MICROEARTHQUAKE SURVEY IN NORTHEASTERN HONSHU, JAPAN

Hiroyuki HAMAGUCHI,* Hikaru WATANABE,** Kei TAKANO,***
Frank J. GUMPER**** and Gary BOUCHER*****

(Received February 8, 1973)

The cooperative microearthquake observation with seven portable seismometers and one fixed seismometer was carried out in the northeastern part (Tohoku) of Honshu, Japan, for twenty days in 1967. Twenty recording sites were used to locate the foci of about fifty microearthquakes during this period. One-half of the events were located in the zone (Morioka-Shirakawa tectonic line) between the western edge of Kitakami mountain and the volcanic front, the others were located on the westward dipping seismic plane. The crust bounded by these two seismic zones is aseismic.

The Morioka-Shirakawa tectonic line, which was inferred from the gravity anomaly, is a shallow seismic belt with a NS trend, however the level of the activity is not high; seven small shocks along this line in the surveyed area had been located by JMA network during the last 15 years. This tectonic line was characterized by the occurrence of small earthquake swarm.

1. Introduction

Preliminary studies on microearthquakes by Asada and Suzuki were published in 1949 and 1951. Later Asada and Asada *et al.* published comprehensive studies on microearthquakes in 1957 and 1958. Later many microearthquake observation stations were established in western Honshu, and microseismicity studies were done by MURAMATSU *et al.* (1963), KISHIMOTO *et al.* (1964), WATANABE and KUROISO (1967). However, a study of microseismicity in northeastern Honshu, which is a typical island arc with high level of seismicity, has not yet been done. It would be interesting to investigate microseismicity connected with tectonics in a tectonically active area. This is the reason why northeastern (Tohoku) Honshu was chosen as an object of

* Geophysical Institute, Tohoku University, Sendai, Japan.

** Abuyama Seismological Observatory, Kyoto University, Takatsuki, Japan.

*** Geophysical Institute, University of Tokyo, Tokyo, Japan.

**** Lamont-Doherty Geological Observatory. Now at New York Telephone Company, New York.

***** Lamont-Doherty Geological Observatory. Now at CIRES, University of Colorado, Boulder, Colorado.

the Japan-US cooperative microearthquake survey. The survey was carried out for 20 days in October and November in 1967.

In the Tohoku area of Honshu, a major tectonic structure, a remarkable geological line, was detected by a gravity survey (Tsuboi *et al.*, 1956) as shown in Fig. 1. This geological line called the Morioka-Shirakawa tectonic line divides the Tohoku area into two parts. In the western part of the Tohoku area, Tertiary and Quaternary volcanic rocks prevail and the contours of the Bouguer anomaly show an irregular slope. In the eastern part of the Tohoku area, the Bouguer anomaly is positive and isolines are parallel to the Morioka-Shirakawa tectonic line. The anomaly becomes larger toward the Pacific coast. This region is geologically stable and is called the Kitakami mountains. The geology of this region is composed of Paleozoic formations and Cretaceous intrusive rocks. The active volcanoes are on a line which is parallel to and about 20 km apart from the Morioka-Shirakawa tectonic line; the distance from the axis of the Japan trench to the volcanic zone being about 300 km at 40° north latitude. The amount of terrestrial heat-flow is bigger in the western part (divided by the Morioka-Shirakawa tectonic line) than in the eastern part (UYEDA and HORAI, 1964). According to historical records, most

Fig. 1. Bouguer anomaly (Tsuboi *et al.*, 1956), major earthquakes in historical age (Usami, 1966), and volcanoes in the Tohoku area. The region where the present microearthquake survey was made is defined by dotted lines.

Table 1. Big earthquakes occurred along the Morioka-Shirakawa tectonic line.

Date	Long. (E)	Lat. (N)	Magnitude
1736 APR 30	140.8°	38.3°	6.2
1823 OCT 23	141.1	40.0	5.9
1900 MAY 12	141.0	39.0	7.3
1956 SEP 30	140.6	38.0	6.1
1962 APR 30	141.1	38.7	6.5

of destructive earthquakes occurred in the western part of the Tohoku area, especially near the coast of Sea of Japan, and no destructive earthquakes occurred in the Kitakami mountains. Some destructive earthquakes occurred, however, along the Morioka-Shirakawa line as shown in Fig. 1. The magnitudes and the epicenters of these earthquakes are listed in the Table 1 (after USAMI, 1966). The biggest shock among those in Table 1 occurred in 1900 with a magnitude of 7.3. The location of the epicenter was relocated to be at almost the same position as an earthquake with a magnitude of 6.5 in 1962 (A. TAKAGI, personal communication, 1968). It should be noted that no big earthquake has occurred in the Kitakami mountains. An earthquake whose focus was located on the Pacific coast line is shown in Fig. 1, but it was accompanied by Tsunami waves (USAMI, 1966), indicating that the shock originated on the sea bottom.

The present problems are as follows. Are the Kitakami mountains really aseismic? Can no microearthquake be detected in that area?; Are microearthquakes occurring around the Morioka-Shirakawa tectonic line? How can the Morioka-Shirakawa tectonic line as a minor seismic zone where microearthquakes are occurring be found? Microseismicity in the Tohoku area has not been studied. The principal purpose of the present study is to solve the questions mentioned above.

2. Location of Sites

The northern part of the Morioka-Shirakawa tectonic line in Iwate prefecture was chosen as the area for the survey. The survey was carried out for a period of 20 days from Oct. 27 to Nov. 16, 1967. The area surveyed is shown on the map in Fig. 1. The southern part of the Morioka-Shirakawa tectonic line in Iwate prefecture is mostly covered by the recent alluvium, and is also more populated than other areas. Accordingly it is more difficult to find quiet sites here than in the area shown with the dashed lines in Fig. 1. One of the authors (Hamaguchi) made a noise survey with a small portable noise level meter in order to find very quiet sites. The results of the noise

survey are given in Fig. 3. As estimated from the surface geology, the western side of the Morioka-Shirakawa tectonic line is noisier than the Kitakami (eastern) mountainous region. The location of the sites, the date of the observation, and the type of the instruments are given in Table 2 and in Fig. 3. A total of 18 sites was used, and the mean distance between two sites was about 19 km. On an average, the level of ground noise in the Tohoku area is higher than less populated areas like Nevada in the U.S.

3. Instrumentation

In the present observation three "back-pack" seismometers (WARD *et al.*, 1969), four highly sensitive seismometers with slow speed direct recording tape recorder (DR) and a seismometer with a PWM data recorder were used. The DR recording system was the same as those used in the Caliente, Nevada observation (TAKANO *et al.*, 1972). The last one (PWM recording system) was located at a fixed tripartite station with the length of its sides being 750, 1088 and 1150 meters. At this site the earthquakes and ground noises were constantly monitored with a smoked paper drum recorder. The back-pack seismometers with paper speed of 25 mm per min. (enough for determining S-P times) were used at one-half of the sites. The seismometers with a slow-speed tape recorder were equipped with crystal clocks for the determination of foci based on P times. The frequency responses of the three types of seismometers mentioned above are shown in Fig. 2. The magnification at 10 Hz is about 10^6 , but the peaks are at different frequencies for the three seismometers. The magnification of the instruments used in Tohoku microearthquake survey is about one-sixth of the magnification at Matsushiro (ASADA *et al.*, 1958) and one-sixtieth of the magnification of set No. 1 at Fair View Peaks, Nevada (OLIVER *et al.*, 1966) and one eighteenth of the magnification at Caliente, Nevada (TAKANO *et al.*, 1972). The mean noise level at the Tohoku area is about 6×10^{-8} cm/sec as shown in Table 2, and the noise level at Matsushiro and at Fair View Peaks and at Caliente are estimated to be 0.5×10^{-8} cm/sec and 10^{-7} cm/sec, and 0.6×10^{-8} cm/sec, respectively.

4. Data Analysis

As the time accuracy of the back-pack seismometers is not enough for foci determination, P times were used only for the identification of earthquakes. The precision of S-P times is about ± 0.2 to 0.3 seconds when the onsets of P and S are sharp and about ± 0.5 to 1 second when the phases are not clear. The seismometers with a magnetic tape recorder are accurate to ± 0.1 second in the determination of S-P time.

Fig. 2. Frequency responses of the seismometers.

DR: Seismometer with direct recording data recorder.

TRI: Seismometer with PWM data recorder used at the tripartite station.

BP: Back-pack seismometer (Lamont).

SM: Seismometer with smoked paper drum recorder. This was used as a monitor at the tripartite station.

JMA-59: Seismometer which is used in the JMA network.

At the tripartite station, 124 earthquakes were recorded during the micro-earthquake survey period. The time precision of P is ± 0.01 second for 10 earthquakes, ± 0.02 seconds for 33 earthquakes, ± 0.03 to 0.04 seconds for 47 earthquakes and worse than ± 0.04 seconds for the rest of the earthquakes recorded during this period. The last 34 earthquakes were not included in the analysis

Table 2. Location of sites, instrumentation, number of events recorded at each site, and the hours of low noise recording, in the present microearthquake survey.

Site No.	Date ¹⁾ 1968	Longitude (E)	Latitude (N)	Instrument	Hour of low noise recording	Number ²⁾ of events with S-P ≤ 2.0 sec.	Number ²⁾ of events with 4.0 $<$ S-P $<$ 14.0 sec.	Total recorded events	Ground ³⁾ noise (10 ⁻⁶ cm/sec)	BP gain setting (db)
1-1	OCT 27	141°12.7'	39°52.6'	SM	451	0.4(5)	4.6(22)	239	7	
1-2	OCT 27	141°12.7'	39°52.6'	TR	171	0.7(5)	3.6(26)	288	7	
1-3	OCT 27	141°12.7'	39°52.6'	BP	25.3	0.9(1)	0.9(1)	3	(9)	34, 30
2-1	OCT 28	141°21.8'	39°57.7'	BP	25.5	1.9(2)	4.7(5)	11	(7)	30
2-2	OCT 28	141°21.8'	39°57.7'	DR	86.0	1.7(6)	3.9(14)	64	3	
5	OCT 29	141°22.8'	39°49.6'	DR	—	—	—	—	5	
6-1	OCT 30	141°23.2'	40° 3.7'	BP	81.7	1.2(7)	1.3(8)	23	(3)	24, 18, 24, 24, 24
6-2	OCT 29	141°23.2'	40° 3.7'	DR	89.0	1.2(12)	1.3(13)	29	2	
9	OCT 29	141°11.3'	39°49.1'	BP	27.8	1.6(1)	4.5(3)	7	(16)	36, 36
10	OCT 30	141°10.8'	40° 3.9'	DR	25.8	8.4(6)	8.4(6)	11	9	
11	OCT 29	141°	39°	BP	2.0	(0)	(0)	0	(40)	42
13	OCT 31	141°16.3'	40°13.4'	BP	18.0	(1)	(1)	2	(40)	42
14	OCT 31	141°20.7'	40°18.6'	BP	20.3	(0)	(0)	1	(7)	30, 30
15	NOV 1	141°30.8'	40° 7.8'	BP	69.8	0.7(2)	1.0(3)	42	(6)	24, 30, 30, 30
16	NOV 3	141°38.7'	40°10.1'	BP	46.2	0.9(1)	1.7(2)	20	(3)	24, 24, 24
17	NOV 5	141°43.4'	40° 2.6'	BP	70.1	0.9(1)	2.1(2)	36	(1)	18, 18
18	NOV 5	141°46.9'	39°56.4'	BP	40.2	0.0(0)	0.9(1)	27	(2)	24, 18
19	NOV 6	141°43.3'	39°50.4'	BP	23.8	1.7(1)	1.7(1)	14	(3)	24
20	NOV 2	141°33.8'	39°56.9'	DR	67.0	0.0(0)	0.0(0)	35		
21	NOV 3	141° 8.2'	40°10.8'	DR	—	—	—	—	9	
22	NOV 1	141°32.1'	40°18.9'	DR	69.6	2.8(8)	6.5(19)	118	2	
23	NOV 7	140°53.3'	40° 4.4'	DR	40.0	1.4(6)	1.8(8)	12	6	
Mean						1.6	2.9			

¹⁾ Local time.²⁾ Reduced number per day based on the numeral in the parenthesis (see text).³⁾ Numeral in the parenthesis is estimated from BP gain setting.

because of the poor determination of the arrival times of first waves.

As the mean distance of adjacent sites is about 19 km, the number of earthquakes with S-P times smaller than 2.0 seconds at a site may well represent the seismicity in the vicinity of the site. The earthquakes with S-P times smaller than 4 seconds occur in the crust because the crustal thickness in the Tohoku area is about 30 km. In Table 2 the numbers of the shocks with $S-P \leq 2.0$ seconds and $S-P \leq 4.0$ seconds per day are listed for each site. The numbers are normalized for a standard magnification, or 2.5×10^6 at 25 Hz, under the assumption, $n(A) \cdot dA = c \cdot A^{-1.8} \cdot dA$, where $n(A)$ is the number of shocks with the amplitude between A and $A + dA$ and c is a constant.

The amplifier gain of the back-pack seismometers and the particle velocity of the ground noises are also listed in Table 2, the values in the parentheses being estimates. The normalized frequency of the shocks per day and the level of the ground noise at each site is shown on the map in Fig. 3. The geographical distribution of the frequencies of the shocks is characterized by the fact that the frequencies are zero in the central part of the Kitakami

Fig. 3. The number of microearthquakes per day and the level of ground noise in 10^{-6} cm/sec.

mountains, and they are higher at the western edge of this mountainous area. A more detailed picture of the seismicity in the Tohoku area may be obtained by observing the frequency distributions of S-P time at several sites. These distributions are given in Fig. 4. The frequency distribution at site 1 has the two dominant peaks; one peak is at 2 to 6 seconds and another peak at 8 to 10 seconds. Combining the results of the frequency distributions of S-P time at all sites and the results of the geographical distribution of foci, the following picture on the seismicity is obtained. At site 1, the shallow earthquakes and the earthquakes occurring on the seismic plane dipping westwards are both recorded and they are separated according to S-P time. The shocks with S-P from 2 to 6 seconds at site 1 are occurring in the upper crust near the Morioka-Shirakawa tectonic line, and the shocks with S-P from 8 to 10 seconds belong to the group of the earthquakes of intermediate depth on the dipping seismic plane; the number in the range of S-P time from 6 to 8 seconds is small; this feature is particularly remarkable at site 6.

Fig. 4. Frequency distribution of S-P time. The shocks occurring on the deep seismic plane should have larger S-P times than the limit indicated by the arrow at the respective sites.

The S-P frequency distribution of site 22 is also similar to that of site 1, but at other sites the numbers of earthquakes recorded during the period are not enough to discuss the type of the S-P frequency distribution.

If we combine the characteristic features of S-P distribution at other sites, the characteristic features of the seismicity in the Tohoku area will be made clear. Nineteen shocks with S-P times smaller than 2 seconds were observed for 70 hours at site 6, and nine shocks with S-P times from 1.5 to 3.0 seconds were observed for 86 hours at site 2. At site 20 the shortest S-P time recorded for 67 hours was 5 seconds and the second shortest one 6.5 seconds, or no shocks with S-P shorter than 5 seconds had occurred around site 20. The total number of the events recorded at this site was 35 (Table 2).

At site 19 which was about 17 km apart from site 20, no earthquakes with S-P shorter than 5.5 seconds were recorded except one whose S-P was 0.5 seconds. The lack of the events with shorter S-P times leads to an important conclusion. Taking into account the geographical distribution of the sites and the above-mentioned facts, we may conclude that the microearthquakes occur in the area north west from site 2, and do not occur in the crust under the Kitakami mountains. This conclusion goes well with the results on the geographical distribution of foci obtained with the tripartite and other methods.

At sites 15, 16, 17 and 18 on the Pacific coast side, the percentage of the earthquakes with S-P times shorter than 4 seconds is small, or the seismicity in the crust is less active than the seismicity in the upper mantle.

The events recorded at these sites and having S-P times of 4 seconds or longer belong to the earthquakes of intermediate depth occurring on the dipping seismic plane. The shortest S-P times of the "deep" earthquakes at site 6 about 32 km west from the Pacific coast is 6 seconds, and that at site 1 about 50 km west from the Pacific coast is 8 seconds. As the seismic plane dips westwards, the S-P time become longer when the shock is recorded at a western site. Assuming the velocity of S-P to be 8 km/sec, the distances from sites 18, 6, to 1 and the dipping seismic plane are 32, 48 and 64 km, respectively. As shown in Table 2 the seismicity of the shallow shocks is low and the frequency of the shallow events with larger S-P times is smaller than the frequency of the shocks of intermediate depth, and we may neglect the effect of a shallow shock on the frequency distribution of S-P times in a range bigger than several seconds. Accordingly, it is possible for us to separate the group of the shallow shocks from the group of the shocks of intermediate depth, observing the features of the frequency distribution of S-P time at a site. Under the assumption adopted previously the numbers of shocks on intermediate depth per day recorded at a site can be obtained. The frequencies of the "deep" shocks are 15.7/day, 16.7/day and 1.4/day at sites 17, 18 and 6-1, respectively. The

level of the seismicity of shocks of intermediate depth is 2 to 10 times that of the seismicity of shallow shocks in the upper crust.

5. Location of Foci

5.1 Tripartite station

As mentioned already, the apparent velocities and azimuths of incident waves of earthquakes with S-P times smaller than 10 seconds were calculated and corrected for the dip of the ground surface by MARUYAMA's method (1965). The velocity of P waves in the superficial layer was assumed to be 5 km/sec. The dip of the surface was 3.65° and its strike was $N122.8^\circ E$. The maximum correction was 24 percent in apparent velocity and 30 percent in the direction of the azimuth. In determining the location of foci the following crustal structure was adopted: the V_p is 5.0 km/sec in the upper layer with the thickness of 3 km, the V_p are 6.0 km/sec in the layer from the depth of 3 to 15 km, and 6.6 km/sec in the layer from the depth of 15 to 30 km, respectively. The depth of the Mohorovicic discontinuity is 30 km and the V_p of the upper mantle is 8.0 km/sec (HASHIZUME *et al.*, 1968).

The location of the foci can be determined using the values of the apparent velocities, the azimuths of the direction of approach and the crustal structure described above. The distribution of the foci obtained by the tripartite station method is shown in Fig. 5. Most of earthquakes are situated on the northern side of site 1. The location of foci determined by this method is usually dependent on the assumed crustal structure; the error becomes bigger as S-P time becomes bigger. The foci of about 50 percent of the events, whose azimuths and apparent velocities had been determined, were left undetermined because of false values of the time of first arrivals. It may be necessary to compare the location of the foci determined by the tripartite station method with the result obtained by other methods because the tripartite station method may cause systematic errors. Unfortunately, during the observation period only one earthquake occurred whose focus could be determined with JMA network. The comparison of results by the two independent method is shown in Table 3.

The errors in the epicentral distance and the depth obtained by the tri-

Table 3. Location of the epicenter of the earthquake which was recorded by JMA network and by the present tripartite station simultaneously.

	Long. (E)	Lat. (N)	Depth (km)	Delta (km)	M	S-P Time (sec)
JMA	$142^\circ 21'$	$39^\circ 53'$	20	97	4.5	—
Tripartite	$142^\circ 11'$	$39^\circ 53'$	15	83	—	10.0

partite station method may be as big as 20 percent. If S-P time is smaller than 5 seconds, however, the error is probably smaller than 20 percent.

5.2 Location of foci by S-P method

As mentioned in the preceding paragraph, the speed of the recording paper of the back-pack seismometers is 25 mm/minute and this accuracy is not enough to determine the location of epicenter. In the present temporary network, however, more accurate seismometers are operated at some of sites and the S-P data obtained with the back-pack seismometers may be used for the determination of the foci together with the data obtained by the seismometers with magnetic tape recorders. Here, the mean velocity V_p and the Poisson's ratio in a semi-infinite crust are assumed to be 6.0 km/sec and 0.25, respectively. The number of events with S-P times less than 15 seconds recorded at 3 sites simultaneously was 28 and those recorded at 4 sites was 11, and those recorded at 5 sites was 8. Only one earthquake was recorded at six station during the period of the present microearthquake survey. The foci of 32 of 48 shocks were determined; 19 among the 32 are earthquakes occurring on the dipping seismic plane.

Fig. 5. Location of foci of microearthquakes. Big open circles denote earthquakes bigger than magnitude 7. The two epicenters in the Pacific Ocean connected by dotted line indicate the same event determined by the different methods (see text). The focal depth shallower than 30 km is indicated by the solid mark and the depth deeper than 30 km is indicated by the open mark.

The errors in locating epicenters are at least ± 10 km, when they are outside the network especially in the eastern side. The epicenters obtained by the S-P method and those determined by the tripartite station are shown with different marks in Fig. 5; solid symbols denote the shocks shallower than 30 km and open symbols denote deeper earthquakes. The characteristic features in the spatial distribution of foci in Fig. 5 are as follows:

1. Most of earthquakes occur on the eastern side of the longitudinal line of 141°E . As expected from S-P time distribution, there is a group of shallow shocks near site 10.

2. The shallow earthquakes generally occur around the Morioka-Shirakawa tectonic line.

3. There is also a group of earthquakes on the coast line, however, the area between these shocks and those on that tectonic line is aseismic; the sites 18 and 20 are located in this area.

4. The earthquakes beneath Kitakami mountains occur in the upper mantle.

These features, or the existence of shallow shocks around the tectonic line, the earthquakes on the dipping seismic plane and the aseismic area between these two groups of earthquakes are shown clearly in the east-west section in Fig. 6. These features in Fig. 6 are almost the same as the spatial distribution in the section in Fig. 8 which is determined by JMA based on the data from 1952 to 1967. It must be noticed that the microearthquake survey for two weeks gave the same results as the observation with the JMA network for 15 years.

Fig. 6. Section of the spatial distribution of microearthquake foci in the Tohoku area. M.S means the Morioka-Shirakawa tectonic line. Horizontal to vertical exaggeration is 1 : 2.2; topography being exaggerated.

The depth of the deep earthquake on the dipping seismic plane is about 80 to 90 km beneath the Morioka-Shirakawa tectonic line. There is an aseismic gap between the shallow shocks and these deep earthquakes can be realized in Fig. 6 and 8.

5.3 Swarm of earthquakes

Three swarms at least occurred in the region for the present microearthquake survey. The locations and other data of these swarms are listed in Table 4 and the locations are also shown on the map of Fig. 5. All of these three swarms were situated near the Morioka-Shirakawa tectonic line. During the present observation eight earthquakes with S-P times ranging from 2.5 to 5 seconds were recorded by the tripartite station within 9 hours from 20 o'clock on Nov. 20. The main earthquakes of this small swarm occurred within 4 hours from 22 o'clock to 2 o'clock on the next day; the depths of their foci were about 15 km and the two of them are listed in the Table 4. The location of this small swarm is very close or the same as the location of the earthquake swarm in August, 1933.

Table 4. Earthquake swarms in the northern part of Iwate prefecture.

Date	Location		Active period (months)	Maximum magnitude	Reference
1823 AUG	141.1°E	40.0°N	3	5.9 ¹⁾	USAMI (1966)
1933 AUG	141.2°E	40.5°N	3	IV ²⁾	KATO (1934), MATUZAWA (1964)
1968 MAY	141.2°E	40.2°N	0.5	3.5	HAMAGUCHI <i>et al.</i> (1970)
1967 NOV 10 22H 58M	141.38°E	40.04°N	4 hour		Present paper
1967 NOV 11 01H 09M	141.29°E	40.08°N			

¹⁾ The biggest shock ($M=5.9$) occurred on 23 October.

²⁾ Intensity: Rossi-Forel Scale.

The other microearthquakes shown in Fig. 5 also occurred near the location of these swarms; the seismicities around sites 10 and 2 were high. This leads to the conclusion that the sequence of earthquake activity has been continuous in this locality. The level of the seismicity in the northern area where these earthquake swarms occurred was not clearly determined because of the high noise level at sites 13 and 14. The seismic activity near sites 14 and 22 was fairly high probably because these sites are situated at the northern end of the Morioka-Shirakawa tectonic line.

5.4 Spatial distribution of foci determined by JMA

The foci of the earthquakes from 1952 to 1967 and earthquakes shallower than 50 km recorded with JMA network are shown in Fig. 7; most of them

Fig. 7. Foci of earthquakes shallower than 50 km determined by JMA during the period from 1952 and 1967.

are shallower than 40 km. The area of the map in Fig. 7 is wider than the area for the present microearthquake survey. The biggest earthquake occurred on 30 April, 1962 at $141^{\circ}08'E$, and $38^{\circ}44'N$ and its magnitude was 6.5; The 48 aftershocks which occurred in 1962 are excluded in Fig. 7. In the area between $141^{\circ}00'$ and $141^{\circ}10'E$, and $38^{\circ}40'$ and $38^{\circ}50'N$ earthquakes with magnitudes bigger than 3.5 had occurred; this sequence is quite similar to the microearthquake occurrence sequence around site 10.

The shallow earthquakes on this map may be divided into three groups. The one is the group of the earthquakes occurring on the Pacific coast; these are the earthquakes occurring on the shallow part of the dipping seismic plane as shown in the section in Fig. 8. The second group consists of earthquakes occurring around the line with direction from north to south and curving to southwestward at longitude $38^{\circ}50'N$. This seismic belt coincides with the Morioka-Shirakawa tectonic line and is situated east of the volcanic front. The third group is very shallow earthquakes close to active volcanoes and around the coast of Japan sea where shocks shallower than 20 km occur.

The section of the spatial distribution of foci from latitude $39^{\circ}N$ to $41^{\circ}N$ is shown in Fig. 8, where the Morioka-Shirakawa tectonic line is perpendicular to the sections. Events deeper than 50 km are also shown in this figure. These

Fig. 8. Section of the spatial distribution of foci from 39°N to 41°N determined by JMA during the period from 1952 to 1967. Horizontal to vertical exaggeration is the same in Figure 6.

foci were determined with the JMA network, but their spatial distribution is quite similar to the results of the present microearthquake survey. The section consists of three parts, shallow earthquakes around the Morioka-Shirakawa tectonic line, aseismic part of the crust under Kitakami mountains, and deep earthquakes occurring on the dipping seismic plane.

The seismic belt around the Morioka-Shirakawa tectonic line has not been so active and the number of foci determined by JMA is not enough for it to be realized as a seismic belt. Only seven earthquakes have been located in the surveyed area by JMA during the past 15 years. Through the analysis of the result of the present microearthquake survey, however, the existence of a seismically active belt is recognized, and the spatial distribution of seismicity obtained with JMA network goes well with the result of the present microearthquake survey.

6. Discussion and Conclusions

A map of the geological provinces in Tohoku area is shown in Fig. 9 (Geological Survey of Japan, 1968). In the east, there are Kitakami mountains which consist of Paleozoic deposits and tectonically stable, and the volcanic rocks in Early Miocene are distributed in the west; deposits of Neogene to

Fig. 9. Geological provinces in the Tohoku area (after Geological Survey of Japan, 1968).

1) Zone of Variscan geosynclinal deposits (late Carboniferous to Silurian), 2) Zone of Variscan geosynclinal deposits (Permian and upper Carboniferous), 3) Zone of Variscan geosynclinal deposits of late Carboniferous to middle Mesozoic, 4) Zone of early Miocene volcanism, mainly submarine, 5) Zone of Neogene folding, 6) Zone of deposits of Neogene to recent age.

Quaternary cover the narrow area between these two regions. The east boundary of these young deposits or the west boundary of the Kitakami mountains is very close to the Morioka-Shirakawa tectonic line. The western boundary of these young deposits is almost at the same location as the volcanic front (Fig. 1). The shallow earthquakes in Tohoku area are clearly distributed in the area covered by these young deposits (Figs. 7 and 9).

The area where the present microearthquake survey was carried out is a limited part of the Tohoku area including a part of the Morioka-Shirakawa tectonic line. Even in this limited area, however, the above-mentioned correspondence between the distribution of the geological province and the distribution of the seismicity is clearly shown. This region covered by the young deposits is called the Kitakami River Valley. Because of the existence of this valley the Tohoku area becomes a double arc (SUGIMURA and UYEDA, 1968). The outer arc is non-volcanic and the inner arc is volcanic.

The seismic belt along the Morioka-Shirakawa tectonic line is surrounded by these two arcs. The lowest part or the bottom of this seismic belt seems to be separated from the dipping seismic plane on which "deep" earthquakes are occurring. KATSUMATA and SYKES (1969) described about Izu-Bonin arc that the shallow earthquakes along the volcanic front merged into the dipping seismic plane. The precise seismicity, therefore, seems to differ with different arcs.

The present microearthquake survey, the observation with JMA network and the study of the historical records of big earthquakes lead to the conclusion that the part of the crust beneath Kitakami mountains is aseismic.

The conclusions of the present microearthquake survey of the Tohoku area are summarized as follows:

- a) Shallow microearthquakes occur in the zone between the western edge of Kitakami mountains and the volcanic front.
- b) The level of the activity of this microseismicity is low. Only 7 shocks in this narrow area have been recorded with the JMA network during the past 15 years.
- c) The seismic belt exists just on the Morioka-Shirakawa tectonic line.
- d) There are historical records of several earthquake swarms on this tectonic line.
- e) The part of the crust beneath Kitakami mountains bounded by the earthquakes occurring around the Morioka-Shirakawa tectonic line and those on the dipping seismic plane is aseismic.
- f) The level of the ground noise is several times as high on the average as the noise level in Nevada.

The cooperative research survey was directed by Prof. Toshi Asada, University of Tokyo and Prof. Jack Oliver, Columbia University. We would like to thank both of them for their advice and encouragement. We also thank Profs. Ziro Suzuki and Akio Takagi and Mr. Kiyohiko Yamamoto of Tohoku University for their valuable discussions and assistance in field programs. The authors acknowledge the close assistance in the field observations of Dr. T. Matumoto, Messers K. Yamamoto, A. Hasegawa, M. Kasahara and A. Yamamoto of Tohoku University, and Drs. T. Asada and H. Shimamura and Messers I. Furuya and Y. Okada of the University of Tokyo. Our thanks are also due to Profs. T. Asada and Z. Suzuki for their critical reading of the manuscript and their valuable suggestions.

This study was supported by the Japan Society for the Promotion of Science and the National Science Foundation.

REFERENCES

- ASADA, T. and Z. SUZUKI, On microearthquakes having accompanied aftershocks of the Hukui earthquake of June 28, 1948, *Geophys. Notes*, **2**, 1-14, 1949.
- ASADA, T. and Z. SUZUKI, On microearthquakes observed after the Imaichi earthquake; Dec. 26, 1949, *Bull. Earthq. Res. Inst.*, **28**, 415-420, 1951.

- ASADA, T., Observations of near-by microearthquakes with ultra sensitive seismometers, *J. Phys. Earth*, **5**, 83-113, 1957.
- ASADA, T., S. SUYEHIRO and K. AKAMATU, Observations of near-by microearthquakes with ultra sensitive seismometers at Matsushiro, Japan, *J. Phys. Earth*, **6**, 23-33, 1958.
- Geological Survey of Japan, Tectonic map of Japan, II Geological provinces, 1 : 2,000,000 map series, No. 12, 1968.
- HAMAGUCHI, H., A. HASEGAWA and M. KASAHARA, Microearthquake activity excited by the Tokachi-oki earthquake of 1968, *Zisin Ser. II*, **23**, 72-81, 1970 (in Japanese).
- HASHIZUME, M., K. OIKE, S. ASANO, H. HAMAGUCHI, A. OKADA, S. MURAUCHI, E. SHIMA and M. NOGOSHI, Crustal structure in the profile across the northeastern part of Honshu, Japan, as derived from explosion seismic observation. Part 2. Crustal structure, *Bull. Earthq. Res. Inst.*, **46**, 607-630, 1968.
- KATO, Y., Investigation of the changes in the earth's magnetic field accompanying the earthquake or volcanic eruption (continued), *Zisin*, **6**, 54-62, 1934 (in Japanese).
- KATSUMATA, M. and L. R. SYKES, Seismicity and tectonics of the western Pacific: Izu-Mariana-Caroline and Ryukyu-Taiwan regions, *J. Geophys. Res.*, **74**, 5923-5948, 1969.
- KISHIMOTO, Y., M. HASHIZUME, K. OIKE and K. MINO, Some properties of microearthquakes in the western part of Kinki district, *Special Contrib. of Geophys. Inst. Kyoto Univ.*, No. 4, 51-62, 1964.
- MARUYAMA, T., Slope corrections in tripartite net observation, *Bull. Earthq. Res. Inst.*, **43**, 409-420, 1965.
- MATUZAWA, T., *Study of Earthquakes*, Uno Shoten, Tokyo, p. 66, 1964.
- MURAMATSU, I., Y. ENDO, H. SIMONO, H. KOKETU and S. SUZUKI, Observation of micro-earthquakes in Mino district in Gifu prefecture, central Japan, *J. Phys. Earth*, **11**, 35-48, 1963.
- OLIVER, J., A. RYALL, J. N. BRUNE and D. S. SLEMMONS, Microearthquake activity recorded by portable seismograph of high sensitivity, *Bull. Seis. Soc. Amer.*, **56**, 899-924, 1966.
- SUGIMURA, A. and S. UYEDA, Island arc, II, *Kagaku (Science)*, **38**, 138-145, 1968, in Japanese.
- TAKANO, K., H. HAMAGUCHI and H. WATANABE, Aftershock observation of a Southeastern Nevada Earthquake at Caliente, *J. Phys. Earth*, **20**, 409-415, 1972.
- TSUBOI, C., A. JITSUKAWA and H. TAJIMA, Gravity survey along the lines of precise levels throughout Japan by means of a Worden gravimeter. Part VII. Tohoku district, *Bull. Earthq. Res. Inst.*, Suppl. Vol. 4, part VI, 312-406, 1956.
- USAMI, T., Descriptive table of major earthquakes in and near Japan which were accompanied by damages, *Bull. Earthq. Res. Inst.*, **44**, 1571-1622, 1966.
- UYEDA, S. and K. HORAI, Terrestrial heat flow in Japan, *J. Geophys. Res.*, **69**, 2121-2142, 1964.
- WARD, P. L., G. PALMASON and C. DRAKE, Microearthquake survey and the Mid-Atlantic ridge in Iceland, *J. Geophys. Res.*, **74**, 665-684, 1969.
- WATANABE, H. and A. KUROISO, Some properties of microearthquakes in the west of Kii peninsula, central Honshu, Japan, *Zisin Ser. II*, **20**, 180-191, 1967 (in Japanese).