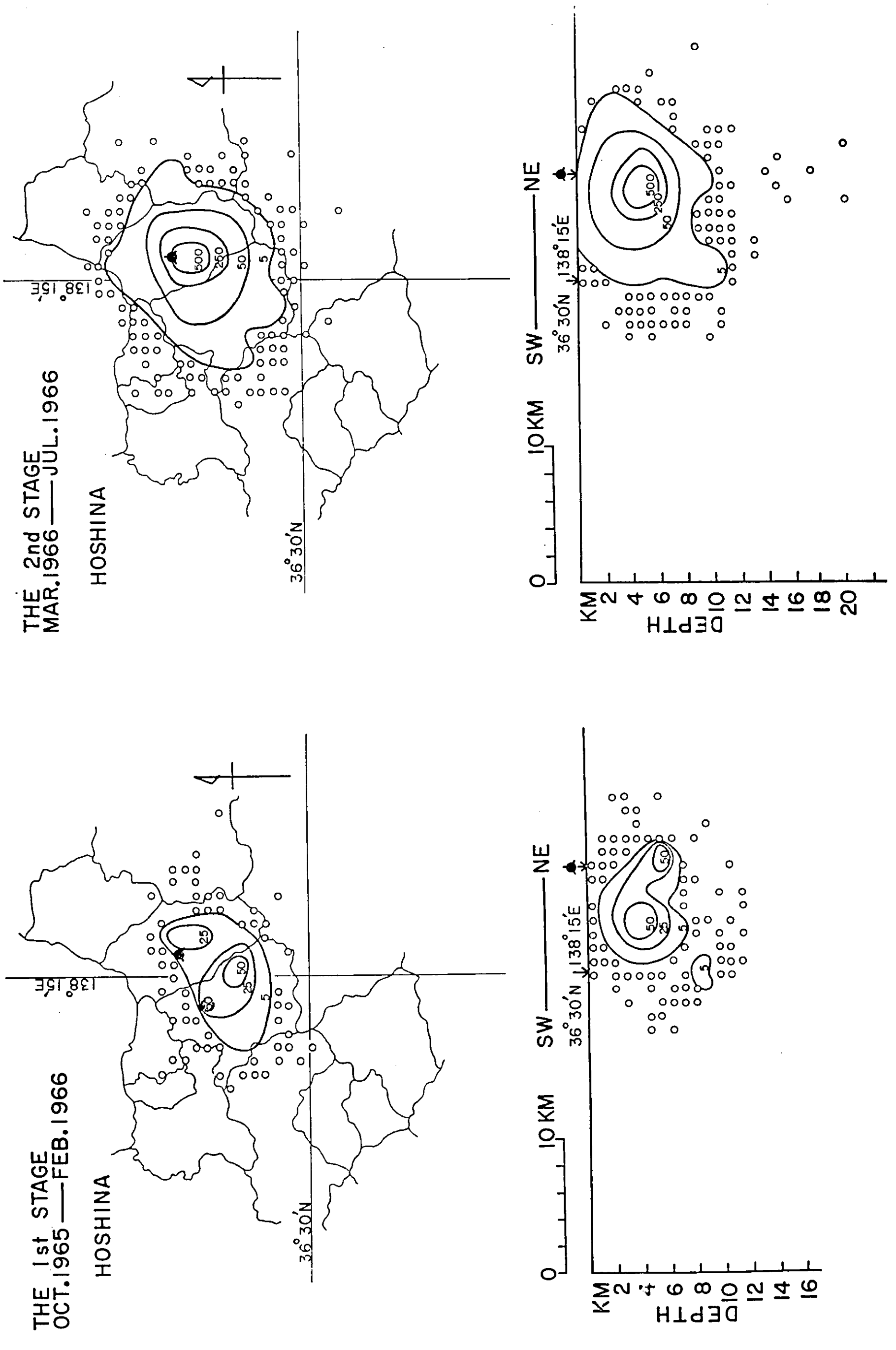
[22] K. NAKAMURA *et al.*, "Ground Cracks at Matsushiro Probably of Underlying Strike-slip Fault Origin, II-The Matsushiro Earthquake Fault." *Bull. Earthq. Res. Inst.*, **5** (1967), 417.

The difference of the hypocentral distribution from that in the second stage was that the epicentral area extended to Azumamura, Suzaka, Takayama in the northeastern region of Matsushiro, to Kōshoku in the southwestern region and to Sanada in the southeastern region. The counter line of the number 5 drawn in the figure illustrates this very well. The situation of the center of the concentration of the shocks did not change in comparison with the second stage and it was still on the northeast side of Mt. Kimyō. The depths of the shocks were distributed in the range $0\sim14$ km, being concentrated mostly at $2\sim4$ km.

Comparing the distribution of the ultra micro-shocks with that of felt ones, the domain of the felt shocks in this stage also extended northeastwards, southwestwards and southeastwards, *i.e.*, towards Azumamura, Suzaka, Takayama, Kōshoku, Tokura, Kamiyamada and Sanada. The epicentral area of the ultra micro-earthquakes was larger than that of felt earthquakes as shown in the figure, but the ultra micro-earthquakes which occurred in Tokura and Kamiyamada in the southwestern part were detected by the Hoshina station only 4 times during the period of 5 months, in spite of the frequent occurrence of felt earthquakes in that area. As will be described later, this does not mean the seldom occurrence of ultra micro-earthquakes in the area of Kamiyamada and Tokura but it was due to the detectability of the Hoshina station. The regions in which the ultra micro-earthquakes and the felt shocks occurred very frequently were consistent with each other.

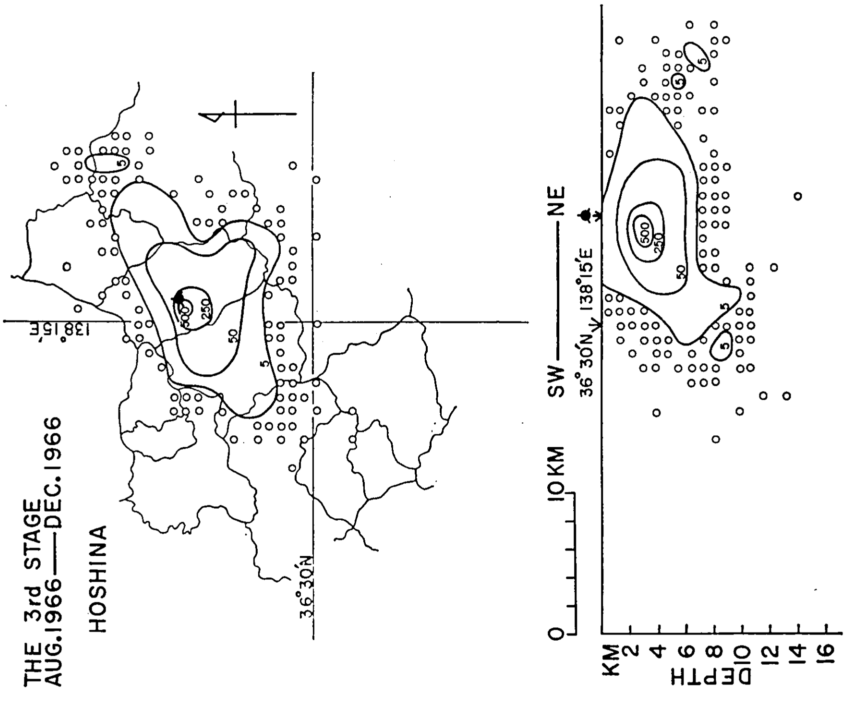
The high sensitivity tripartite observation was started at Sanada on September 5, 1966, with a view to investigate the activity of ultra micro-earthquakes in the southeastern part of the area of Matsushiro earthquakes. The hypocentral distribution of the shocks observed at the Sanada station in the third stage is shown in Fig. 11-F. At the Sanada station, 2,500 shocks were analyzed and the total analyzing time was 104 hours in this period. Since the depths of the shocks were unreliable, only the epicentral distribution was illustrated in the figure without any correction, therefore it contains the systematic deviation stated in the foregoing. The area of the Matsushiro earthquakes that extended in the northeast-southwest direction was able to be looked out over by the Sanada station from the southeastern side, with wider view angle than the Hoshina station. The area looked out over extended from Suzaka and Azumamura to Tokura and Kamiyamada, so that the ultra micro-earthquakes that occurred in Tokura, Kamiyamada, Sakaki and Sanada were well detected by the Sanada station in the third stage.



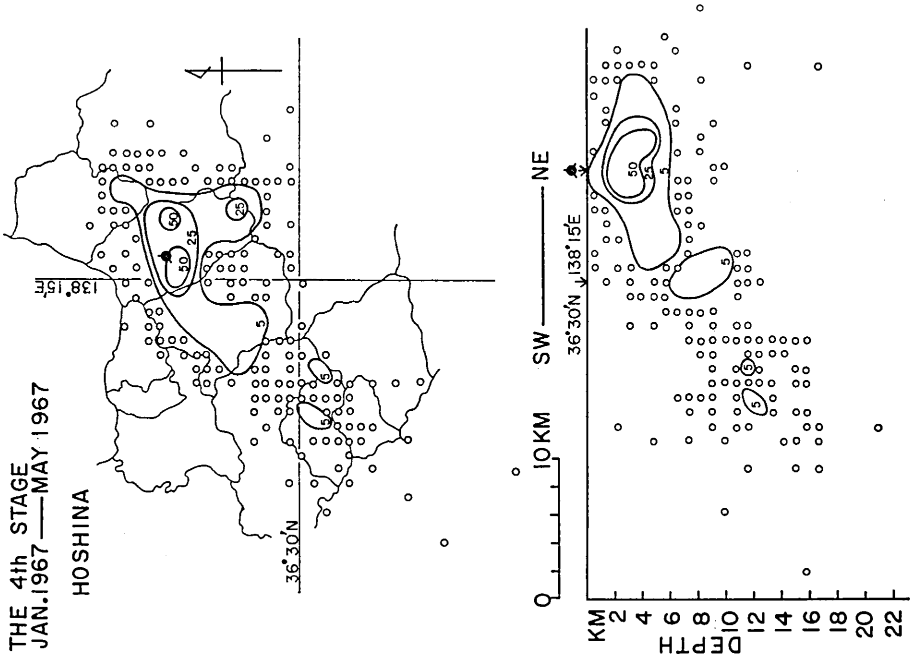
A; the first stage, Hoshina. B; the second stage, Hoshina.

Fig. 11. Hypocentral distribution of the ultra micro-earthquakes. Counter lines show the number of the ultra micro-earthquakes in a mesh (1.015×0.846 km).

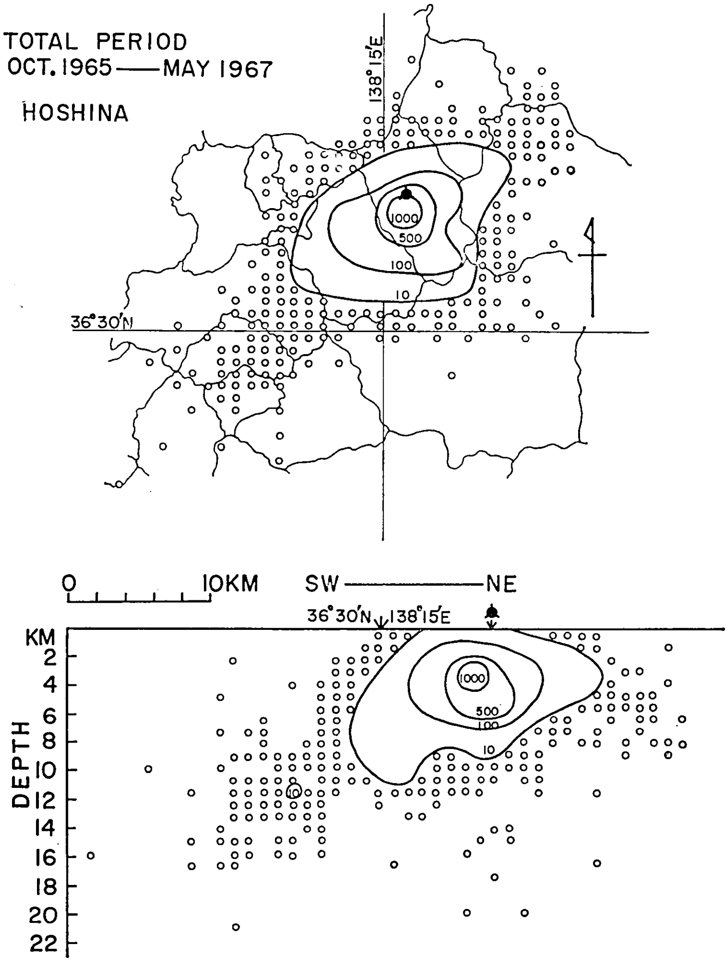
▲; location of the tripartite station.



C; the third stage, Hoshina.



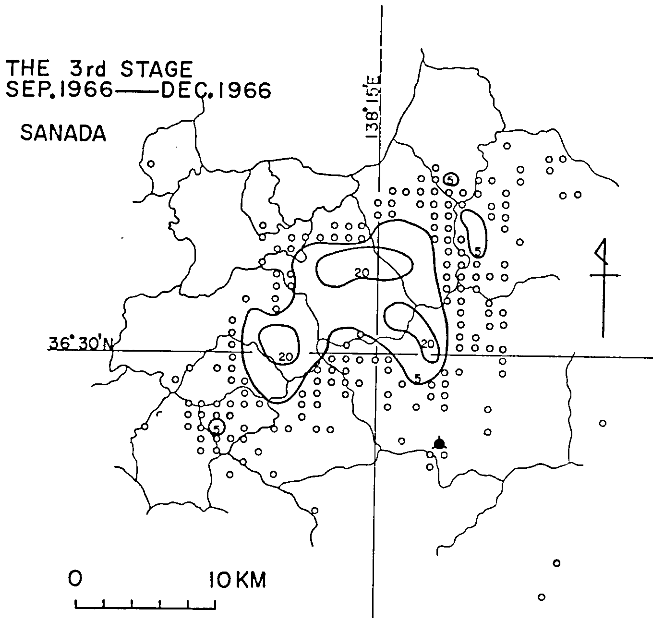
D; the 4th stage, Hoshina.

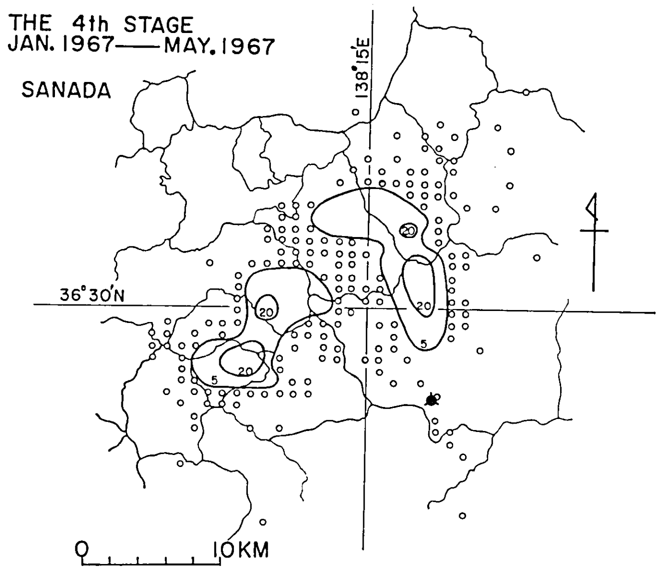


E; the total period, Hoshina.

From the results of the observations at Hoshina and Sanada, it was found that the active area of the ultra micro-earthquakes was larger than that of felt ones, as was the case in the first and second stage, the ultra micro-earthquakes occurring very frequently in the place where the felt earthquakes occurred frequently.

The 4th stage (*January～May 1967*). In the 4th stage, 2,300 ultra micro-earthquakes which occurred in the total time of 82 hours were analyzed from the data obtained at Hoshina, and 1,800 shocks which occurred during the total time of 82 hours were analyzed in the case of the Sanada observation. The hypocentral distribution of the seismic





F; the third stage, Sanada (above).
G; the 4th stage, Sanada (below).

foci is illustrated in Fig. 11-D and-G. The characteristics of the epicentral distribution in the 4th stage are such that the number of the shocks increased in the southwestern part Tokura, Kamiyamada and Sakai, while they decreased remarkably in Matsushiro where a large number of the shocks had been occurring hitherto. Such changes in the distribution of the ultra micro-shocks coincide with the distribution of the felt shocks in the 4th stage as shown in the previous section. The changes in the distribution of the ultra micro-shocks stated above are seen clearly in Fig. 11-G which illustrates the epicentral distribution determined by the tripartite observation at Sanada. In Fig. 11-G, if we move the epicenters located in Matsushiro and Wakaho northeastwards by about 3 km, they will well agree with the epicentral distribution determined by the Hoshina tripartite observation.

The epicentral area of ultra micro-shocks determined by the observations at Hoshina and Sanada was also broader than that of felt ones in the 4th stage, except for the region around the village of Sakai where an areal extention of felt shocks is somewhat larger than that of ultra micro-shocks. But according to the report of the observation carried out at Kamimuroga[23] in Kawanishi village adjacent to Sakai, the ultra micro-earthquakes were distributed more widely around the village of Sakai than the felt shocks.

As regards the region on the northeastern side of Mt. Minakami, a strike-slip fault was created there with its center at Takehara in the N 60° W direction.[24] The ground fissures in echelon were discovered there in April 1966 their opening movement progressing gradually, and then their movement nearly stopped in July 1966. However, their displacement proceeded at a higher rate than before in August and September 1966 and it stopped or showed a reverse movement after October 1966.

The hypocentral distribution of the ultra micro-earthquakes determined by the tripartite observation at Hoshina during the whole period from October 1965 to May 1967 is shown in Fig. 11-E. The ultra micro-earthquakes occurred very frequently in Matsushiro and Wakaho throughout the whole period of observation as shown in the figure.

Roughly speaking, the ultra micro-earthquakes within a distance of 20 km were detected by the tripartite observation at Hoshina and

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[23] M. OHTAKE, H. CHIBA and T. HAGIWARA, "Ultra Micro-earthquake Activity at the Southwestern Border of the Area of Matsushiro Earthquakes. Part 1," *Bull. Earthq. Res. Inst.*, **5** (1967), 861.

[24] K. NAKAMURA *et al.*, *loc. cit.*, 22).

Sanada throughout the whole observation period from October 1965 to May 1967. The magnifications of the instruments used at Hoshina and Sanada were 500,000 and 1,000,000 for the vibration of 20 cps respectively. Besides the tripartite observations at Hoshina and Sanada, we are carrying out observations by the same method at Asakawa and Kamimuroga at the present time, determining the location of each shock. The results of determination of the hypocenters by the tripartite observation at four spots during the period from January to March 1967 are shown in Fig. 12. In this figure, the whole area of the Matsushiro earthquakes was divided into four regions indicated by a dotted line, and the hypocenters were determined by the tripartite observation at the nearest station independently from other tripartite observations. Fig. 12 illustrates the ultra micro-earthquakes which could not be detected at the Hoshina and Sanada stations. Roughly speaking, the observation at each station detected ultra micro-earthquakes only within a distance of 20 km, which was an

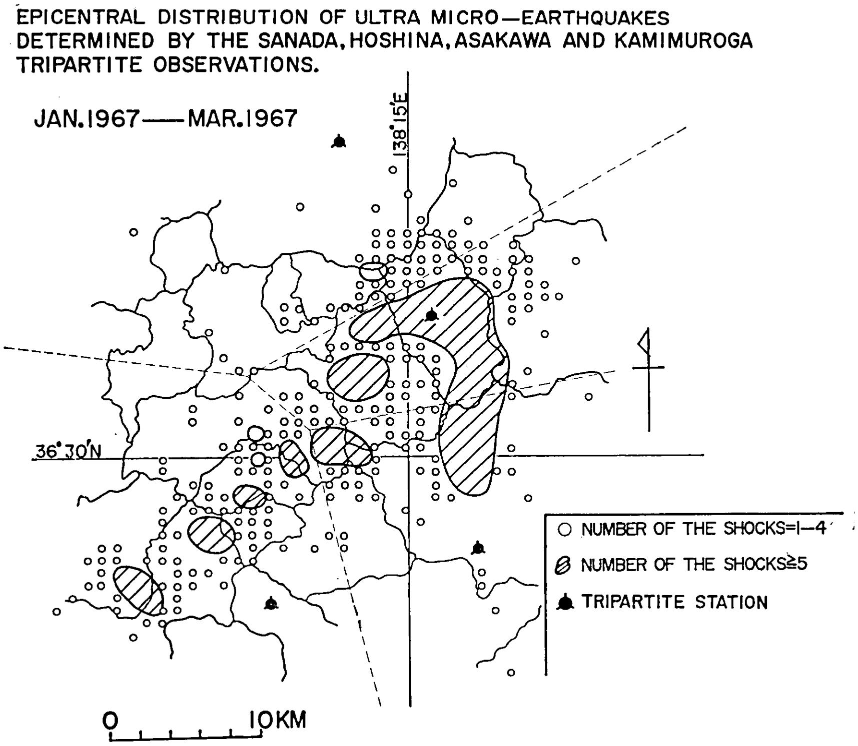

Fig. 12. Epicentral distribution of the ultra micro-earthquakes determined by the tripartite observation at Hoshina, Sanada, Asakawa and Kamimuroga.

unexpectedly small distance of detection capability. It is noticed that the shocks that occurred in a specific place could not be observed by a certain station even though their hypocenters lay within a distance of 20 km from the station. For example, the Hoshina station could not detect the shocks in Nagano City and in the southern part of Sanada, though they were detected by the observations at Asakawa and Sanada. As regards the detection capability of ultra micro-earthquake, it depends, needless to say, on the hypocentral distance but in addition to this there seemed to be a complicated phenomenon caused by some local irregularity in the area of the Matsushiro earthquakes.

7. Ultra micro-earthquake activity before and after a large shock

As stated in the previous section, the hypocentral area of ultra micro-earthquakes was broader than that of felt ones, and they occurred more frequently in the region where felt ones occurred concentrically. We will further investigate the activity of ultra micro-earthquakes before and after a large shock with intensity larger than IV on the JMA scale for three cases, *i.e.*, the first one is the first shock with intensity of V ($M=5.1$) which occurred in Azumamura on October 26, 1966 and which became the beginning of the high seismic activity in Azumamura and Suzaka; the second one is the first shock with intensity of V ($M=5.1$) which occurred near Mt. Kamuriki on January 16, 1967, the seismic activity in that place becoming active thereafter; the third one is the first shock with intensity of IV ($M=4.8$) which occurred in the northern part of Sanada on March 2, 1967. According to the report of the Matsushiro Seismological Observatory, JMA, before the occurrence of the large shocks in the first stage, evident increase of ultra micro- and micro-shocks was recognized around the town of Matsushiro since August 1965. According to the result of the tripartite observation at Hoshina, the number of ultra micro-earthquakes have increased in Azumamura and Suzaka since April 1966 and then large shocks began to occur frequently in October 1966. From the results of the tripartite observations at Hoshina and Sanada, the ultra micro-earthquakes increased already in Sanada in October 1966 preceding a large shock that occurred in Sanada on March 2, 1967.

The same phenomena as stated above were pointed out in the report of the tripartite observation[25] at Kamimuroga. According to this report,

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[25] M. OHTAKE *et al.*, *loc. cit.*, 23).

a strong shock with intensity of V (M=5.0) occurred in Kōshoku first on August 28, 1966, while the ultra micro-earthquakes were occurring already there since at latest April 1966 when the observation at Kamimuroga was started. The first strong shock with intensity of V (M=5.1) occurred near Mt. Azumaya on February 3, 1967, while a group of ultra micro-earthquakes around that place was recognized since August 1966. In these areas, the activity of ultra micro-earthquakes was recognized several months before the occurrence of a strong shock. Such a fact is very noteworthy from a view-point of earthquake prediction. A certain relation may exist between the activity of ultra micro-earthquakes and a following strong shock.

7-1. Ultra micro-earthquakes in the area of after-shock

Next, we examined the number of ultra micro-earthquakes that occurred in the after-shock area. The areas of the after-shocks of respective strong shocks were represented with a circle, which was actually of radius 4 or 6 km, as shown in Fig. 13, and the number of the ultra micro-earthquakes that occurred before and after the main shock in this circular area was examined. The results of the examination are shown in Fig. 13, in which the number of the shocks is normalyzed in such a way that the analyzed time interval and the analytical method are the same throughout the whole observation period.

Fig. 13-A shows the ultra micro-earthquake activity before and after the main shock (V, M=5.1) that occurred in Azumamura on October 26, 1966, in which the hypocenters of ultra micro-earthquakes were determined by the tripartite observation at Hoshina for 90 minutes per two days. The increase in the number of ultra micro-earthquakes was already recognized in Azumamura in April 1966, and then, the number of them further increased during the period from August to the begining of October 1966. But it decreased remarkably during the period of October 8 to 25 just before the main shock and, at last, it became zero in 90 minutes, the sampled observation interval in October 25. After the occurrence of the main shock, many after-shocks were still observed at the end of October, the after-shock activity continuing until the middle of November 1966. The decrease in the number of ultra micro-earthquakes before the main shock is typical in the case of the shock which occurred in Azumamura on October 26, 1966 as shown in the figure. Unfortunately the observation was not made for 15 hours before the occurrence of the main shock, so that the seismic activity of ultra micro-

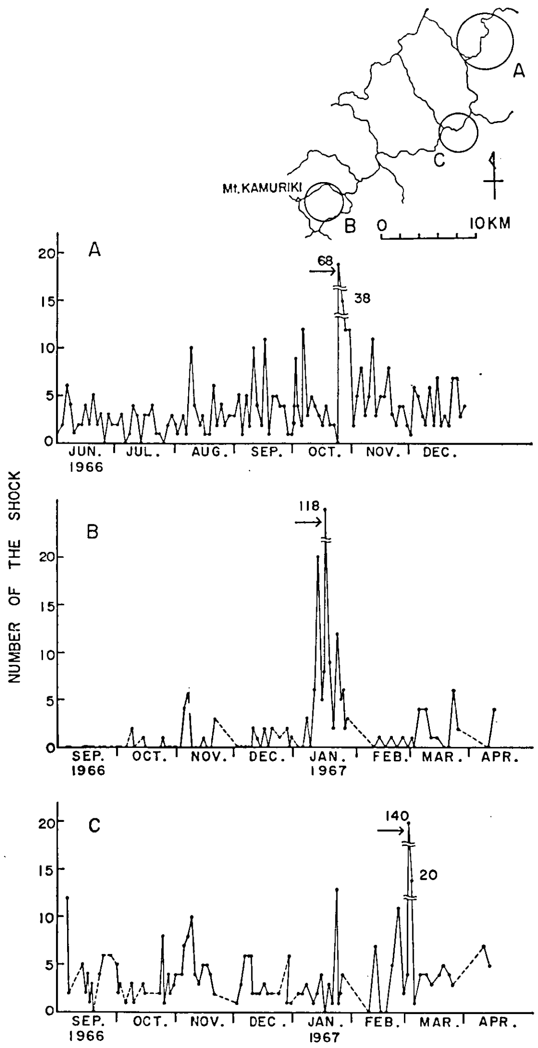

Fig. 13. Ultra micro-earthquakes within the area of the after-shocks.

→; the time of the occurrence of the main shock.

A; the case of the shock (M=5.1) in Azumamura on 26 th 03 h 04 m October 1966.

B; the case of the shock (M=5.1) near Mt. Kamuriki on 16 th 12 h 32 m January 1967.

C; the case of the shock (M=4.8) in Sanada on 2 th 03 h 40 m March 1967.

shocks was not clear for 15 hours just before the occurrence of the main shock.

Fig. 13-B illustrates the number of the ultra micro-earthquakes before and after the large shock (V, M=5.1) which occurred near Mt. Kamuriki on January 16, 1967. The hypocenter of the ultra micro-shocks was determined by the tripartite observation at Sanada. According to the report[26] of the observation carried out at Kamimuroga which is nearer to the epicenter, the ultra micro-earthquakes near Mt. Kamuriki have been detected since April 1966, however, they have been recognized there from observations at Sanada since October 1966. As seen in the figure, the number of the shocks shows a large fluctuation, so that we can say nothing as regards the increase or decrease in the number of the shocks. A peak in the number of the shocks appeared on January 14, two days before the occurrence of the main shock. Since the tripartite observation was done continuously at Sanada, the number of the shocks in two hours just before the occurrence of the main shock was also examined, their number being 8 which was larger than the usual number. The after-shocks were observed until January 25, 1967.

Fig. 13-C illustrates the number of the shocks before and after the large shock (IV, M=4.8) which occurred in the northern part of Sanada on March 2, 1967, where the seismic focus of ultra micro-earthquakes was determined by the tripartite observation there. The ultra micro-earthquakes were already registered in Sanada in September 1966. Thereafter, their number was of no simple increase or decrease as a general tendency, the number of them fluctuating greatly. A peak in the number of the shocks appeared on February 25 five days before the occurrence of the main shock. The four shocks occurred in two hours just before the occurrence of the main shock, of which the number was equal to the usual number. The after-shocks were observed until March 5, 1967. Thereafter, the seismic activity returned to the usual active level.

Summarizing the results in the three cases above-mentioned, the number of ultra micro-earthquakes which occurred in the after-shock area indicated no simple increase or decrease before the main shock. But the variation of the number of the ultra micro-earthquakes was typical in the case of the shock which occurred in Azumamura, *i.e.*, it was increasing gradually up to the beginning of October and decreased remarkably during the period of October 8 to 25 just before the occurrence of the main shock.

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[26] M. OHTAKE, H. CHIBA and T. HAGIWARA, *loc. cit.*, 23).

7-2. The number of ultra micro-earthquakes before and after a large shock

The number of ultra micro-shocks will be examined in detail for every ten minutes in several days before and after the large shock. The shocks with the maximum trace amplitude larger than a certain value were picked up and examined regardless of the location of the hypocenter. The large shocks with magnitude larger than 3.0 were also picked up in order to examine the relation between the occurrence of the large shock and the number of ultra micro-shocks.

The results are shown in Fig. 14, in which the open circle means the large shock with magnitude larger than 3.0. Fig. 14-A shows the number of the ultra micro-earthquakes before and after the main shock that occurred in Azumamura on October 26, 1966. In this case the number of shocks was counted in such a way that the shocks with the maximum trace amplitude larger than 1.5 mm on the film reader were picked up from the record of the HES electromagnetic seismograph of E-W component (Vmax=10,000) set up at Nire. After the occurrence of the main shock, the number of the shocks was extremely large so that they were superimposed with each other in many cases and accordingly the number was not able to be counted in several hours just after the main shock. It is very important to investigate whether the number of the ultra micro-shocks changed significantly or not before the occurrence of a main shock. However we find it difficult to point out such a change from the figure, the only noticeable fact is that the number of the observed shocks per 24 hours showed a tendency to decrease from October 22 to 25 in such way as 320, 300, 260 and 240, the strong shock occurring on October 26. A large number of after-shocks was observed just after the main shock, their daily number of occurrences was still as many as 450 on the last day of October.

As regards the relation between the number of ultra micro-earthquakes and the occurrence of the shock with magnitude larger than 3.0, the ultra micro-shocks sometimes occurred concentrically with respect to time before and after the occurrence of the large shock but such concentrical occurrence of ultra micro-shocks was never common for many large shocks. Figs. 14-B and-C show the results examined from the data observed at Sanada concerning the number of occurrences of ultra micro-earthquakes before and after the large shocks that occurred near Mt. Kamuriki on January 16, 1967 and at Sanada on March 2, 1967 respectively. The shocks with the maximum trace amplitude larger than 10 mm

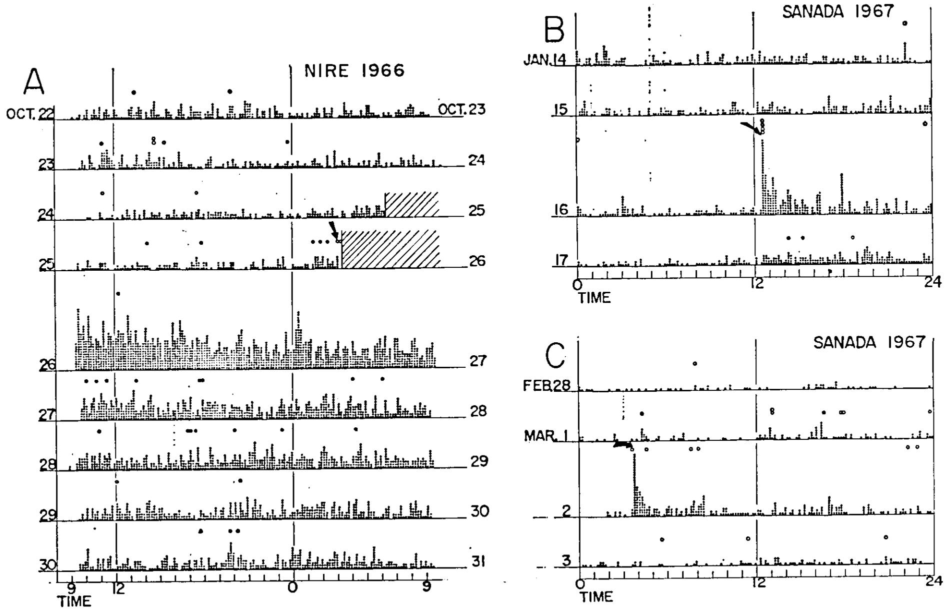

Fig. 14. Number of ultra micro-earthquakes before and after a strong shock.
→; the time of the occurrence of the main shock.
A; the case of the shock (M=5.1) in Azumamura on 26 th 03 h 04 m October 1966.
B; the case of the shock (M=5.1) near Mt. Kamuriki on 16 th 12 h 32 m January 1967.
C; the case of the shock (M=4.8) in Sanada on 2 th 03 h 40 m March 1967.

(1 mm = 6.8 μ kine) were picked up from the monitor record and their numbers were plotted in the figure. As seen from these figures, we cannot point out any significant variation in the number of ultra micro-shocks. The ultra micro-shocks did not always increase in number at the time of the occurrence of a large shock with magnitude larger than 3.0. The after-shocks were found clearly but they declined rapidly within several hours in the case of the shocks that occurred near Mt. Kamuriki and at Sanada as shown in Figs. 14-B and-C. On the other hand, the after-shock activity continued till the end of October 1966 in the case of the shock that occcurred in Azumamura as shown in Fig. 14-A.

7-3. Time intervals of occurrence of the ultra micro-earthquakes before and after a large shock

In the following, we shall investigate the time intervals of occurrence of the ultra micro-earthquakes before and after a large shock only from an aspect of their frequency distribution not touching their order of succession. We shall treat the same shocks that have been examined in the previous section. If the phenomena that are to be studied here are not common in the total area of the Matsushiro earthquakes but are limited to the narrow region around the focus of a main shock, it might be better to study only the data of the shocks that occurred within a narrow region near the focus of the main shock. However, we did not have such data in the present case so that the data of the shocks were treated regardless of their location. Fig. 15 shows the cumulative frequency distribution of the time intervals of the ultra micro-shocks before and after the main shock. The abcissa and the ordinate in the figure indicate the time intervals of the shocks and the logarithm of the cumulative frequency of the time intervals of the shocks respectively. Such a graph was made for the sake of comparison with a model showing that the occurrence of the shocks is at random and depends upon a certain probability. It is well known that if the probability of occurrence of the shocks is constant and independent of time, the probability P of appearence of the time interval of shocks larger than a time interval t is given as $P=\exp(-mt)$, in which m means the probability of occurrence of the shocks per unit time.[27] The straight line drawn together with the data in the figure means P above-mentioned. The m was given from the actual observation as $m=(N-1)/(t_2-t_1)$, in which N is the number of the shocks in the period between the times t_1 and t_2, t_1 is the time of the first shock and t_2 the time of the last shock. So that the straight line means the cumulative frequency distribution of the enormous number of time intervals from an infinite population, in which the occurrence of the shocks is at random and the mean value of the time intervals is equal to that obtained by actual observation. As regards the two curves drawn above and below the straight line, when the time intervals of the shocks are taken out from the infinite population stated above, the cumulative frequency of the time intervals show the binomial distribution depending upon the number of the samples. The curves drawn in the figure indicate the standard deviation of such a binomial distribution, in which the number of the samples is the same as that obtained by the actual observation. Therefore, if the occurrence of the shocks is at random, about 70 percent of the frequency of the time intervals must lie in the range indicated by the two curves. Exactly speaking, the mean value of the time intervals of the infinite population which is

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[27] C. TSUBOI, "Adjustment of Observational Data," *Primary Physics Course*, Vol. 6, (Tokyo, 1965), p. 19, (in Japanese).

used in comparison with the observational results is a probability distribution function, which is expected by the observational data. But we used approximately the mean value of the observational time intervals as the fixed mean value of the infinite population stated above. However, this may be practically no obstruction because we used many time intervals for determining their mean value.

Fig. 15-A shows the result concerning the shock which occurred in Azumamura on October 26, 1966, in which the data were obtained by the HES electromagnetic seismograph set up at Nire. The cumulative

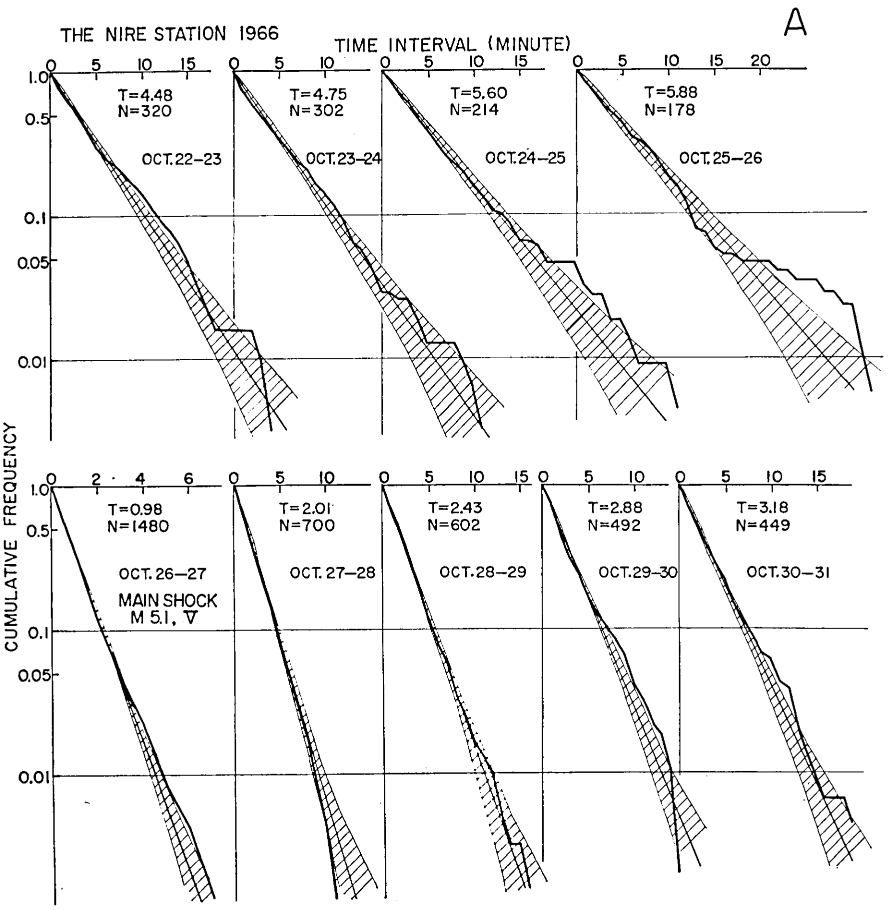
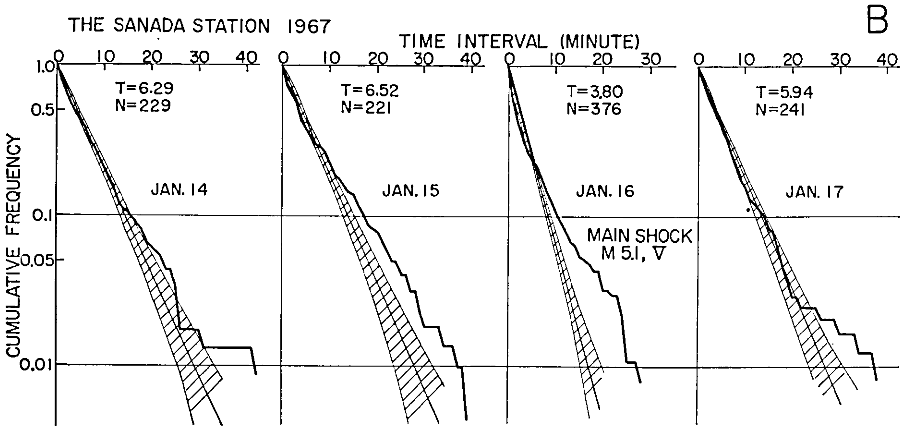
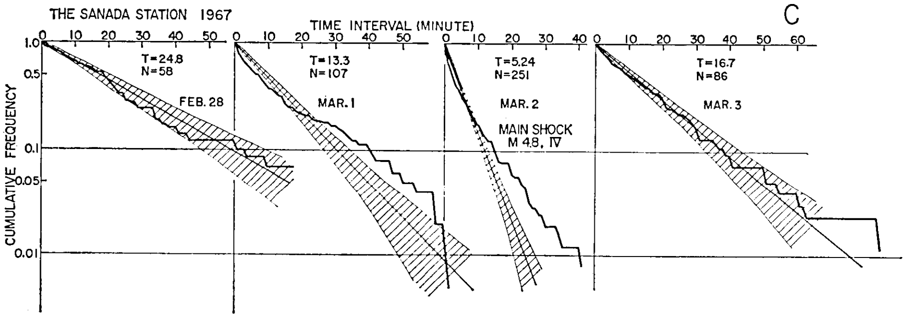


Fig. 15. Distribution of time intervals of the ultra micro-earthquakes before and after a large shock. N and T are the number of the shocks and the mean value of the time intervals respectively.

A: the case of the shock (M=5.1) in Azumamura on 26th 03 h 04 m October 1966.



B; the case of the shock (M=5.1) near Mt. Kamuriki on 16th 12h 32m January 1967.



C; the case of the shock (M=4.8) in Sanada on 2th 03h 40m March 1967.

frequency distributions of the ultra micro-shocks during the period from October 22 to 24 lay mostly in the range indicated by the two curves, therefore, the cumulative frequency distributions are consistent with that of the random occurrence in this period. The cumulative frequency of the time intervals larger than 20 minutes was a little larger than the random occurrence in the period from October 24 to 25. In the period from October 25 to the time of the occurrence of the main shock of October 26, the cumulative frequency of the time intervals larger than 20 minutes was larger than the random occurrence, with larger deviation than in the previous period from October 24 to 25. In the period from the main shock to the last day of October, the cumulative frequency distribution of the time intervals also showed the random occurrence. A very interesting fact is that the cumulative frequency distribution of the time intervals of the ultra micro-earthquakes in the period from 25th to the time of occurrence of the main shock was different from the distribution in other periods in comparison with the random occurrence, in other words, the ultra micro-shocks showed a tendency to occur concentrically and intermittently on the day before the main shock. Fig. 15 clarifies the characteristics of the occurrence of the shocks which could not be made clear in Fig. 14.

The result of examination in the case of the main shock which occurred near Mt. Kamuriki on January 16, 1967 is illustrated in Fig. 15-B. The cumulative frequency distributions of the ultra micro-earthquakes on January 14 and 17 showed the random occurrence except of the time intervals larger than 30 minutes. On the other hand, the cumulative frequency distributions on January 15 and 16 were different in their pattern from those seen on January 14 and 17, *i.e.*, the former showed a tendency to occur concentrically and intermittently rather than random occurrence. We expected the frequency distribution of the time intervals after the occurrence of the main shock on January 16 to be a different pattern from that of the random occurrence because it contains many after-shocks as shown in Fig. 14-B. On the day before the main shock that occurred near Mt. Kamuriki, the frequency distribution of the time intervals of the ultra micro-shocks showed the same tendency as was seen in the case of the strong shock that occurred in Azumamura. This fact is of much interest.

The frequency distribution of the time intervals of the ultra micro-shocks before and after the main shock that occurred at Sanada on March 2, 1967 is shown in Fig. 15-C. The cumulative frequency distributions of the time intervals on February 28 and March 3 showed clearly the pattern of random occurrence, while the cumulative frequency distributions on March 1 and 2 were different in their pattern from that of the random occurrence. The ultra micro-earthquakes also showed a tendency to occur concentrically and intermittently on the day before the main shock that occurred at Sanada on March 2, 1967.

Summarizing these three cases, the common facts were found to be as follows: 1. The ultra micro-earthquakes usually occurred at random following a certain probability of occurrence. 2. On the day before the shock with magnitute of about 5, the ultra micro-earthquakes did not occur at random but showed a tendency to occur concentrically and intermittently. To the author's knowledge, this is the first paper that ever pointed out such a phenomenon concerning the ultra micro-earthquakes on the day before a large shock. The author believes that the phenomenon was not an accidental one but was caused by the natural character of the occurrence of ultra micro-shocks. We may say that the ultra micro-shocks occur concentrically and intermittently before a large shock, just like the occurrence of usual aftershocks.

8. Ishimoto-Iida's coefficient *m* for ultra micro-earthquakes

The Ishimoto-Iida's coefficient m with respect to ultra micro-earthquakes was examined for the shocks which occurred after October 1965 when our tripartite observation was commenced at Hoshina. The results are shown in Fig. 16, in which the daily number of unfelt and felt shocks reported from the Matsushiro Seismological Observatory, JMA are shown together for the sake of comparison.

As shown in the figure the value of m fluctuates in the range $1.4 \sim 2.6$ throughout the whole period of observation, and the changes in the value of m and the daily number of unfelt and felt shocks are, in a wide view, inversive with each other, *i.e.*, the value of m being smaller when the number of the shocks is larger and vice versa. It is noteworthy that the relatively large value $m = 1.8 \sim 2.4$ appeared before a peak in the daily number of shocks at the beginning of April and at the end of August 1966 and the relatively small value $m = 1.4 \sim 1.6$ appeared just after these peaks.

According to the report of S. Suehiro *et al*,[28] a felt earthquake ($M = 3.3$) accompanying very small fore-shocks and after-shocks occurred

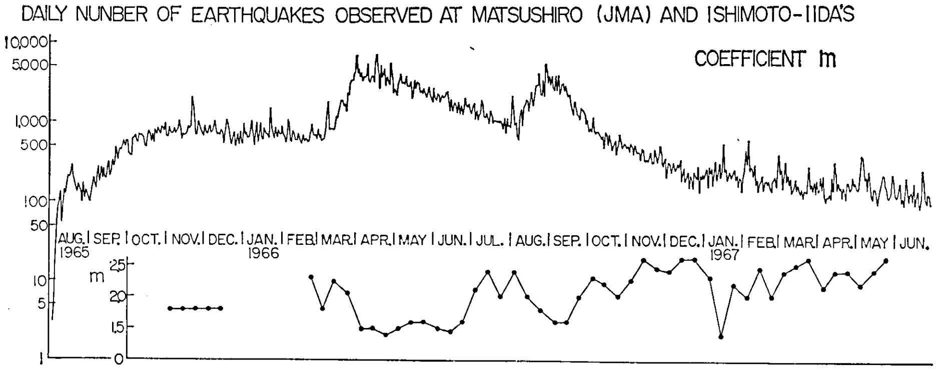


Fig. 16. Comparison of the daily number of unfelt and felt shocks with the Ishimoto-Iida's coefficient m of the ultra micro-earthquakes observed at Hoshina.

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[28] S. Suyehiro *et al.*, *Paper in Meteorology and Geophysics*, **15** (1964), 71.

near Matsushiro in 1964, a year before the commencement of the Matsushiro swarm earthquakes. At that time, the Gutenberg-Richter's b was abnormally of small value 0.35 in the case of fore-shocks but recovered to normal value 0.75 in the case of after-shocks. However such a change in the value of m has not been found as yet by our present observation of the ultra micro-earthquakes carried out at Hoshina.

9. Future program of study

Although the Matsushiro swarm earthquakes have been decreasing in number in the year 1967, if compared to the most active period, the number of the micro and small shocks is still large and their activity shows no sign of coming to an end through October 1967. The ultra micro-earthquakes in the area of the Matsushiro earthquakes during the period from October 1965 to May 1967 were studied in this paper. The same study will be continued further and the result will be reported in due course.

The reading off of the basic data from the seismograms forced hard labor on us. The importance of the investigation of ultra micro-earthquakes is not to study each individual shock but to treat many shocks as a group, so that a considerable number of the shocks are required for the study. In such a case, a certain automatic reading device of seismogram would be of great convenience. Not only in the case of the Matsushiro earthquakes but other usual observations of micro- and ultra micro-earthquakes, which are developing in recent years, also requires an automatic data processing system. The author intends to undertake the development of such a data processing system hereafter, with a view to analyze automatically the observational data of the ultra micro-earthquakes in the area around Matsushiro.

Summary

For the sake of convenience, the period from the beginning of observation, October 1965, to the end of May 1967 was divided into four stages, *i.e.*, the first stage (October 1965~February 1966), the second stage (March~July 1966), the third stage (August~December 1966), the 4th stage (January~May 1967).

The first stage (*October 1965~February 1966*). This stage contains the first climax of the seismic activity, the latter part of November 1965. Although the area of felt earthquakes in this period was limited in the town of Matsushiro, the ultra micro-earthquakes was observed also at Wakaho, an adjacent village of Matsushiro. The area of ultra micro-earthquake activity extended to adjacent

Kōshoku and Azuma in February 1966. The depths of the hypocenters of ultra micro-shocks distributed in the range 0~12 km and those of the felt shocks distributed in the range 0~8 km. In the first stage, the fifteen large shocks with intensity of IV on the JMA scale took place, four of them occurring in the period of November 22 to 24, 1965.

The second stage (March~July 1966). This stage contains the second climax of the seismic activity in April and May 1966 that was the highest peak of the activity throughout the whole period up to the present. In this stage, the large shocks with intensity larger than IV occurred 35 times. The area of activity of ultra micro-earthquakes extended to the environs of Matsushiro and Wakaho, Suzaka, Azuma, Sanada, Kōshoku, Shinonoi, Kawanakajima, Kōhoku and Nagano city, more widely than the felt shocks, and the region where the epicenters were densely crowded moved from Matsushiro to Wakaho. The depths of the hypocenters of the ultra micro-earthquakes were mostly 0~12 km and those of the felt shocks distributed in the range 0~10 km.

The third stage (August~December 1966). Beginning with the third climax of the seismic activity in August and September 1966, the third stage contains 23 shocks with intensity larger than IV. The region of activity of ultra micro-shocks extended to a larger area than in the second stage as well as the felt shocks, *i.e.*, Suzaka, Azuma, Takayama, Sanada, Sakaki, Kōshoku, Tokura, Kamiyamada, Shinonoi and Kōhoku in the northeastern and southwestern regions of Matsushiro. The vertical distribution of the shocks was the same as in the second stage, but the depths of the shocks in the southwestern part were a little deeper as a general tendency. The place in which the shocks were the most densely crowded was on the north side of Mt. Kimyō.

The 4th stage (January~May 1967). No remarkable peak of the daily number of shocks existed but 12 shocks with intensity larger than IV occurred in this period. With respect to the active area of the shocks some differences from the third stage were observed *i.e.*, the seismically active area extended, especially towards southwestern parts, towards Tokura, Kamiyamada and Sakai. On the other hand, the number of the shocks decreased remarkably on the northeastern side of Mt. Minakami where the shocks had taken place very frequently in the period from the first to third stage. The large shocks with intensity larger than IV occurred frequently near Mt. Kamuriki in this period. The depths of both the ultra micro-shocks and the felt shock were a little deeper than in the third stage.

Examining the relation between the activity of ultra micro-earthquakes and that of felt earthquakes, the following were found:

1. The earthquakes with intensity larger than IV did not take place in the area where no ultra micro-earthquakes were observed. 2. The region of ultra micro-earthquakes was larger than that of felt shocks. 3. Ultra micro-shocks were densely crowded at the place where felt earthquakes took place frequently. 4. The number of ultra micro-shocks did not increase just before the occurrence of a large shock, even though it increased very gradually up to that time. 5. Examining the time interval of occurrence of ultra micro-shocks before and after a large shock, we found that the cumulative frequency distribution of time intervals showed a different pattern of distribution from the usual one on the day before a large shock, *i.e.*, the ultra micro-shocks had a tendency to occur concentrically and intermittently on the day before a large shock, while they showed a random occurrence at the usual time.

As regards the Ishimoto-Iida's coefficient m examined with respect to the ultra micro-earthquakes, the larger value $m=1.8\sim2.4$ appeared before the two days when the maximum in the daily number of the shocks was counted at the beginning of April and at the end of August 1966, the smaller value $m=1.4\sim1.6$ appearing just after these maxima. It would be very important to study what the above-mentioned fact means.

Acknowledgment

The author wishes to express his sincere thanks to Prof. Takahiro Hagiwara who gave him much useful advice for the present investigation.

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The numerical computations were carried out on an IBM 7090 through the project UNICON to which the author's thanks are due.

13. 松代町周辺地域における極微小地震

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はじめに

1965年8月に発生した長野県松代町 (36°34′N, 138°13′E) 附近の群発地震はいくつかの強震と異状な地殻変動を伴ないながら，1967年10月現在もなお続いている．この間気象庁松代観測所から報告された10万倍の地震計による地震の総回数は66万回を数え，有感地震だけでも6万回に達している．これ等の地震の規模はマグニチュード5.3が最大であり，地震として放出された総エネルギーは 1.6×10^{21} エルグになり，これはちようど $M=6.3$ の地震1個に相当している．この期間地震回数の上で顕著な山は1965年11月下旬，1966年4，5月，1966年8，9月に在り，1967年に入つてからは全体として震源域は拡大したが，地震回数は徐々に減少している．

松代町とその周辺では1965年10月以後東京大学地震研究所のプログラムとして地震観測をはじめ測地学的及び地球物理学的な種々の調査研究が行なわれた．その結果は既にいくつか報告されている．本論文は1965年10月から1967年5月までの期間の松代地震地域における極微小地震の研究であり，極微小地震活動は有感地震とも比較されている．いくつかの極微小地震の観測結果はすでに報告されている．

松代地震に関する調査研究は地震予知の分野における研究としても重要視されている．わが国の地震予知研究グループから提起されている問題の一つとして微小及び極微小地震活動の問題がある．著者はここで松代地域の極微小地震活動について，大きな有感地震の前後の活動の様子を特に注意して調べた．

松代地震の膨大なデータはおそらく普段の10年分に匹敵するだろうと言われているが，ここで取扱われた極微小地震のデータはわれわれの臨時観測点である保科と真田の3点方式観測で得られたもののごく一部分にすぎない．

要約

地震活動の様子を調べるために便宜上，期間を観測の開始された1965年10月から5ヵ月ずつに次のように区切つた．第1期 (1965年10月～1966年2月)，第2期 (1966年3月～7月)，第3期 (1966年8月～12月)，第4期 (1967年1月～5月)，各期間の地震活動の概要は次の通りである．第1期 (1965年10月～1966年2月)，この期間は地震活動の第1のクライマックスとよばれる1965年11月下旬を含んでいる．この間震度 IV の有感地震は計15回発生している．特に65年11月22～24日だけで震度 IV が4回起つている．有感地震の震源域は主に松代町に限られているが，極微小地震のそれは主に松代と若穂町であり，1966年2月には松代，若穂の周辺部の更埴市，東村にも拡大した．有感地震の深さは0～8 km の範囲に分布しているが，極微小地震は0～12 km の範囲である．

第2期 (1966年3月～7月)．この期間は第1のクライマックスをはるかにしのぎ，全期間の中で最大の地震回数を数えた第2のクライマックス1966年4，5月を含んでいる．この間震度 IV 以上の有感地震は実に35回に達している．震源域は有感も極微小も松代町と若穂町の周辺に広く拡大し，極微小地震は須坂市，東村，真田町，更埴市，篠ノ井市，川中島村，更北村，長野市にも拡大した．特に震源の密集している位置は松代町から若穂町の方へ移動した．有感地震の震源の深さは0～10 km の範囲にあり，極微小地震は0～12 km の範囲にある．

第3期 (1966年8月～12月)．この期間は第3のクライマックスである1966年8，9月から始まり，この間の震度 IV 以上の有感地震は計23回である．震源域は有感も極微小も第2期より更に拡大し松代町，若穂町の周辺の須坂市，東村，高山村，真田町，坂城町，更埴市，戸倉町，上山田町，篠ノ井市，更北村方面に広がり，特に松代町から北東と南西方向に拡大した．深さの分布では有感も極微小も第2期と特に変りはない．但し南西方面の戸倉，上山田の地震は全体として少し深くなつている．特に震源が密集しているのは奇妙山の北側である．

第4期 (1967年1月～5月)．第4期は地震回数の上で特に活発な時期を含むわけではないが，震

度 IV 以上の有感地震は計 12 回発生している．この期間は震源域の上で第 3 期とは異なつた特徴がある．即ち北東-南西方向とりわけ南西方向に震源域は広がり，戸倉町，上山田町から坂井村にまで及んだ．一方従来は非常に震源が密集していた松代町の皆神山北東側でこんどは逆に地震は少なくなつた．震度 IV 以上の有感地震はこの期間に冠着山近傍に目立つて発生している．

極微小地震活動と有感地震の活動の関係について調べられた結果は次のごとくまとめられる．

1．極微小地震の無かつた場所に大きな有感地震（震度 IV 以上）は起つていない．

2．極微小地震の震源は有感地震の震源をとり囲んでより広い地域に分布している．

3．有感地震が密に発生している場所は極微小地震も密集して発生している．

4．極微小地震は大きな有感地震の直前では増加はしなかつた．それまで徐々に増加をしてきた場合でもそうである．

5．大きな地震の前後で極微小地震の発生間隔の頻度分布を調べると，大きな地震の前日では平常と異なる発生間隔の頻度分布を示した．つまり普段はほぼ任意な発生をしているが，大きな地震の前日には極微小地震は任意な発生ではなく間歇的に集中して発生する傾向を示した．これは興味ある事実である．

極微小地震の石本-飯田の係数mは，1966年 4 月の初めと 8 月末の地震回数のピークの前で 1.8～2.4 のより大きな値を示し，その直後は 1.4～1.6 のより小さな値を示した．このことが一体何を意味しているのかを研究するのは興味あることであろう．

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