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45. Ultra Micro-earthquake Activity at the Southwestern Border of the Area of Matsushiro Earthquakes. Part 1.

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For the purpose of investigating ultra micro-earthquake activity in the southwestern part of the Matsushiro earthquake region, we set up a temporary station by the tripartite method at Kamimuroga on April 18, 1966. It was just after the discovery[1] of upheaval of the ground around Aoki Village, with an unusual speed of more than 40 mm in three months, which was made from precise levelling along the route from Matsumoto City to Ueda City. The observation was conducted as part of the Matsushiro earthquake investigation by the Earthquake Research Institute, and is as yet still continuing. The paper is the first report of the observation during the period of one year.

1. Method of observation and data processing.

Our temporary station is situated at Kamimuroga, Kawanishi Village in Nagano Prefecture, the latitude and longitude of the base point lying at 36°41.'5N and 137°12.'3E, respectively. Selecting an exposed fresh bed rock, we set the pick-ups of vertical component on the points, A, B and C as shown in Fig. 1. The pick-ups of two horizontal components were added at C, which we call the "base point". The lengths of the triangle ABC were measured to be 923 m, 1,276 m and 1,227 m, the highest point A being 59 m higher than the lowest one C. The natural frequency of pick-ups is 3.5 cps in the vertical component and 5.0 cps in the horizontal component, the damping parameter being $h=1$ in either case. The output signals from the five pick-ups are once amplified with head amplifiers and transmitted to the recording station through cable

1) I. TSUBOKAWA *et al.*, "Levelling Resurvey Associated with the Area of Matsushiro Earthquake Swarms. (1)," *Bull. Earthq. Res. Inst.*, **45** (1967), 265.

lines, where the signals are recorded on a magnetic tape. This recorder is a type of direct recording with six channels, one of which is for time signals supplied from a crystal clock. A tape speed of 7.6 mm/sec was adopted in order to record seismic signals successively for 24 hours or

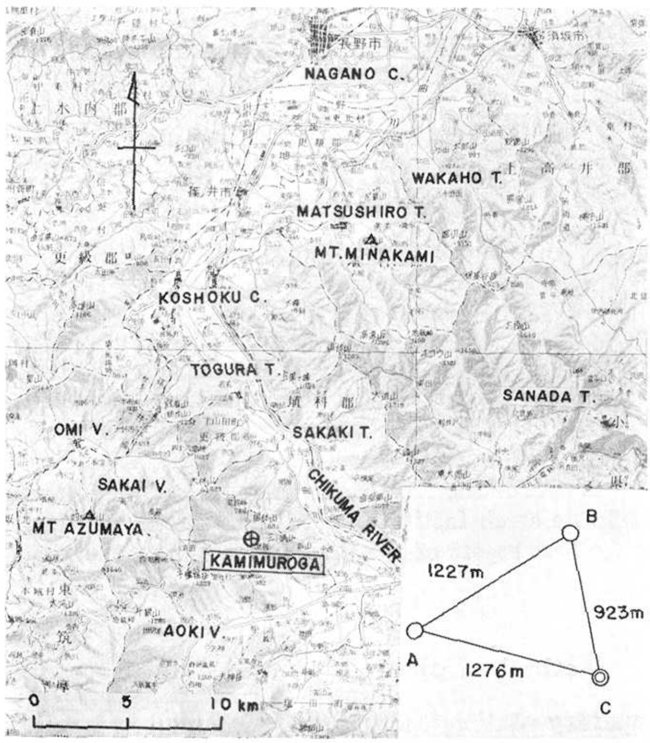

Fig. 1. Location of the tripartite station at Kamimuroga.

more on a single reel of magnetic tape of 1/2 inch width and 10 inches diameter. The recorded reels were mailed to Tokyo and reproduced with an optical or pen-writing oscillograph. In order to save time, the reproducing was carried out in 12.5 times (optical) or twice (pen-writing) tape speed. The recorded data were available continuously for the whole 24 hours of each day, but we reproduced only a part of them in the interval from 0 h to 4 h, because of the restriction of data processing capability. The block diagram of the system is illustrated in Fig. 2 and the overall sensitivity curves in Fig. 3. The magnification was calculated to be 310,000 at 10 cps in the vertical component.

The co-ordinates of origins of the observed earthquakes were calculated, solving a system of three simultaneous equations of the second degree under the assumption that the medium was a homogeneous half space and that the seismic waves spread out spherically from their origins. The observable quantities in this case are the difference in

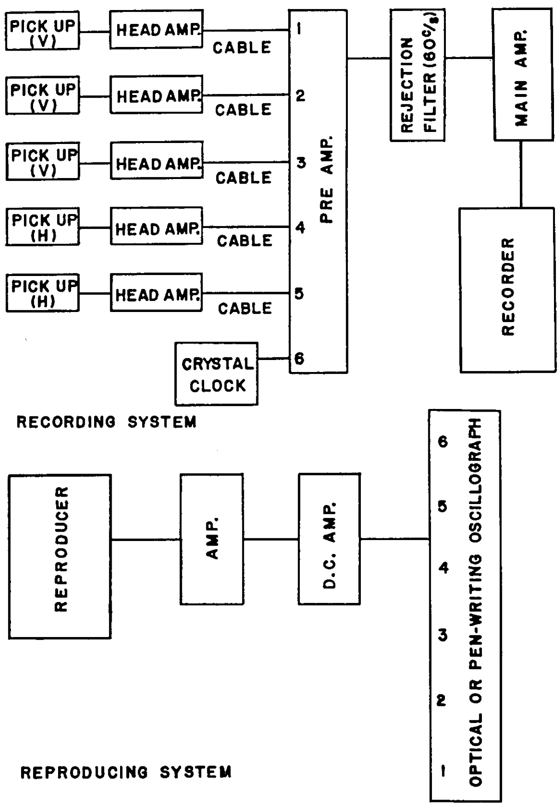

Fig. 2. Block diagram of recording and reproducing systems.

arrival time of the initial wave between each point, A, B and C, and the *S–P* time at the base point C. This is just the same with the method that has been used by Hamada *et al.*[2] for their tripartite study at Hoshina. In order to solve the equations, the velocity of *P* wave v_p and Omori's coefficient k must be estimated beforehand. Basing on the other independent observational data at Kamimuroga, we obtained

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

$$v_p = 5.0\,\text{km/sec}$$

and

$$k = 6.47 + 0.65 \times (S\text{–}P)\,, \tag{1}$$

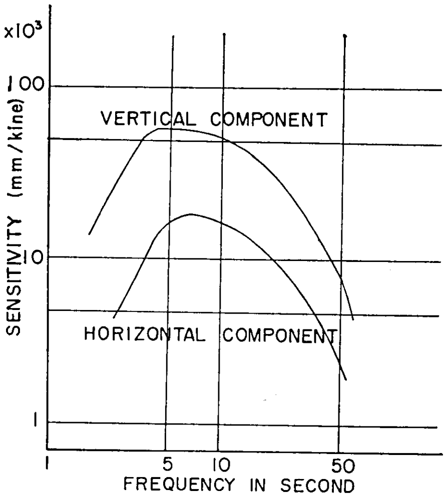

Fig. 3. Overall frequency responce of the instruments.

where the unit of k and the S–P time are km/sec and sec, respectively. The detailed description of these data will be found in the later section.

2. Frequency of shocks.

Table 1 shows the daily frequency of shocks observed at Kamimuroga in four hours. The number of shocks whose maximum trace amplitude was larger than 2.5 mm (corresponding to 50 μkine of the velocity of the ground motion) were counted on the records of the vertical component. Earthquakes with magnitude larger than -1 would not be missed when they occurred within 20 km from the Kamimuroga station, estimating from Muramatu's formula.[3] For the benefit of comparison, the daily frequency of shocks at Matsushiro announced from J. M. A. were tabulated together. The magnification of the vertical component was altered on November 19, 1966, sensitivity before this day being half of that shown in Fig. 3. For the con-

3) I. MURAMATU, "Correction and Remarks of the Equation of Magnitude," *Zisin*, [ii], **19** (1966), 282.

Table 1. Number of shocks observed at Kamimuroga in four hours every day and number of shocks at Matsushiro announced from J. M. A.

Date	Number of shocks		Main shocks near Kamimuroga	Date	Number of shocks		Main shocks near Kamimuroga
	Kamimuroga	Matsushiro			Kamimuroga	Matsushiro	
1966				Jun. 1	124	2583	
Apr. 18	108	4350		2	—	2033	
19	178	2548		3	79	1820	
20	124	4930		4	83	2212	
				5	56	2168	
21	210	3585					
22	—	3896		6	75	1792	
23	—	4554		7	123	1963	
24	324	2800		8	126	2144	
25	225	3609		9	107	2044	
				10	45	2091	
26	364	3070					
27	280	2890		11	34	2295	
28	279	5280		12	49	2307	
29	248	3610		13	74	1997	
30	—	2291		14	55	1382	
				15	—	1850	
May 1	—	2549					
2	338	2325		16	—	1322	
3	—	2193		17	133	1578	
4	—	2890		18	71	1711	
5	214	3345		19	97	1599	
				20	117	1293	
6	98	3885					
7	145	3006		21	—	1704	
8	86	3095		22	—	1224	
9	192	2975		23	65	1572	
10	147	3615		24	115	1202	
				25	123	1416	
11	131	2841					
12	131	2815		26	130	1897	
13	368	2785		27	—	1591	
14	204	3195		28	—	1542	
15	172	1945		29	—	1664	
				30	—	1353	
16	140	2383					
17	103	3220		Jul. 1	89	1257	
18	106	2615		2	95	1530	
19	108	3175		3	—	1655	
20	112	3050		4	—	1054	
				5	—	1343	
21	103	2312					
22	93	2340		6	—	1021	
23	81	2235		7	91	1200	
24	90	2585		8	82	1237	
25	80	2259		9	111	1805	
				10	93	1614	
26	70	2010					
27	101	2264		11	117	1140	
28	84	2640		12	79	1106	
29	81	2187		13	—	1272	
30	—	2025		14	—	1079	
31	—	1785		15	76	940	

(to be continued)

Table 1. (continued)

Date	Number of shocks: Kamimuroga	Number of shocks: Matsushiro	Main shocks near Kamimuroga
16	73	1343	
17	57	1151	
18	76	946	
19	—	997	
20	—	967	
21	—	778	
22	—	927	
23	—	707	
24	—	969	
25	—	947	
26	—	806	
27	67	1075	
28	98	716	
29	95	1079	
30	58	886	
31	73	857	
Aug. 1	74	840	
2	74	2025	
3	286	1321	
4	78	916	
5	81	946	
6	80	652	
7	78	606	
8	89	1114	
9	87	1403	
10	85	903	
11	60	1508	
12	65	1615	
13	85	1865	
14	104	1794	
15	57	1355	
16	73	1787	
17	89	2314	
18	—	1563	
19	—	1909	
20	—	2540	
21	—	2729	
22	—	2853	
23	—	3900	
24	82	2197	
25	108	2166	
26	94	3307	
27	126	2095	
28	106	5100	M=5.0 Koshoku (V)
29	320	4230	
30	260	3090	
31	199	3667	
Sep. 1	100	2861	
2	149	3660	
3	92	2631	
4	192	2462	
5	145	3718	
6	127	2484	
7	109	3710	
8	166	2212	
9	118	2400	
10	123	2925	
11	88	3007	
12	68	2407	
13	143	2750	
14	93	2236	
15	123	2091	
16	72	2115	
17	102	1662	
18	62	1473	
19	28	1209	
20	45	1790	
21	—	1420	
22	—	1216	
23	32	1185	
24	48	1077	
25	39	1493	
26	—	1420	
27	—	1360	M=5.0 Koshoku (V)
28	—	1242	
29	—	946	
30	—	1007	
Oct. 1	—	835	
2	—	764	
3	18	834	
4	22	741	
5	22	1102	
6	13	747	
7	15	703	
8	18	748	
9	22	729	
10	19	698	
11	19	641	
12	19	600	
13	16	638	
14	22	470	
15	14	725	

(to be continued)

Table 1. (continued)

Date	Number of shocks: Kamimuroga	Number of shocks: Matsushiro	Main shocks near Kamimuroga
16	6	679	
17	18	495	
18	22	776	
19	33	546	
20	43	446	
21	13	470	
22	11	533	
23	8	579	
24	11	407	
25	11	511	
26	30	676	
27	19	565	
28	19	468	
29	—	487	
30	—	531	
31	21	502	
Nov. 1	12	476	
2	8	481	
3	11	427	
4	13	525	
5	16	483	
6	10	395	
7	14	502	
8	33	452	
9	27	415	
10	6	412	
11	10	407	
12	6	336	
13	6	458	
14	14	429	
15	18	327	
16	7	319	
17	4	337	
18	7	320	
Magnification was changed.			
19	31	362	
20	44	419	
21	25	303	
22	20	307	
23	21	478	
24	39	372	
25	—	309	
26	—	380	
27	13	488	
28	24	414	
29	17	298	
30	32	282	

Date	Number of shocks: Kamimuroga	Number of shocks: Matsushiro	Main shocks near Kamimuroga
Dec. 1	25	353	
2	33	212	
3	21	267	
4	22	320	
5	22	295	
6	—	232	
7	—	277	
8	—	301	
9	—	251	
10	—	264	
11	—	291	
12	—	272	
13	—	328	
14	—	184	
15	11	220	
16	—	261	
17	—	182	
18	—	205	
19	9	237	
20	—	152	
21	—	213	
22	—	191	
23	29	149	
24	25	235	
25	21	214	
26	21	193	
27	20	273	
28	17	134	
29	13	212	
30	14	191	
31	15	222	
1967			
Jan. 1	16	196	
2	16	220	
3	10	258	
4	9	154	
5	7	268	
6	10	246	
7	13	261	
8	15	168	
9	—	250	
10	—	316	
11	—	192	
12	—	237	
13	—	300	
14	52	201	
15	13	246	

(to be continued)

Table 1. (continued)

Date	Number of shocks		Main shocks near Kamimuroga
	Kamimuroga	Matsushiro	
16	41	506	M=5.0 Sakai (V)
17	64	246	
18	45	251	
19	26	188	
20	24	205	
21	21	238	
22	20	202	
23	19	216	
24	15	234	
25	10	251	
26	14	188	
27	17	215	
28	15	158	
29	12	201	
30	18	194	
31	23	135	
Feb. 1	23	202	
2	21	247	
3	20	436	M=4.8 Sakai (V)
4	126	298	
5	121	582	
6	119	250	
7	47	272	
8	36	261	M=4.5 Sakai (IV)
9	80	211	
10	28	289	
11	31	163	
12	33	188	
13	45	137	
14	41	172	
15	39	181	
16	28	210	
17	90	142	
18	17	180	
19	10	185	
20	21	165	
21	40	182	
22	20	157	
23	25	139	
24	25	182	
25	9	191	

Date	Number of shocks		Main shocks near Kamimuroga
	Kamimuroga	Matsushiro	
26	27	207	
27	33	158	
28	23	216	
Mar. 1	20	392	
2	45	229	
3	21	258	
4	14	150	
5	24	208	
6	20	312	
7	28	186	
8	44	223	
9	37	169	
10	22	200	
11	90	132	
12	85	142	
13	52	155	
14	68	192	
15	57	141	
16	52	165	
17	36	144	
18	40	128	
19	44	148	
20	37	116	
21	58	140	
22	22	139	
23	41	132	
24	55	161	
25	41	276	
26	68	152	
27	60	168	
28	37	149	
29	38	179	
30	28	130	
31	19	184	

venience to glance over the changes in the number of occurrences of earthquakes, frequency of shocks before the day of sensitivity alteration are doubled in Fig. 4. This treatment should be completely justified if the values of Ishimoto-Iida's coefficient was exactly 2.0. We shall follow the change in daily frequency of shocks using such converted values as mentioned above.

Our observation was begun in April 1966, when the Matsushiro earthquakes were at the last half of their second active stage, as we call it. Even at Kamimuroga, 17 km apart from Mt. Minakami where the earth-

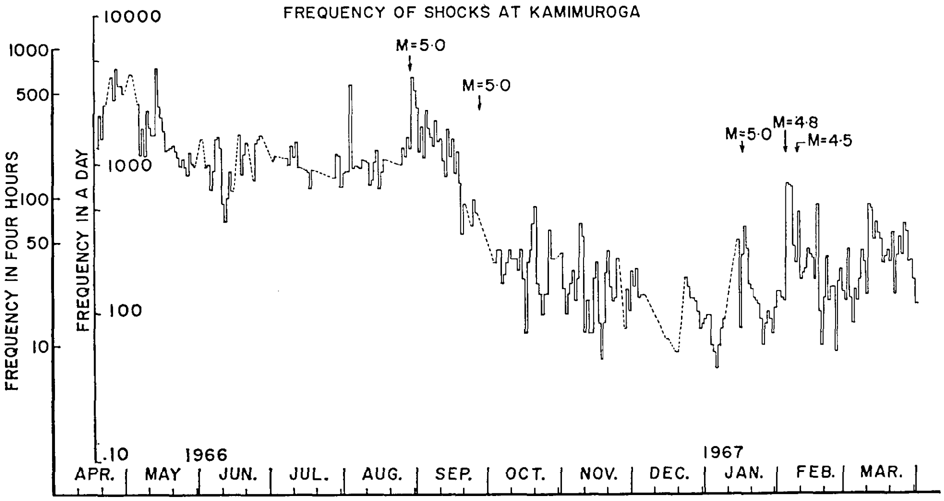

Fig. 4. Number of shocks observed at Kamimuroga. Arrows indicate main shocks that occurred near the station.

quakes were most active, seismic shocks were counted at the rate of about 3,000 in a day just after the beginning of the observation. The frequency decreased slowly till the beginning of June and kept at an almost constant level of 900 per day from June to August. Unfelt shocks at Matsushiro decreased to one-fifth in those four months. Since the latter part of August, the frequency increased, giving a record of 3,800 per day on August 29, the day following a strong shock with maximum intensity of V at Koshoku City. After that, the daily frequency diminished exponentially to an extent of 150 per day in mid-October. In the period from October to December, continuous observation was not obtainable, but it seems that the activity level was almost constant or subject to a slight decreasing. In spite of the approximately constant level of activity at Kamimuroga during the periods June—August and October—December, the frequency at Matsushiro tended towards exponential decay with a half life of about 50 days. This fact suggests some high level activity of micro-earthquakes in the region near Kamimuroga, this suggestion being also supported by the frequency distribution of S–P time (Fig. 5). The S–P times were distributed mostly between 2.0 and 3.0 seconds from April to July, but in August a small peak appeared around 1.5 second, which grew up to a noticeable peak in September. Since the beginning of 1967, the frequency of

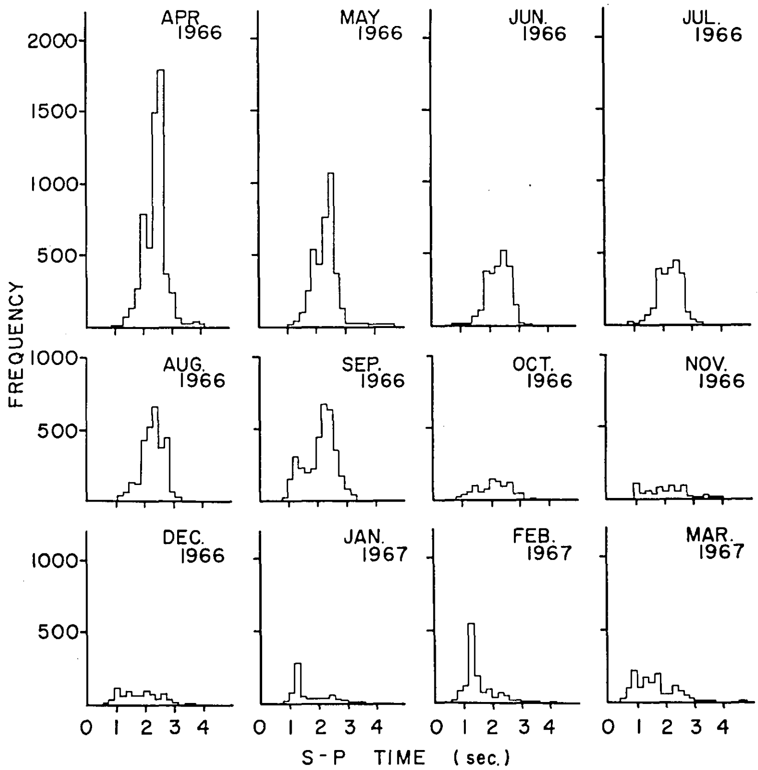

Fig. 5. Frequency distribution of S–P times.

shocks began to change in a quite different way from that of former days. After drawing a noticeable trough of 50 times per day, the curves of the frequency of shocks went on increasing to the extent of 400 per day in mid-January. The general trend of frequency time series was of slight increase with large peaks and troughs until the last day of March. In this period, the seismicity of the Matsushiro earthquakes was violent in the southwestern region. Around Sakai Village, shocks of magnitude 5.0 or so occurred on January 16, February 3 and 8. Arrows in Fig. 4 indicate the earthquakes whose epicentral distance was less than 10 km with magnitude more than 4.5. In every case, the frequency of micro-earthquakes increased from about ten days before those significant shocks. It seems improbable that the frequency of micro-earthquakes should increase more and more until a remarkable earthquake finally took place, as far as our present observations are concerned. The seismic activity was rather low on the day just before the occurrence of a strong shock. We shall discuss this problem in more detail on another occasion.

3. Space distribution of hypocenters.

Fig. 6 illustrates the epicentral distribution and the vertical profile of determined foci, three month's data being plotted on a single map. The numerals on the maps mean the number of earthquakes located in a mesh 0.85 km × 1.02 km. Data in 556 hours were analysed for determining hypocentral co-ordinates.

Before our observation was commenced, it had been thought that the active area of the Matsushiro earthquakes was restricted within an area including Matsushiro Town, Wakaho Town and the eastern part of Koshoku City.[4),5)] From Fig. 6 (a), however, we can discern some micro-earthquakes even in Sakai Village in as early a stage as April—June, 1966. One group of earthquakes around Togura-Kamiyamada has been recorded since the beginning of this observation, but another group around Sakai-Omi began to occur on April 29. The depths of foci were concentrated at about 10 km on the average, and were inclined to become deeper to the northeastern side. In the first three months no shocks occurred near Aoki Village, where an unusual upheaval was detected by precise levelling. In the period between July and September, a group of earthquakes around Mt. Azumaya was distinguished from other ones, the frequency of occurrence being five in a day. The depth of this group was rather shallow, that is to say, 2–7 km. On August 26, two ultra micro-earthquakes of magnitude −1 occurred successively in the eastern part of Aoki Village. Their depth was 10.3 km and 10.5 km respectively. This was the sole indication of seimic activity around Aoki Village through the year. On August 28, the intensity V was

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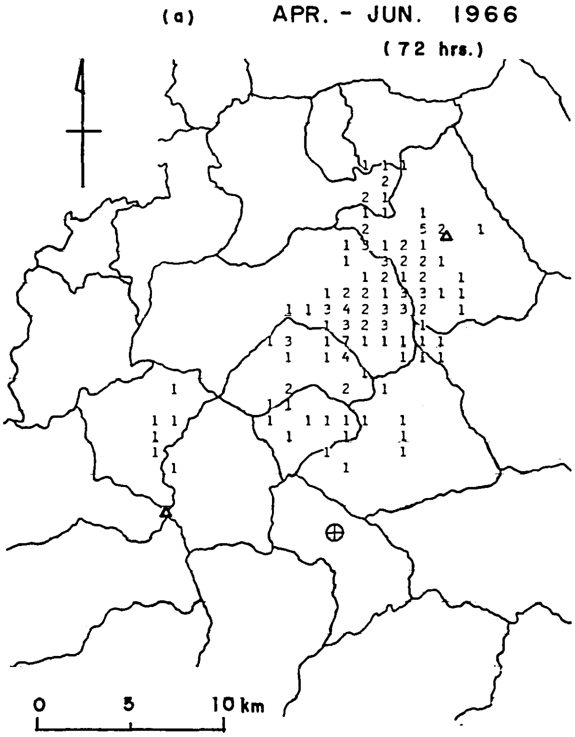
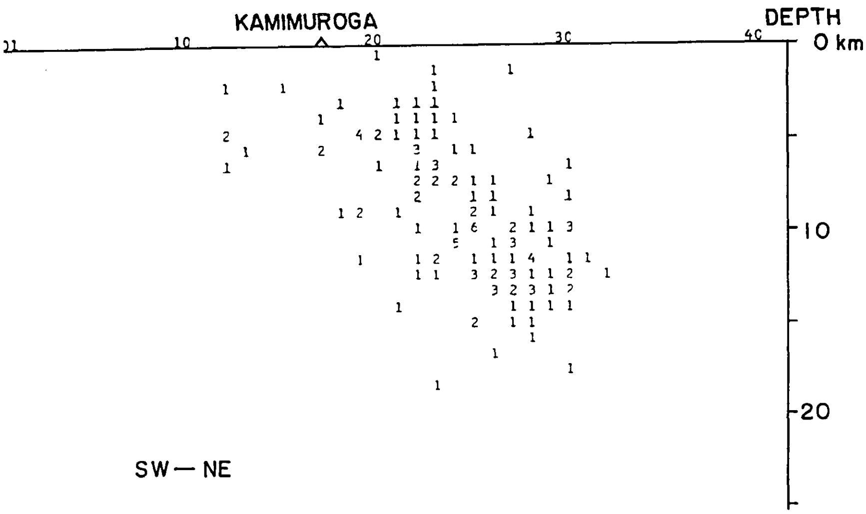
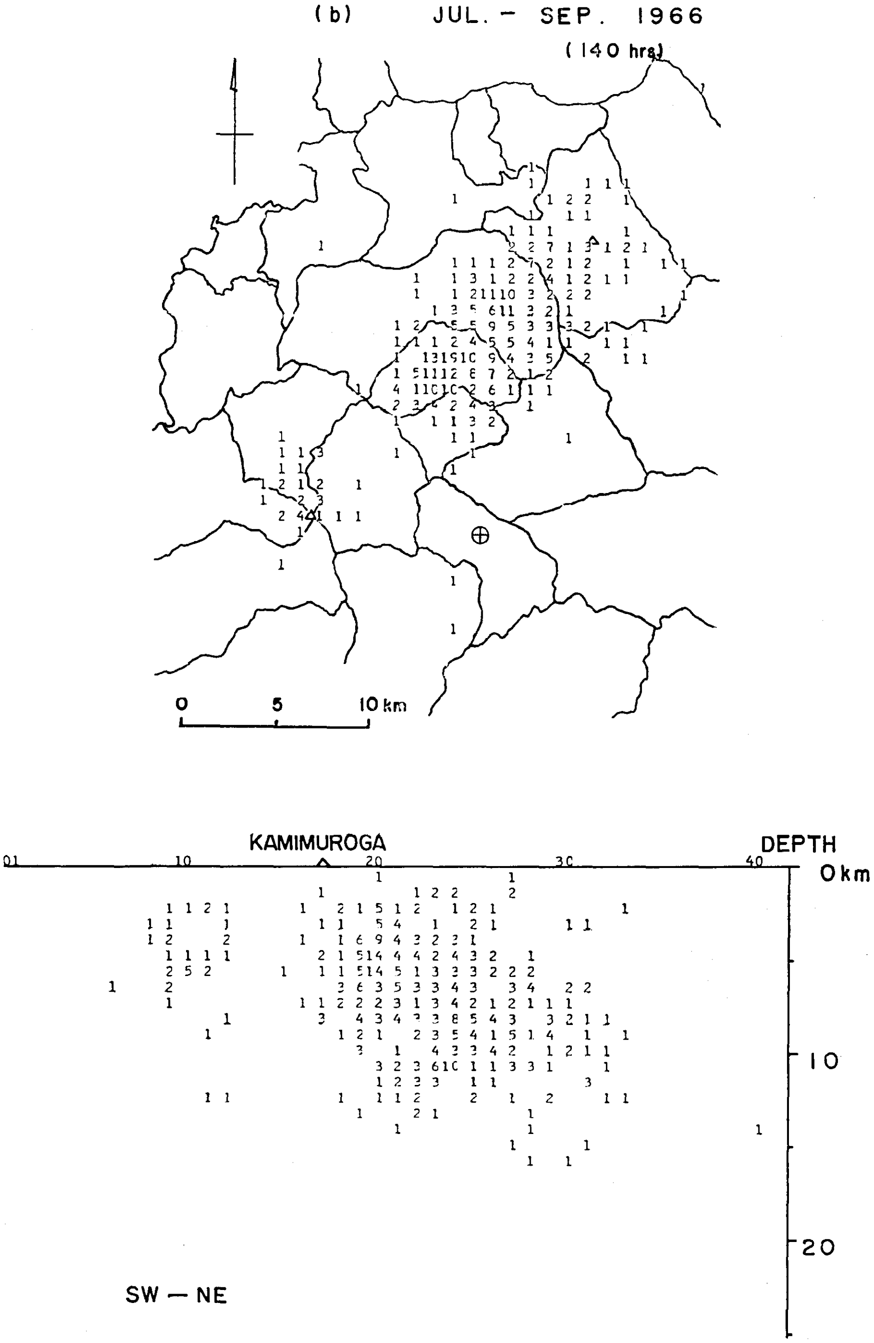
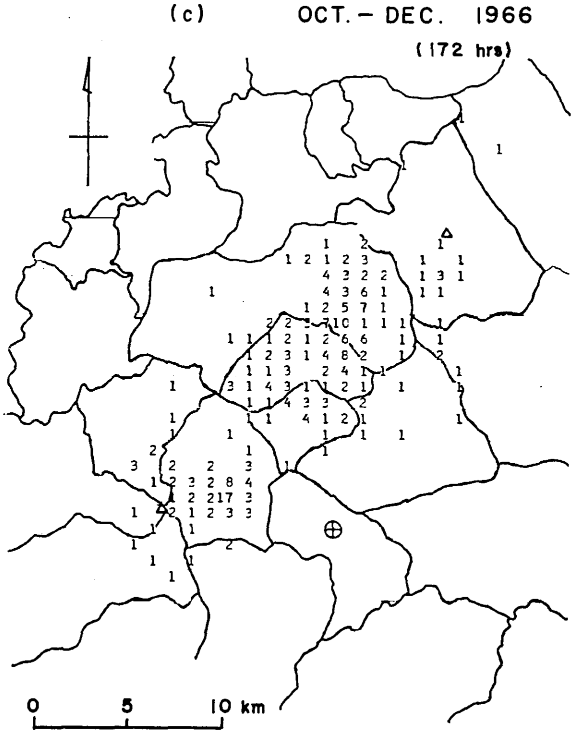
4) THE PARTY for SEISMOGRAPHIC OBSERVATION of MATSUSHIRO EARTHQUAKES and THE SEISMOMETRICAL SECTION, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network. Part 1," *Bull. Earthq. Res. Inst.*, **44** (1966), 309.

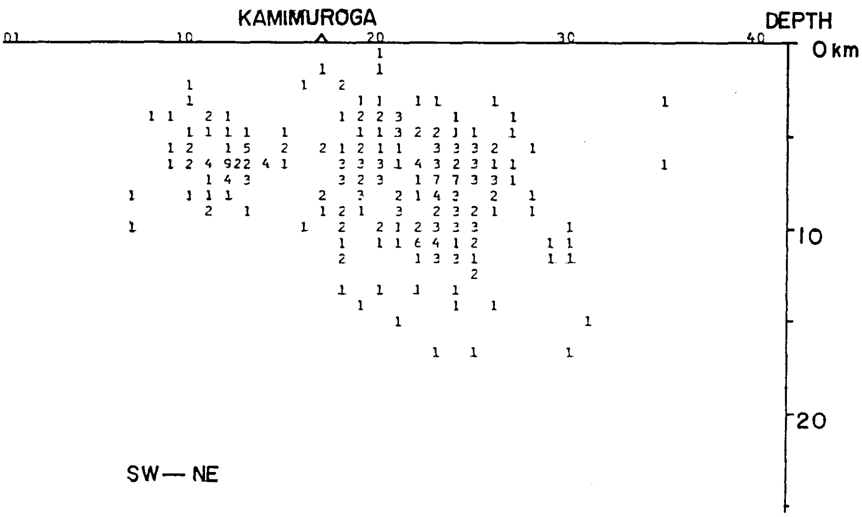
5) THE PARTY for SEISMOGRAPHIC OBSERVATION of MATSUSHIRO EARTHQUAKES and THE SEISMOMETRICAL SECTION, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network. Part 2," *Bull. Earthq. Res. Inst.*, **44** (1966), 1689.


(a) APR. - JUN. 1966
(72 hrs.)
0 5 10 km


KAMIMUROGA
DEPTH
0 km
10
20
SW — NE


(b) JUL. - SEP. 1966
(140 hrs)
0 5 10 km
KAMIMUROGA
DEPTH
0 km
10
20
SW — NE


(c) OCT. – DEC. 1966
(172 hrs)
0 5 10 km


KAMIMUROGA
DEPTH
0 km
10
20
SW — NE

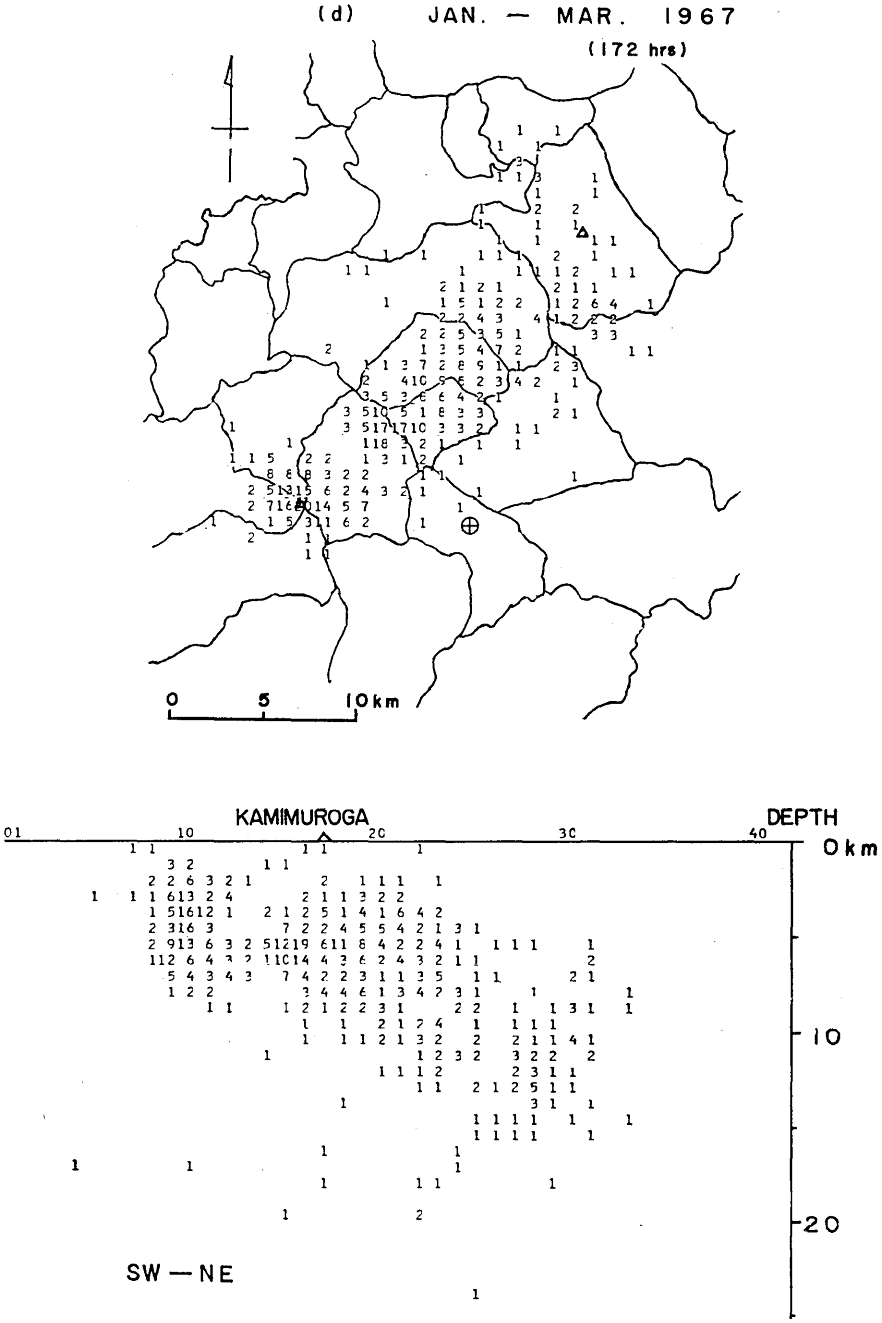


Fig. 6. Distribution of hypocenters determined by tripartite method.

observed at Koshoku City for the first time due to an earthquake located near Mt. Gori-ga-mine, 9 km SSW from Mt. Minakami. This location was considerably apart from the foci of the shocks with maximum intensity IV or V that have been hitherto occurred. It must be noticed that a significant activity of micro-earthquakes had been observed in this region for at least four months before the occurrence of this large shock. In the period from October to December, the earthquakes around Mt. Azumaya were activated to an average rate of 9 per day in contrast with the general tendency that the total frequency at Kamimuroga was decreasing. The seismic activity near Kamimuroga was accelerated from the beginning of 1967, and a strong shock with magnitude 4.8 occurred in the Mt. Azumaya group on February 3. This was the first occurrence of a shock with magnitude about 5 in this group, but micro-earthquakes had been detected for those nine months as mentioned in the foregoing.

From Fig. 6 (d), three groups of seismic activity will be clearly distinguished from each other. They are the Mt. Azumaya group ($h=$ 0–8 km), the Togura—Kamiyamada group ($h=$0–12 km) and the Koshoku group ($h=$5–16 km). The micro-earthquakes near Kamimuroga mostly belonged to one of these three groups throughout one year, the boundaries between seismic and aseismic regions being easily discriminated. Except for two cases at Aoki Village, the earthquakes, even of very small magnitude, have never been detected on the southern side of the station. The forerunning activity of micro-earthquakes had been observed for several months without exception around the regions where an earthquake with magnitude about 5 subsequently occurred.

4. Time and space distribution of aftershocks.

We examined the time and space distribution of aftershocks in three cases. The observational data of the earthquakes by the Seismometrical Section of the Earthquake Research Institute are listed on Table 2. The table includes all the shocks that occurred on the southwestern side of

Table 2. Main shocks of which aftershocks were analysed.

Date	Time	Epicenter		Depth	M
Jan. 16, 1967	12^h32^m	36°26.′3N	138°05.′6E	10.2^{km}	5.0
Feb. 3, 1967	17 17	36 25.7	138 03.4	11.2	4.8
Feb. 8, 1967	18 50	36 26.6	138 05.5	12.5	4.5

Chikuma River with magnitude more than 4.5 in a year since our observation was started. Fig. 7 illustrates the hourly number of aftershocks for those three cases. For the shocks which occurred within one hour after the occurrence of a main shock, we counted the numbers at intervals of 0.1 hour and then plotted them in the figure, converting into hourly

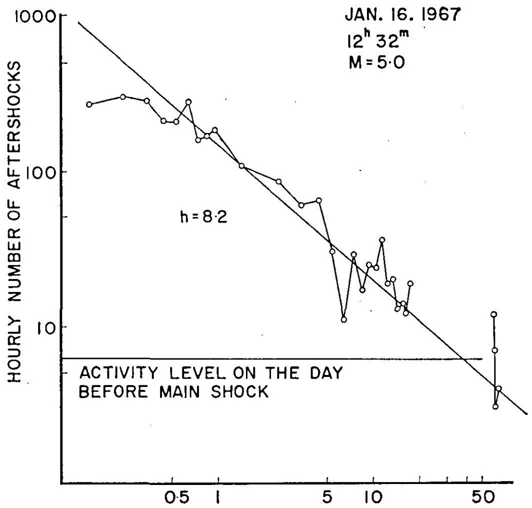


Fig. 7 (a)

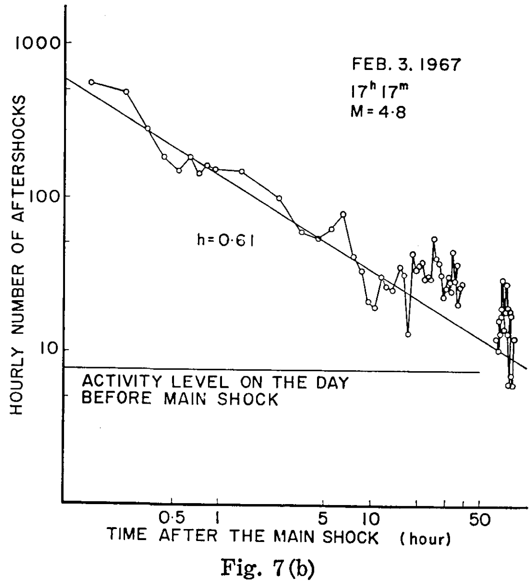


Fig. 7 (b)

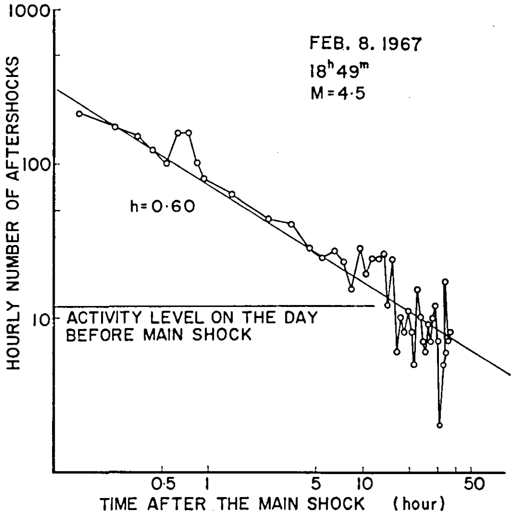


Fig. 7 (c)

Fig. 7. Time series of frequency of aftershocks observed at Kamimuroga following main shocks whose magnitude was 4.5–5.0. Applying the formula, $n(t)=n_1t^{-h}$, we obtained 0.60–0.82 as value of h.

values. We regarded all the shocks thus counted as "aftershocks," because there was some apprehension regarding an increasing "artificial noise" caused by ambiguity of S–P time and errors in initial time, if we attempt to distinguish "real" aftershocks by means of S–P time or location of foci. The horizontal underlines in Fig. 7 indicate the average frequency of shocks per hour observed on the day before a main shock. Applying the formula,

$$n(t)=n_1t^{-h} \qquad (2)$$

to the time series of aftershocks on February 3 and 8, we obtained $h=0.61$ and 0.60, respectively. In the case of the earthquake on January 16, the numbers of aftershocks were approximately on a constant level of 300–400 per hour till 0.7 hour after the main shock. We cannot consider that such deviation from the hyperbolic decrease was caused only by miscounting. Applying the formula (2) to the part beyond this state, we obtained $h=0.82$. If we subtract the numbers of shocks that are expected to occur on normal days as indicated by a horizontal line in Fig. 7, from the total number, the values of h are altered to 0.95 (Jan. 16), 0.83 (Feb. 3) and 0.74 (Feb. 8). According to Mogi,[6] the

6) K. MOGI, "On the Time Distribution of Aftershocks Accompanying the Recent Major Earthquakes in and near Japan," *Bull. Earthq. Res. Inst.*, **40** (1962), 107.

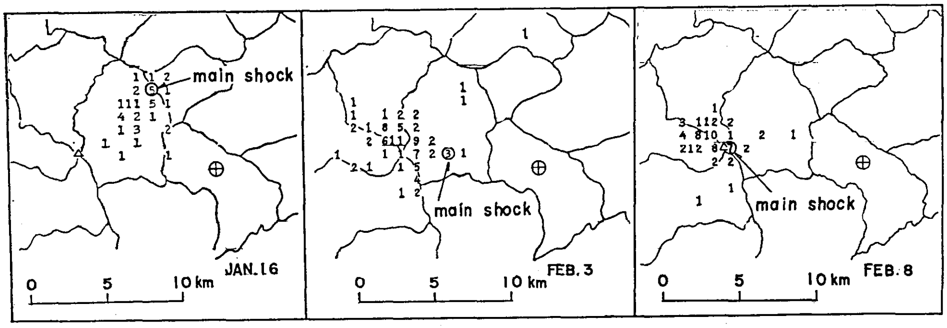


Fig. 8. Epicenters of aftershocks which occurred within thirty minutes after main shocks.

values of h which have been obtained from ordinary earthquakes that have hitherto occurred are rather small in the northern part of Nagano Prefecture. Our values of h are considerably small compared with 1.13 or 1.05 that have been obtained by Mogi from the aftershock sequences following the Nagano-Omachi earthquake (1918, $M=6.1$) and the Nagano earthquake (1941, $M=6.2$).

Fig. 8 illustrates the horizontal distribution of the aftershocks which occurred within thirty minutes after the main shocks. The location of the main shocks indicated here was determined by the observation at Kamimuroga. These aftershock sequences took place under a specific condition such as the Matsushiro swarm earthquakes, but the aftershock areas were of elliptical form and the main shocks occurred near the margin of the aftershock region as had been so in many cases of previous investigations. The observed aftershock area was, however, slightly larger than the estimated value from the Utsu's formula,[7)]

$$\log D = 0.5\,M - 1.8\ ,$$

Table 3. Linear dimension of aftershock area calculated from Utsu's formula, $\log D = 0.5\,M - 1.8$, and actually observed aftershock area.

Date	Magnitude	D	Aftershock area
Jan. 16	5.0	5.0 km	7.2 km × 4.8 km
Feb. 3	4.8	4.0	8.0 × 5.4
Feb. 8	4.5	2.8	4.8 × 3.6

7) T. Utsu, "A Statistical Study on the Occurrence of Aftershocks," *Geophys. Mag.*, **30** (1961), 521.

where D is the linear dimension of aftershock regions and M the magnitude of main shocks. The values in both the cases are compared in Table 3.

5. Discussion on the accuracy of calculated co-ordinates of foci.

In order to locate hypocenters by the tripartite method, we must assume the velocity of P wave v_p and the Omori's coefficient k. The value of v_p can be estimated from observed apparent velocity in the following procedure. In Fig. 9, the apparent velocity along the surface of 615 earthquakes measured by our tripartite net is plotted versus the direction of approach of the seismic waves. Any systematic deviation of the apparent velocity due to the direction of approach is not found from the distribution of dots in the figure. If we make a frequency distribution diagram of this apparent velocity, it is clear that a sharp scarp exists at 5.0 km/sec, so we adopted this value as v_p. Other scarps can be seen at 5.4 km/sec and 5.9 km/sec. Omori's coefficient k was

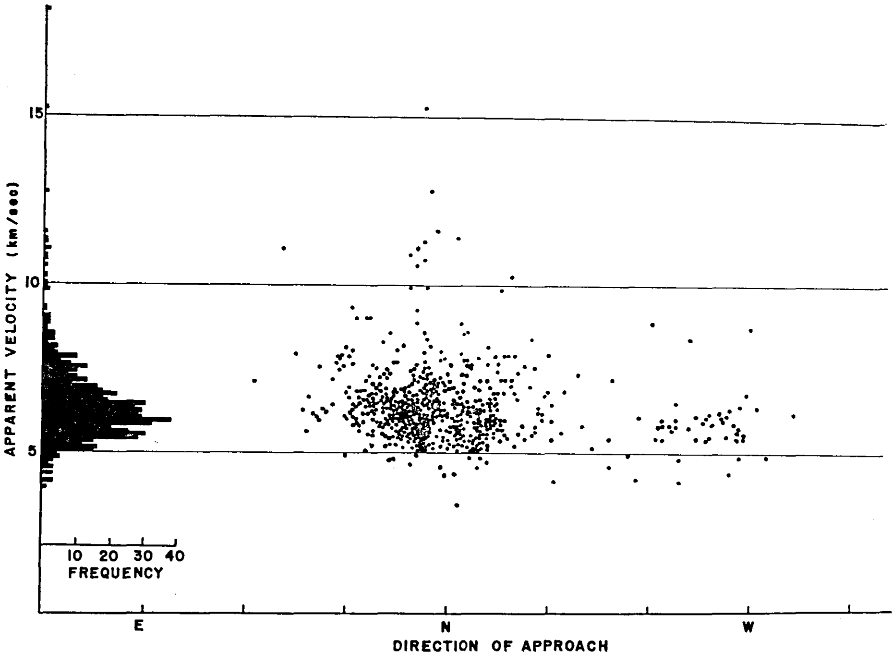


Fig. 9. Distribution of apparent velocity versus direction of approach of seismic waves, with cumulative sum of frequency.

obtained from the slope of the curve in Fig. 10, which shows the relation between hypocentral distance and *S–P* time of the same shocks. Plotted data are of the earthquakes whose hypocenters were determined by the Seismometrical Section of the Earthquake Research Institute while the *S–P* time used here was obtained by our Kamimuroga station. The value of k is not constant but has a tendency to increase with hypocentral distance. Therefore we approximated k with a linear function of *S–P* time, as expressed in formula (1).

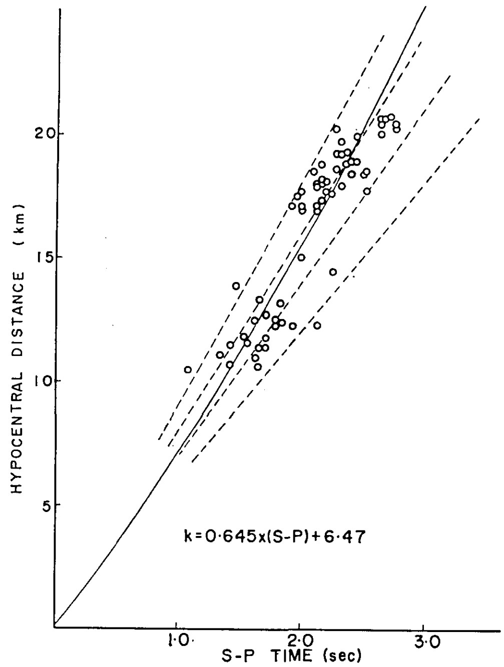


Fig. 10. Plot of hypocentral distance versus *S–P* time, and adopted formula for Omori's coefficient.

The errors in the reading of visible records would not cause appreciable distortion to the calculated parameters of hypocenters, in the worst cases, the errors being less than $\pm 6°$ in the direction of approach, $\pm 10\%$ in apparent velocity and ± 0.05 sec in *S–P* time. Then, for instance, the epicenter would be decided with error less than 1 km for an earthquake whose epicentral distance is 10 km and depth 5 km. On the other hand, the estimation of the depth would be rather rough and the calculated values might distribute scatteringly in the range from 0 km to 7 km for the same earthquake. The solid and open circles in Fig. 11 point to the epicenters calculated from S–P times at the Akashiba, Mori and Sakaki stations maintained by E. R. I. and those from our Kamimuroga tripartite station, respectively. The two points corresponding to an identical shock are bound with a solid line. At a glance over the figure, we notice that the distance of the two points exceeds the limit of error examined above. Compared with the solid circles, the open circles are dislocated systematically, the azimuth seen from the station being twisted anti-clockwise by 10°–30°. The calculated depth seems to be overestimated. These distortions are considered to be caused by the assumption of homogeneous half space. If a layered medium is assumed, it must be inclined to the east. We cannot make such comparison for the earthquakes which occurred in other areas outside the network of Akashiba, Mori, Sakaki, because the accuracy of hypocentral positions

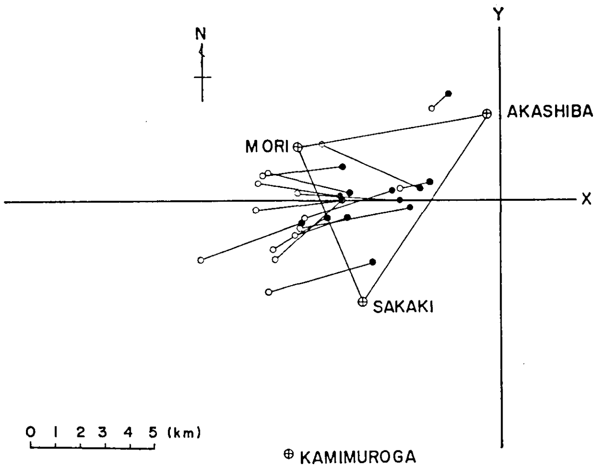


Fig. 11. Comparison of epicenters determined by tripartite method at Kamimuroga (open circles) with those determined independently from S–P times of Mori, Sakaki and Akashiba (solid circles).

is not sufficient when the foci are located outside the network. Therefore, in Fig. 6, we showed the foci determined by the tripartite station without adding any correction. Hence, the correct foci are expected to be located three or four kilometers east of the points shown here. However, the explanation on the distribution of foci in Section 3 will not be altered because every group of micro-earthquakes is of considerable extent and the relative localities of foci are much more reliable.

Acknowledgement.

The positions of observation points were surveyed by Dr. Atushi Okada of the Geodetic Section of the Earthquake Research Institute. Mrs. Akiko Yamamoto supported us by her efforts in keeping the recording system at the station. The records reproduced were read by Miss Sachiko Inoue. Mr. Kazuo Hamada kindly afforded us the advantage of the use of his computer program for tripartite analysis. We wish to express our sincere appreciation for all such assistance.

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45. 松代地震群の南西周縁部における極微小地震活動 (第1報)

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松代地震群の南西周縁部での極微小地震活動を調べる目的で，1964年4月18日，高感度三点方式による上室賀極微小地震臨時観測点を設けた．北信一帯の水準路線の改測から，松本，上田の中間に当る青木村付近に3ヶ月間で40mmを越える異常隆起が明らかにされた直後のことである．東京大学地震研究所の綜合的な松代地震群調査の一環として計画されたこの観測は現在も続行中であるが，1年間の観測結果を第1報として報告する．

1. 観測およびデータ処理の方法

上室賀臨時観測点は，松代町の南南西 17km の長野県小県郡川西村上室賀に置かれている．基点の緯度・経度は，36°41.'5N, 137°12.'3E である．しつかりした露岩を選んで，第1図の A, B, C 3カ所に上下動地震計を配置し，C点にはさらに水平動二成分を加えてこの点を基点とした．3点間の距離は，BC 923m，CA 1,276m，AB 1,227m で，標高差は最大 59m である．地震計は固有振動数 3.5サイクル（上下動），5.0サイクル(水平動)の動コイル型で，いずれも $h=1$ で使用している，地震計の出力は尖頭増幅器で増幅の上ケーブルで一カ所に集中され，沪波・増幅回路を通つがて磁気テープに記録される．記録部は6成分の交流バイアス直接録音方式のデータレコーダで，内1成分は水晶時計からの刻時マーク用である．1/2インチ幅，10インチ径のリールで24時間連続記録できるように，テープ送り速度は 7.6mm/sec としてある．記録済テープは東京に郵送されて，光学オシログラフまたはペンオシログラフで再生される．再生用ガルバノメーターの周期特性を考慮に入れて，再生時のテープ送り速度は 12.5倍(光学オシログラフの場合)または2倍(ペンオシログラフの場合)に上げて作業の能率化を図つている．記録は24時間連続で行なわれているが，処理能力の点から，再生は原則として毎日0時から4時までに限つた．記録再生方式の概要を第2図に，このシステムの綜合感度周波数特性を第3図に示す．倍率にひき直すと，10サイクルで31万倍(上下動)である．

震源座標の決定は，若穂町保科における三点観測の場合と同じく，3点での発震時差と基点での S-P 時間を観測値として，半無限均質媒質の仮定，球面波近似の下に3元2次連立方程式を解く方法によつている．この際媒質中の P 波の速度 v_p と，大森係数 k を与えておかねばならない．上室賀での観測から，$v_p=5.0$km/sec, 大森係数は，S-P (sec) の函数として，

$$k=6.47+0.65\times(S\text{-}P)\,, \qquad (1)$$

とした．データの詳細については節を改めて後述する．

2. 地震回数

上室賀における毎日 4 時間の地震回数を第 1 表に掲げる．基点の上下動成分で最大振幅 2.5 mm (地動で 50 μkine に相当する) 以上の地震の数である．村松の計算図表によれば，震源距離 20 km 以内でマグニチュード −1 以上の地震は残らず数えられていることになる．比較のために，気象庁から発表された松代での総地震回数もあわせて示してある．1966 年 11 月 19 日に上下動成分の感度の変更を行ない，それ以前は第 3 図に示した標準感度の 1/2 となつている．地震回数の時間的推移を概観する便宜上，第 4 図では，感度変更以前の回数をすべて 2 倍して図示してある．これは，石本一飯田の係数 m を 2 と仮定したことに相当する．以下，この換算回数に従つて地震回数の変動の経過を見て行こう．

観測を開始した 1966 年 4 月は，松代地震群のいわゆる第 2 の活動期の後半に当り，上室賀でも 1 日の数にひきなおして 3,000 回内外の極微小レベル以上の地震が記録されている．6 月上旬まではゆるやかに減少し，6 月から 8 月にかけては 1 日 900 回程度の横這状態が続いた．松代ではこの間に無感地震回数が約 1/5 に減少している．8 月下旬から数は増勢に転じ，8 月 28 日の更埴市の震度 V (参考) を契機に 1 日 3,800 回にはね上つた．以後数は指数函数的に急速に減少し，10 月なかばには 1 日 150 回の水準にまで落ちた．10 月後半から年末まではかなり欠測が多く不明確な時期もあるが，概ね横這乃至微減少で推移したと見てよい．6 月～8 月にかけて，また 10 月～12 月にかけて，上室賀ではほぼ横這状態であるにもかかわらず，松代での回数は半減期 50 日程度の指数函数的な減衰傾向にあり，上室賀附近にかなり活発な地震活動が予測される．第 5 図の S-P 頻度分布図からこの間の事情はいつそう明らかである．1966 年 4 月から 7 月の期間は S-P 2～3 秒に圧倒的多数が集中しているが，8 月に S-P 1.5 秒に小さい極大が現われ，9 月には顕著な一群を形成するに至つた．

1967 年にはいると活動のありさまは一変する．1 月上旬に 1 日 50 回以下の深い谷を刻んだ後，有感地震を含みながら上昇に向い，中旬には 1 日 400 回にも及んだ．1 月以後激しい増減をくり返しつつ上昇傾向で 3 月末に至つている．この間マグニチュード 5 程度の有感地震が 1 月 16 日，2 月 3 日，2 月 8 日と坂井村近辺で続発しており．松代地震群南西部の活動が相対的に活発化してきた．第 4 図の矢印は，上室賀から震央距離 10 km 以内に起つたマグニチュード 4.5 以上の地震をあらわしている．いずれも 10 日程度前から地震回数の増加が認められる．しかし，地震回数が徐々に増加してついに最高調に達して大きい地震の発生をみる，といつた単純な図式は成立たない．付近で大きい地震が発生する前日の地震回数はむしろ少ないことが特徴的である．この問題についての詳しい議論は別の機会にゆずる．

3. 震源の分布

決定された震源の震央分布図および垂直断面図を 3 カ月ずつまとめて第 6 図 (a)～(d) に示す．地図上の数字は縦横 0.85 km×1.02 km のメッシュ内に震源の決つた地震の個数を意味している．1 年を通じて 556 時間のデータが震源決定に用いられた．各期間別の解析時間は第 6 図に示してある．

上室賀での観測が始まるまで松代地震群の震源域は有感・無感地震ともに松代，若穂両町全域と更埴市東部に限られるものと考えられていた．しかし第 6 図 (a) から，1966 年 4 月～6 月の段階で極微小地震が千曲川を西に渡つて東筑摩郡坂井村にまで及んでいることがわかる．戸倉・上山田の一群は 4 月 18 日の観測開始以来はつきりと認められるが，坂井・麻績 (おみ) に震源をもつものは 4 月 29 日に初めて現われた．深さは 10 km 前後のものが最も多く，北東側で深くなる傾向にある．土地の異常隆起が見出された青木村付近には極微小地震は起つていない．7 月～9 月の震源分布図 (b) では，四阿屋山 (あずまやさん) をとりかこむ一群の活動が明瞭となる．1 日当り 5 個の頻度である．このグループの深さは 2～7 km でかなり浅い．8 月 26 日には青木村東部にマグニチュード −1 程度の極微小地震が相ついで 2 個観測された．深さは 10.3 km，10.5 km といずれも深い．1 年間を通じて青木村付近に震源の決められた地震はこの 2 個のみである．8 月 28 日，皆神山の南々西 9 km の五里ケ峰付近にマグニチュード 5.0 の地震が発生し，更埴市で初めて震度 V (参考) が記録された．最大震度 IV 以上の有感地震としては従来の震源域に比して最も南に片寄つた地点で起つたものであるが，少なくとも 4 カ月以前からこの地域で顕著な極微小地震活動が捕えられていたことになる．10 月～12 月にかけて，総地震回数は上室賀でも下向傾向にあつたが，四阿屋山グループの活動はかえつて活発化し，平均して 1 日当り 9 個の水準を保つている．1967 年にはいると戸倉・上山田・坂井の極微小地震活動は活発の度を加え，2 月 3 日には四阿屋山グループ内にマグニチュード 4.8 の発生をみた．四

阿屋山付近の極微小地震群が観測されはじめてから9ヵ月目である．2月以後，震源域は四阿屋山の西方に拡大した．

第6図(d)から，四阿屋山グループ(h=0～8 km)，戸倉・上山田グループ(h=0～12 km)．更埴グループ(h=5～16 km)の3活動群が明瞭に区別できる．1年間を通じて，上室賀付近の極微小地震はほとんどこの3グループのいずれかに属しており，震源域の境界は画然としている．とくに，青木村の2個を例外に，観測点の南象限には全く極微小地震が見当らない．同時に，マグニチュード5内外の地震が発生する地域には，数ヵ月前から例外なく極微小地震の前駆的活動がみられる．

4. 余震個数の時間的減衰および余震域

上室賀付近に起つた主な地震3個について，その余震の個数の時間的減衰および余震域の大きさを調べた．とりあげた地震は観測期間中に千曲川南西岸に起つたマグニチュード4.5以上のものすべてで，第2表に地震研究所計測部で決められた諸要素を記してある．

これら3個の地震について1時間ごとの余震の数を両対数目盛で示したのが第7図である．ただし主震後1時間までは，0.1時間刻みで1時間当り換算個数をプロットしてある．計算に当つては，観測された地震をすべて余震として数えた．震源位置や S-P でふるいわけようとしても，初動の発震時差や S-P が読み取れないものが 10～20% あつて，かえつて人為的な雑音を増すおそれがあるからである．なお，常時活動水準のめやすとして，主震前日の1時間当り地震回数も第7図に示した．2月3日，8日の余震個数の時系列は，

$$n(t)=n_1 t^{-h} \qquad (2)$$

で近似され，h の値はそれぞれ 0.61, 0.60 である．1月16日の場合は主震直後の0.1～0.7時間にかけて余震個数は300～400個でほとんど減少せず，頻発時の数え落しを考慮に入れてもなお双曲線には乗らない．0.7時間目以後の部分に(2)式をあてはめれば，h=0.82 を得る．上に述べた常時活動水準の個数を差し引いた数を余震個数とみなすと，h=0.95 (1月16日)，0.83 (2月3日)，0.74 (2月8日) となる．茂木によれば長野県北部は h が小さい地域とされている．われわれが得た値は，茂木が長野・大町地震 (1918年，M=6.1)，長野地震 (1941年，M=6.2) の余震群から得た h=1.13, 1.05 よりもさらに小さい．

主震後30分間に起つた余震の震源分布を第8図に示す．主震の位置は，上室賀の三点方式観測によつて決められたものが示してある．松代地震群という特別の環境の中での余震群であるが，一般の余震分布と同様に，余震域は長円形を成し，主震はその一方の端近くで起つている．しかし余震域のひろがりは第3表に掲げるように，宇津の経験法則，

$$\log D=0.5\,M-1.8$$

から見積られた値よりもやや大きい．

5. 震源決定の吟味

震源の決定には，P 波の速度及び大森係数 k を与えておかねばならない．P 波の速度は，観測された見かけ速度から推定した．第9図に615個の地震の見かけ速度が地震波の到来方向に対してプロットされている．方位による系統的な見かけ速度の偏りは見られない．すべての方位にわたつて加え合わせた積算図から，見かけ速度 5.0 km/sec 以上のものが急にふえていることが明らかなので，P 波の速度として 5.0 km/sec を採用した．5.4 km/sec，5.9 km/sec にも鋭い頻度の増加が見られる．大森係数は，地震研究所計測部で震源が決められ，かつ上室賀で S-P が判読された地震について，S-P と震源距離の値を直交座標上にプロットして，その勾配から求めた．第10図に示されているように，震源が遠いほど k も大きくなる傾向が明らかなので，最も簡単に k を S-P の一次式で近似して (1) 式で与えることにした．

記録読取の不正確さのために生ずる誤差は，この観測の場合，高々到来方向で 6°，見かけ速度で 10%，S-P で 0.05 sec 程度である．これは例えば，震源距離 10 km，深さ 5 km の地震ならば震央が ±1 km 以内の精度で決まることを意味する．深さの方はもつと精度が悪く，計算値が 0～7 km の範囲内にばらつく可能性がある．

第11図から，震央位置の誤差が読取の不正確さによる誤差の限界を超えていることが明らかである．黒丸が赤柴，森，坂城の S-P から決つた震央，白丸が上室賀の三点観測から決つた震央である．われわれが決めた震央は系統的に 10°～30° 反時計まわりに回転している．深さについても深く見

積りすぎる傾向にある．これらの偏りは，半無限均質媒質の仮定から生じている．均質な層構造を考えるならば，東側で深くなる向きに傾斜していなくてはならない．赤柴・森・坂城ネットからはずれた場所ではよい精度で同様の比較をすることができないので，第6図には上室賀で決めた震源の位置をそのまま示してある．震源分布の節で述べた3つの活動群が実際は 4 km ぐらい東寄りに位置しているかもしれない．しかし，いずれの活動群も数 km 以上のひろがりをもち，また決められた震源の相対的な位置関係は信頼できるから，前述の震源分布に関する議論は変更されない．

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