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25. *Earthquake Swarm Activity in the Northern Tokyo Bay.*

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Abstract

An earthquake swarm sequence occurring in the northern Tokyo Bay during the period from July 11 to August 3, 1979, was studied on the basis of the waveform analysis. The sequence was monitored by the magnetic-tape recording system consisting of six stations distributed around the swarm area. The seismograms obtained at each station exhibit similar waveforms belonging to an earthquake family. The precise epicenters of the 16 earthquakes determined, using the detailed differences of *S-P* times, show a very small focal region of about 400 meters in dimension, including four groups where the locations between the events are separated by, at most, few ten meters. Within the focal regions, a SE-NW trend was observed with events apparently migrating up and then back down. The source spectra obtained from *S* waves at two stations show identical forms having similar corner frequency, and the linear dimension estimated from the corner frequency is constant with a value of about 200 meters for the earthquakes with magnitudes of 1.8 to 3.0. Considering the epicentral area and the source dimension, it is expected that the earthquake swarm occurred over the same fault as a repeated slipping, especially the events locate within few ten meters occurred as the earthquakes of a stick-slip type.

Introduction

It is well known that large shallow earthquakes frequently accompany foreshocks. JONES and MOLNAR (1976) studied the frequency of foreshocks using the world-wide data from 1950 to 1973, and pointed out that 44% of large shallow earthquakes ($M>7.0$) accompanied foreshocks. Recent observations with high magnification seismograph will be expected to detect foreshocks at a much higher rate. In fact, many small foreshocks were observed even in the moderate-size earthquakes ($M\leqq5.5$)

that occurred in the eastern Yamanashi Prefecture (UCHIIKE and ICHIKAWA, 1976), Kawazu area of Izu Peninsula (TSUMURA *et al.*, 1977), and off the cape of Erimo, Hokkaido (SUZUKI, 1979).

On the other hand, it is also well known that there are earthquake swarms which are not accompanied by a major earthquake. When seismic activity is increasing in a certain region, it is very important to discriminate whether these earthquakes are foreshocks preceding a large earthquake or are earthquake swarms without a major earthquake. If a method for discriminating these two activities is found out, it will be important for earthquake prediction. In some cases, special spectral features associated with foreshocks in certain regions were found (FEDOTOV *et al.*, 1972; TSUJIURA, 1977; ISHIDA and KANAMORI, 1980). The discrimination by the spectral method, however, seems to be difficult in the case of the 1978 Izu-Oshima-kinkai earthquake (TSUJIURA, 1978b). The difficulty of discrimination by the spectral method is also reported for the 1966 Parkfield and the 1975 Oroville earthquakes (BAKUN and MCEVILLY, 1979).

In order to avoid such difficulty, we studied the nature of earthquake swarm by analyzing the waveform. This analysis pointed out some interesting features which differ from the other seismic activities. One of the most striking features in the swarm activity was that the earthquakes generated in a given time interval consist of those with similar waveforms (TSUJIURA, 1979a), belonging to the so-called "earthquake family" (HAMAGUCHI and HASEGAWA, 1975). Such a behavior differs clearly from that of the foreshock activity (TSUJIURA, 1979b). Similar behavior indicating an earthquake family was found in the other swarm activities (SATO *et al.*, 1979; OKADA *et al.*, 1980; TSUKUDA, 1980).

Recently, the earthquake swarm occurred in the northern part of Tokyo Bay. Tokyo Bay is located in the middle of our seismological net. Fortunately, the observation by the magnetic tape recording system with sensitive magnification has continued since April of 1979. The analysis of waveform using the tape therefore will give us the detailed information related to the nature of earthquake swarm. We shall show that spectral features of seismic waves differ significantly from those of normal seismic activity.

Data

Since July 11 of 1979, many earthquakes occurred in the northern part of Tokyo Bay, and their activities continued for about one month,

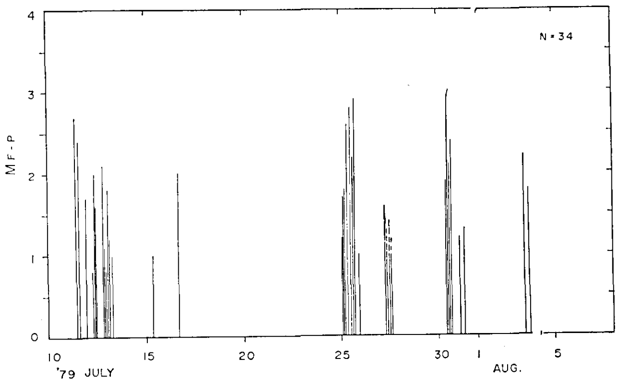

Fig. 1. Temporal distribution of earthquakes in the sequence.

repeating an irregular sequence. Figure 1 shows the time sequence of earthquakes located within an area of N. Tokyo Bay taken from the monthly lists of epicenter currently determined at Earthquake Research Institute (ERI). The 34 earthquakes with magnitudes between 1 and 3 are found in the sequence. As inferred from the background seismicity and the character of the activity, this sequence is of the swarm type.

The observation by the magnetic tape recording system using short-period seismographs has been carried out since April, 1979. The output of the short-period seismographs telemetered from nine stations have been recording continuously on a 14-channel tape recorder. Detailed description of the recording system will be given in a separate paper (TAKAHASHI, in preparation). Figure 2 shows the distribution of the seismic stations used in this study and the epicentral locations of earthquakes taken from the lists of epicenter determination of ERI. Our stations surround the swarm area with roughly equal distance (50–80 km). The data from magnetic tape therefore are very useful for the analysis of waveform. Sixteen earthquakes with moderate amplitudes on magnetic tape were finally selected they cover the magnitude range from 1.8 to 3.0. These earthquakes are indicated by closed circles on the same figure (B).

In the previous studies of this series (TSUJIURA, 1979a, 1979b), we pointed out that the seismograms of the earthquake swarm for a given time interval (e. g., one hour) consist of events with similar waveform which differ clearly from those of the other activities. In order to check the facts described above, we first studied the similarity of waveform, using the seismograms recorded at a high paper speed, and later we conducted a spectral analysis using the data of narrow band-pass filters

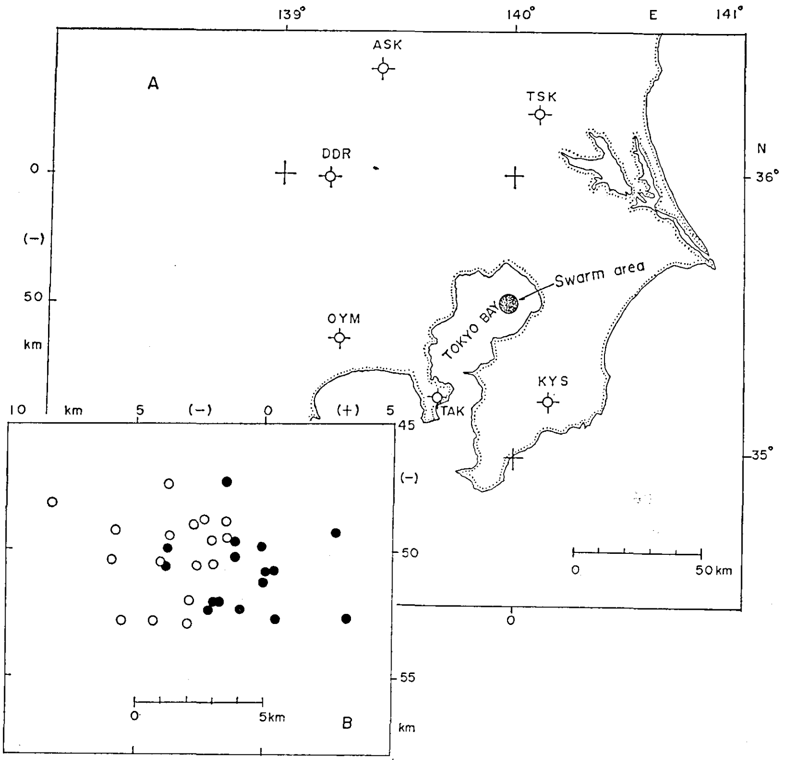

Fig. 2. Distribution of seismological stations used in this study (A), and epicentral locations of the earthquakes taken from the monthly lists of ERI (B).

operating routinely (TSUJIURA, 1978a) in order to determine the source parameter of their earthquakes.

Similarity of waveform

For the analysis of waveform, the seismograms are produced at a paper speed of 50 mm/sec for six stations, and visual examination of the waveform is made on the seismograms of each station. Figure 3 shows the arrangement of the seismograms, obtained by the vertical component (Z) at Kiyosumi station (KYS). The amplitude of each event is adjusted to take a similar size by changing the gain of the play-back amplifier. The relative differences of the gain are shown at the end of the seismogram by the error bars. Although the absolute amplitudes are diffrent by a factor of more than 10, similarity of waveforms are apparent between the seismograms, especially in the peaks and troughs of the P and S-wave groups which coincide throughout the swarm sequence. The ear-

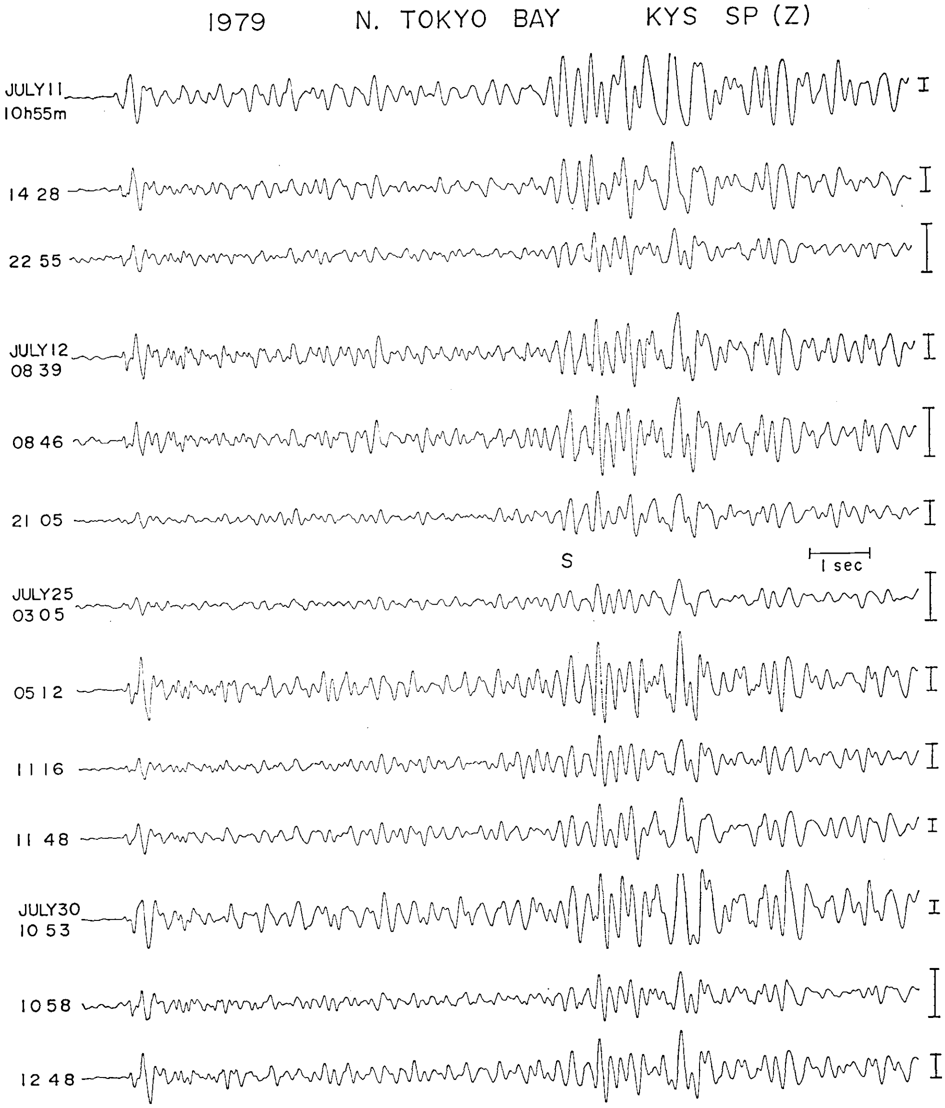

Fig. 3. An arrangement of seismograms observed by short-period vertical component (Z) at Kiyosumi station (KYS). The magnitudes of these events lie between 1.8 and 3.0. Note the high correlation of the corresponding traces between the seismograms.

thquakes with similar waveform, of course, have a similar *S–P* times. In fact, we found that the *S–P* times of these earthquakes differ no more than by 0.06 sec.

Figure 4 shows the seismograms of the same events obtained by the horizontal component (E–W) at Tsukuba station (TSK). Although the

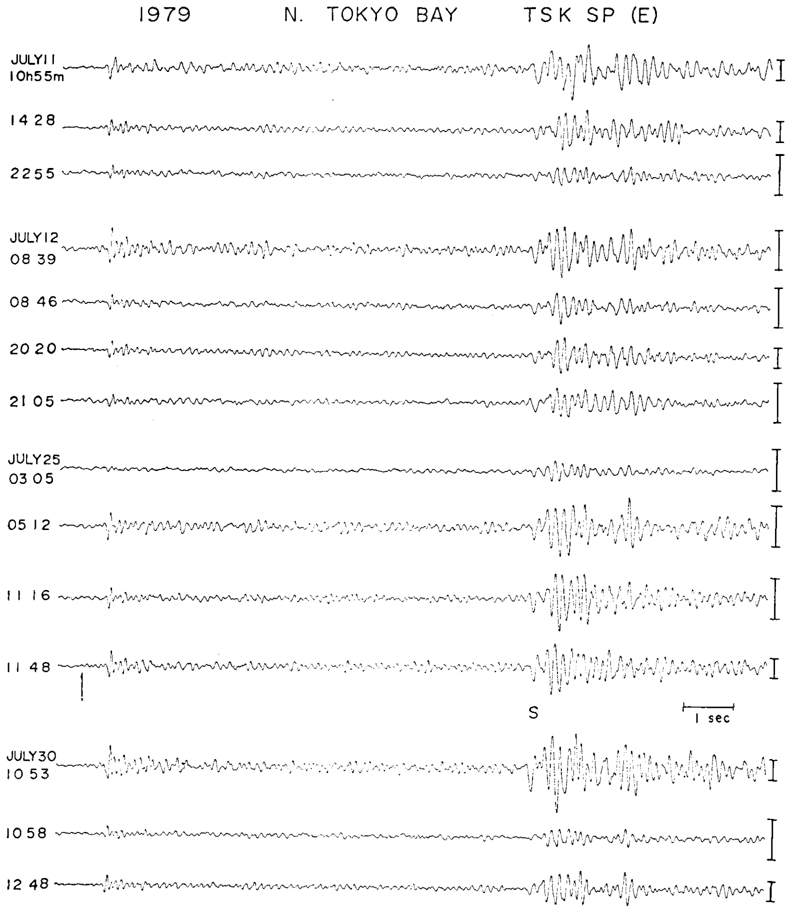

Fig. 4. The seismograms for the same events presented in Fig. 3 obtained at Tsukuba station (TSK).

waveforms of *S*-coda are somewhat different for some events (05 h 12 m, 10 h 58 m, 12 h 48 m), similar waveforms are seen between the seismograms of *P* and *S*-wave groups. The relative difference of *S–P* times is also similar to that obtained in KYS. Similar results for the seismograms were obtained for the other four stations although not shown here. Despite of our uncertain criterion of the discrimination, there exists a clear difference for the similarity of waveforms when these seismograms are compared with the normal seismic activity as will be discussed later. Thus, we may conclude that the present earthquake swarm is also consisted by events with similar waveforms, called earthquake family. Especially, the concentration of *S–P* times within a range of 0.06 sec suggests that the distance between the events cannot be as large as that shown in Fig. 2, which was taken from the monthly bulletin of ERI.

Epicentral location

In view of the observed time difference of *S–P* at our stations, the epicentral area determined by the conventional method seems to be too large. In order to obtain the precise location of the epicenter, we measured the detailed difference of *S–P* times using the seismograms recorded at a paper speed of 50 mm/sec, and the seismograms passing through the band-pass filters, when they have different spectra. Although the initial motion of *P*-wave onset for small events is somewhat uncertain, as shown in the previous figures, some wavelets of *P*-wave group are clearly identified. If we correlate these traces among different seismograms, detailed differences of the *S–P* time can be obtained by the superposition of the seismograms (TSUJIURA, 1979a). In such procedure, however, we must consider an earthquake in which relative *S–P* times are measured. The earthquake of 14 h 28 m, July 11, was selected because it was large enough to measure the *S–P* time. Figure 5 shows an example of the superposition of the seismograms for the referenced earthquake (solid line) and the event of July 25 (dashed line) obtained at two stations. The peaks and troughs for the corresponding traces closely coincides with the seismograms at each station. The relative difference of the *S–P* time therefore can be obtained from the time difference of *P*-wave group when the seismograms of *S*-waves are fixed to agree closely with each other.

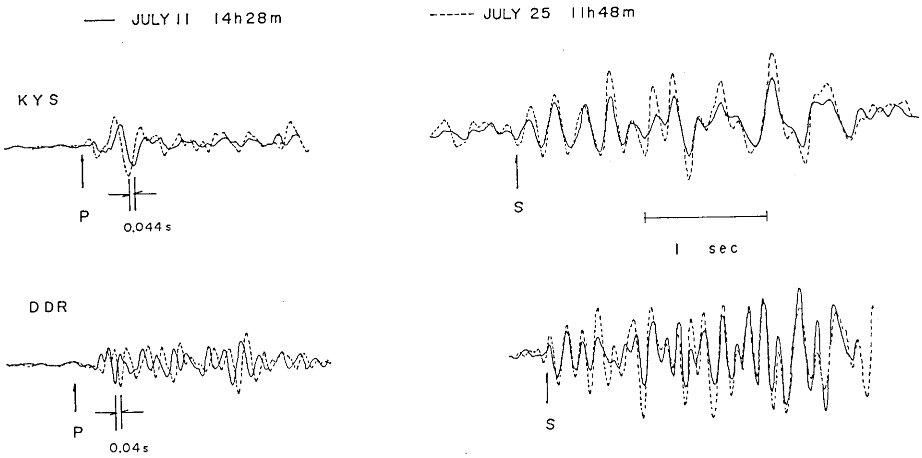

Fig. 5. Superposition of the seismograms for two earthquakes obtained at KYS and DDR. Note small differences of the $S-P$ time for both stations.

Table 1. Distribution of the relative differences of $S-P$ time (Δt_{S-P}) against the reference earthquake (No. 2). The origin time and magnitude (M) are taken from the monthly list of ERI, and M_J is taken from the list of earthquakes published by the Japan Meteorological Agency.

No.	Date	Time			M	M_J	Δt_{S-P}			sec	
		h	m	s			KYS	DDR	TSK	TAK	OYM
1	July 11	10	55	54.4	2.7	2.9	0.008	−0.01	0	0.01	0
2		14	28	45.1	2.4	—	0	0	0	0	0
3		22	55	15.3	1.8	—	0.01	−0.012	−0.024	0.016	0
4	July 12	08	39	11.3	2.0	—	0.012	−0.02	−0.024	0.024	−0.01
5		08	46	39.0	1.9	—	0.012	−0.02	−0.02	0.02	−0.01
6		20	20	01.6	2.1	—	0.036	−0.03	−0.024	0.024	−0.014
7		21	05	03.0	1.8	—	0.036	−0.032	−0.028	0.02	−0.014
8	July 16	17	55	11.6	2.0	—	−0.01	0.008	—	—	—
9	July 25	03	05	08.6	1.8	—	−0.04	—	−0.04	—	—
10		05	12	28.1	2.6	2.8	−0.01	0.016	−0.01	0.018	0.018
11		11	16	23.9	2.2	2.5	0.044	−0.04	−0.04	0.03	−0.01
12		11	48	10.7	2.9	3.0	0.044	−0.04	−0.044	0.034	−0.01
13	July 30	10	53	51.0	3.0	3.3	0.05	—	−0.046	0.028	0.014
14		10	58	44.1	2.1	—	0	—	−0.01	0.018	0.018
15		12	48	28.7	2.4	2.7	0	—	−0.01	0.016	0.016
16	Aug. 3	08	58	39.7	2.2	—	0	0.02	−0.038	0.044	0.044

Table 1 shows the distribution of the relative differences of *S*-*P* time obtained from such procedure. It can be found that the deviation of *S*-*P* time falls within a range of 0.06 sec, indicating the systematic differences in each station. Considering the station arrangement, such a behavior suggests the migration of the epicenter within a small area.

Further examination of the difference of *S*-*P* time in Table 1 shows the existence of the event groups with closer *S*-*P* time. We found four groups, in which each group has the same *S*-*P* time within 0.01 sec at all stations. Figure 6 shows a typical example of the seismograms belonging to one event group with *S*-*P* time closer than 0.01 sec. The similarity of waveforms for the event pair is clearly demonstrated from *P*-wave onset until the coda waves, and the *S*-*P* times coincide well within 0.01 sec which is the measurement error of our determination. Similar *S*-*P* times of events are expected to correspond to a similar arrival time of *P* waves. Figure 7 shows the arrangement of the seismograms of *P*-wave group based on KYS. Although the initial motion of *P* waves is somewhat uncertain, similar arrival times for some wavelets of *P*-waves can be seen for the seismogram pair at each station.

Let us come return to Table 1 to obtain the detailed difference of

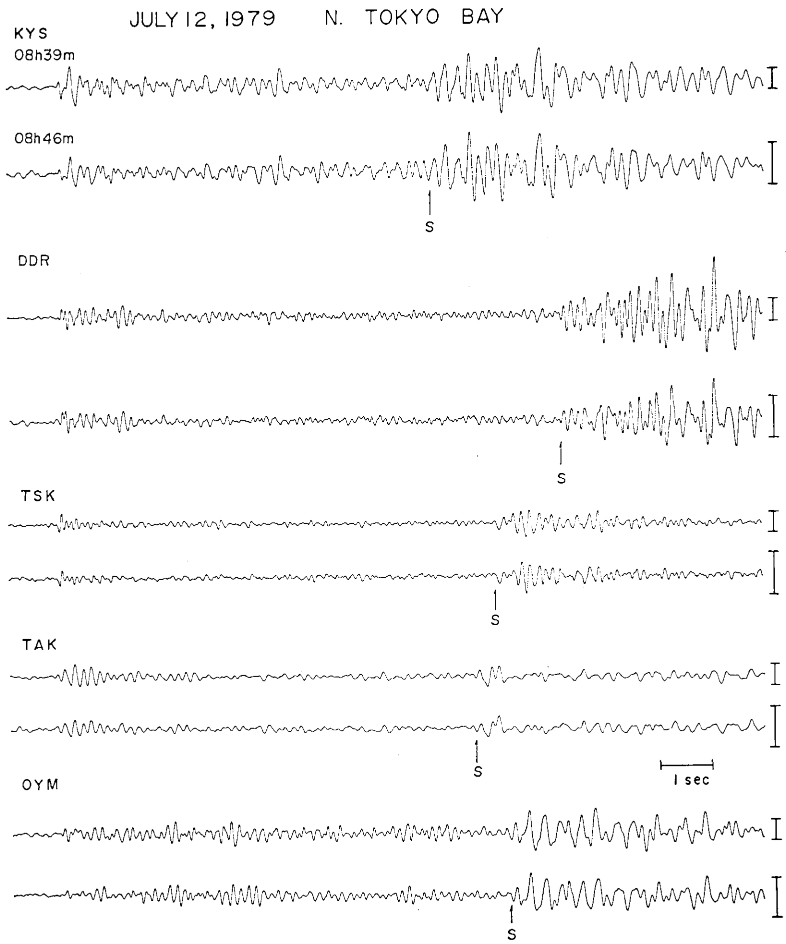

Fig. 6. Examples of the seismograms for the event pair with exact agreement of the waveform at each station.

epicentral locations. However, for this method, at least the epicenter of one earthquake (reference earthquake) must be determined by the usual method. Once the epicenter of reference earthquake is determined, the epicenter of the other events can be obtained from the relative differences of *S–P* times. The re-examined epicenter of reference earthquake using the travel time is as follows

Origin Time	Latitude	Longitude	Depth
14 h 28 m 45.5s	35°31.9′N	139°58.9′E	47.8 km

Figure 8 shows the method used to determine the relative location using the data of three stations. The marks *T*, *K*, and *O* denote the

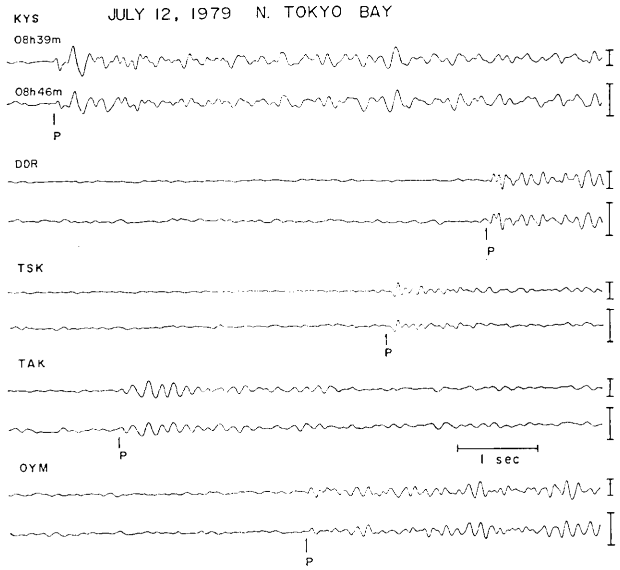

Fig. 7. Examples of the seismograms for the event pair with similar arrival times at each station.

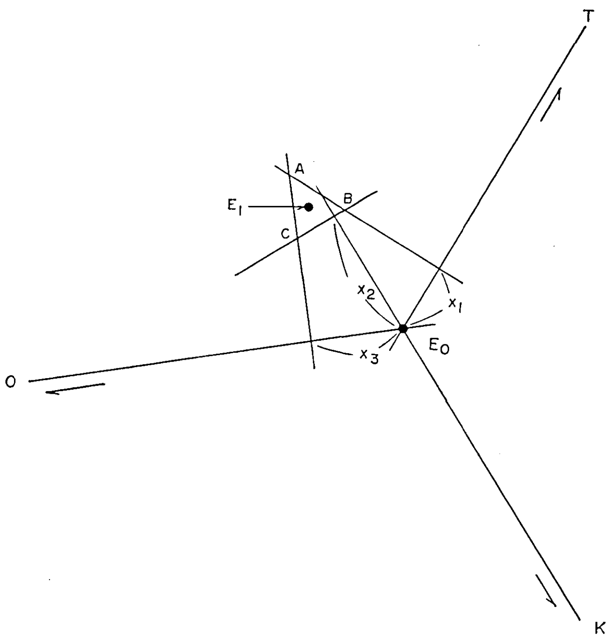

Fig. 8. The method of determining the relative epicenter using the detailed differences of $S-P$ time (Δt_{S-P}) of three stations. E_0: epicenter of reference earthquake, x: distance determined by $\Delta t_{S-P}k$, where k is the Omori constant.

azimuth of far-field station against the epicenter of reference earthquake (E_0), and the x shows the distance determined from the $\Delta t_{s-p}\, k$, where k is the Omori constant. If the distance x for three stations are given by x_1, x_2, and x_3 the epicenter of second event may lie in the area enclosed by A, B, and C. If the values of our reading and the location of E_0 are accurate and if the Omori constant is appropriate, the area of A, B, and C must concentrate to a point. In our case, however, the area of A, B, and C usually takes the form of a triangle with a length of 50–100 meters, and in such a case, the epicenter of second event is taken at the center of the triangle (E_1).

Figure 9 shows the relative location of epicenters against the reference earthquake (14 h 28 m of July 11) determined by using the data of five stations listed in Table 1 and assuming a value of k=8 km/sec. Numerals attached to the circles correspond to the number listed in Table 1, closed circle with cross mark shows the epicenter of reference earthquake (No. 2) and the epicenters inside the dotted circles show the events with S–P times closer than 0.01 sec, showing an exact agreement of waveform (see Fig. 6). Two earthquakes, numbers 8 and 9, are not plotted because the location were not considered to be of similar accuracy, owing to the poor signal-to-noise ratio. As seen in this figure, the epi-

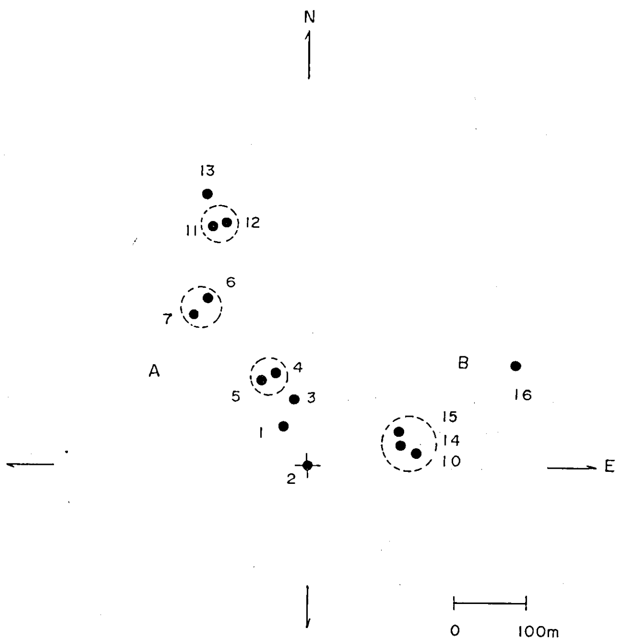

Fig. 9. Relative epicentral locations against the reference earthquake (No. 2), numbered chronologically.

centers are distributed divided into two groups, one consisting of events with a nearly linear trend (A), and the other concentrating on a small area (B). The separation of the groups A and B can be identified also by the difference of waveforms at TSK (see Figure 4). Although our estimation of the epicenter has the error of 50-100 meters, the pattern of the epicenters for the sequence exhibit some interesting features. For example, the earthquake occurs first in the south-east end of this series and its activity migrates mainly to the north-west direction with a length of about 400 meters, terminated by the event No. 13. After that, the activity returns to the initial focal area. Considering the similarity of waveforms and the linear arrangement of the epicenters, the events belong to the group A must have occurred along the same fault plane slipping repeatedly. Especially as inferred from the exact agreement of the waveforms at six stations, the events inside dotted circles must have occurred along the same fault in the manner of a stick-slip. This subject will be discussed further in a later section dealing with the results of spectral analysis.

Spectral analysis

In order to obtain the source parameter of earthquake swarm, spectral analysis for S waves is made, using the records of band-pass filters operating routinely. Examples of the filtered records of six earthquakes obtained at TSK is shown in Fig. 10. The analysis is the same as those for our previous studies (e. g., TSUJIURA, 1978a). The maximum amplitudes (peak-to-peak) for S waves were measured directly on the six band filtered traces. Following AKI and CHOUET (1975), the spectral density from the records of band-pass filters is given as

$$f_m = 2(2F\Delta f)$$

where F is a spectral density and Δf is a bandwidth for a given channel. From the known bandwidth of the bandpass filter and the maximum amplitude for the S waves measured on each frequency, the amplitude spectral density is estimated.

In order to correct the effects of attenuation, spectral amplitudes $F(\omega)$ are multiplied by an exponential term $\exp(-\pi ft/Q_\beta)$, where t is the travel time of S wave, f is the frequency, and Q_β is the quality factor. Figure 11 shows the source spectrum obtained from the data of TSK, assuming values of $Q_\beta=600$ (TSUJIURA, 1978a) and $t=22.6$ sec.

Since our data are the output of band-pass filters, the long-period spectral level (Ω_0) and the corner frequency (f_c) are approximated by

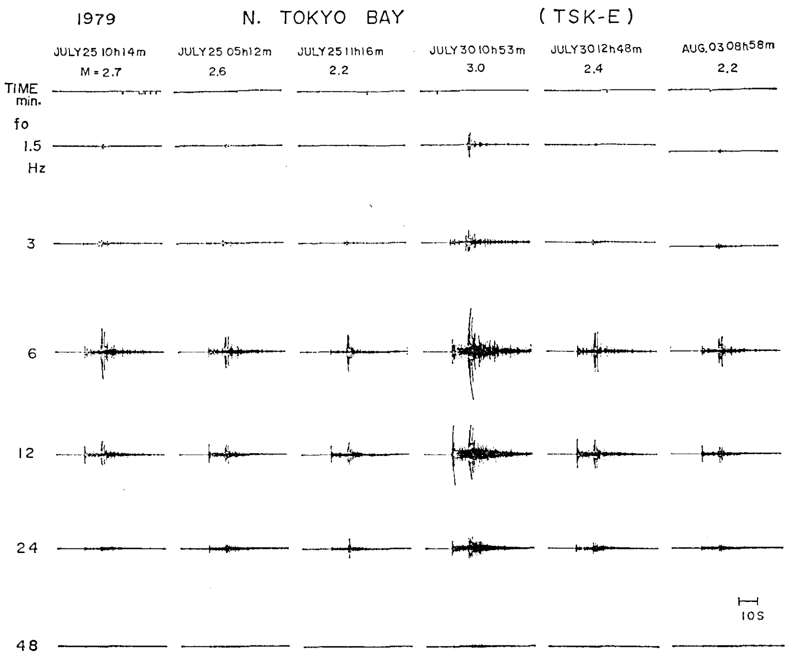

Fig. 10. Examples of the filtered seismograms. f_0: center frequency of the band-pass filter with one octave bandwidth. Note similar spectra except the amplitude of 24 Hz.

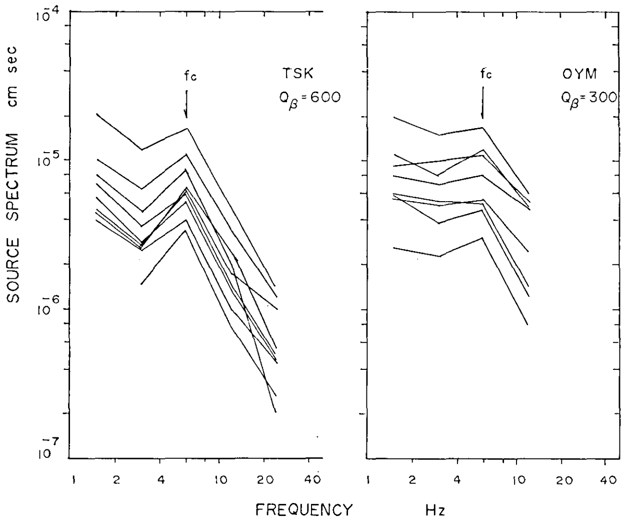

Fig. 11. Examples of the source spectra of S waves obtained at TSK and OYM.

fitting the spectra in two straight lines intersecting at the corner frequency. The approximate corner frequency is indicated by an arrow. The corner frequency obtained here shows the same value, independent of the absolute values of amplitudes, with minor differences in the shape of high frequency component.

In order to check the source spectrum at TSK, the data from OYM equipped with the same filtering system may be used. The source spectra for the same events at TSK, including some smaller events, are shown in Fig. 11. In obtaining the source spectrum, a value of Q_β 300 is assumed as a correction of attenuation (TSUJIURA, 1979a). The spectra of some events commonly obtained with adequate amplitudes at two stations are examined in order to check the adequacy of the choice of Q values. They show nearly the same corner frequency, except the difference of fall-off character of high frequency. From the results obtained above, we may conclude that the corner frequency of the earthquake swarm is nearly constant for the events with magnitudes of 1.8 to 3.0. Such a behavior is consistent with the result of the other swarm activity (TSUJIURA, 1979a).

Using the circular crack model of MADARIAGA (1976), who gives the relation of $f_c = 0.21\,\beta/a$, we estimated the fault radius (a) corresponding to the corner frequency (f_c), assuming $\beta = 3.5$ km/sec, and found a radius of 120 meters, independent of the events with magnitudes of 1.8 to 3.0.

From each flat low-frequency level (Ω_0), we determined the corresponding seismic moment (M_0) by using Brune's model (BRUNE, 1970), assuming the values adopted by TSUJIURA (1979a). The result shows the seismic moment of, on the average, 2×10^{19} dyne cm for $M=1.8$ and 3×10^{20} dyne cm for $M=3$ earthquakes, respectively. Using M_0 and a obtained above, a value of stress drop ($\Delta\sigma$) is determined by using Brune's formula. We found the values of 80 bars for $M3$ and 5 bars for $M1.8$ earthquakes, respectively. It is noted that the stress drop is linearly proportional to the earthquake size for some limited magnitude range.

Earthquake family in the normal activity

From the analysis of waveform, it is confirmed that the earthquake swarm in the northern Tokyo Bay consists of earthquakes with similar waveforms. In order to distinguish the swarm activity from the other activity, it is important to know the nature of the normal seismic activity (background seismicity). For this purpose, we studied the waveforms in terms of similarities, using the data of OYM where the seismogram was

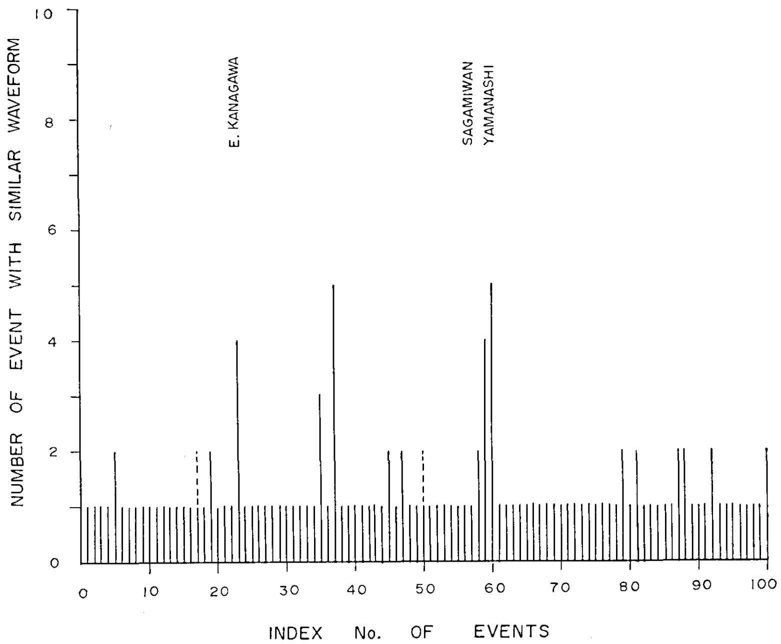

Fig. 12. Distribution of the earthquakes with similar waveforms in the normal seismic activity observed at OYM during the period January, 1979, to April, 1980.

recording at a paper speed of 25 mm/sec in a trigger mode (TSUJIURA, 1979a).

One hundred local earthquakes ($S-P\leqq 6$ sec) with different waveform occurred during the period January to November, 1979, were selected as the reference earthquakes, and examined the existence of events with similar waveforms against the reference earthquakes. Figure 12 shows the distribution of the events with similar waveforms for the 100 reference earthquakes selected from 180 earthquakes occurring during the period January, 1979, to April, 1980. It is obvious that the rate of occurrence of earthquake family is very low compared with the present earthquake swarm. Some event groups with relatively large number of similar earthquakes (Nos. 23, 59, 60) are the earthquakes in areas where swarm activity occurs repeatedly. Although the number of events and the observation period are not enough, we may conclude that the rate of occurrence of earthquake family is very low in the normal seismic activity.

Discussion

Through the analysis of waveform and spectrum, we found the salient features for the mechanism of swarm activity. They are sixteen earthquakes with the source of linear dimension of 200 meters distributed within a linear trend of length of about 400 meters, including some events separated from each at most by few ten meters. Considering the source size and the swarm area, it is expected that they are occurring over the same fault plane slipping repeatedly, especially those events separated by a few ten meters (events within dotted circles in Fig. 9) are occurring over the same fault as a stick-slip type. It is rather difficult to imagine that many earthquakes occur independently on the different fault within an area of 400 meters. Such a behavior as slipping repeatedly on the same fault is reported in the earthquake swarm of another area (TSUKUDA, 1980). Our observation can be understood with the aid of a new earthquake model called "barrier model," proposed by DAS and AKI (1977). The migration of earthquake clusters from A to B may be due to successive stress concentration at barriers distributed on the fault as slipping proceeds from A to B (see Figure 9).

MOGI (1963) distinguished three types of earthquake pattern, and the seismic activity with no specially large earthquake is called the "earthquake swarm". The reason there is no specially large earthquake is partly due to the limited available stress drop. Our observation of the earthquake swarm showed a similar waveform maintaining a constant corner frequency in the source spectrum. This evidence suggests that the stress drop of the earthquake swarm is proportional to the earthquake magnitude. Our estimation of the stress drop shows about 5 bars for $M1.8$ earthquake and 80 bars for $M3$ earthquake, respectively. If the $M4$ earthquake does occur, the stress drop may take a value of about 1 kbars. Such a value will be too large as the stress drop of $M4$ earthquake. In other words, if the stress drop of $M4$ earthquake assumes a lower value, the similarity of the waveform will be diminished, and our assumption that the earthquake swarm in a given area shows a similar waveform must be changed. Further discussion of this problem will be given in a separate paper (in preparation).

Conclusion

The earthquake swarm activity in the northern part of Tokyo Bay was studied, using data recorded on magnetic tape of six stations distributed around the swarm area. The sixteen earthquakes with magnitudes between 1.8 and 3.0 are the basis of the present study.

The spectral features differ significantly from those of the other seismic activities. The earthquakes observed at each station show similar waveforms through the swarm sequence. From the superposition of the seismograms, the detailed differences of the *S-P* times are measured for each station. The selected epicentral locations, using these values, show a very small focal region of about 400 meters in dimension, including four event groups where the locations between the events are separated by a few ten meters at most. Within the focal region, a SE-NW trend was observed with events apparently migrating to NW and then back to SE.

The source spectrum of 16 earthquakes showed indentical forms with similar corner frequency, and the linear dimension estimated from the corner frequency is constant, independent of magnitude with the value of about 200 meters. Considering the epicentral area and the source dimension, it is expected that the earthquakes occurred over the same fault plane as repeated slidings, especially the events located within few ten meters occurred as the earthquakes of a stick-slip type.

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25. 東京湾北部の群発地震活動について

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1979年7月11日より8月3日にかけ，東京湾北部で発生した群発地震について，地震波の波形解析を行ない，その活動様式についていくつかの特徴ある結果を得た．主な結果は次の通りである．

(1)　合計34個の震源決定された地震のうち，$M \geqq 1.8$ の地震16個の波形について調べた結果，1978年の伊豆半島北部で発生した群発地震と同様に，今回の地震も例外なく相似地震によって構成されていることが解った．

(2)　早送り記録 (50 mm/sec) の重ね合わせから得た $S-P$ 時間の違いから震源を決めた結果，夫々の地震は略 400 m の範囲内に分布し，更に時間の経過と共に，SE−NW 方向への移動がみられた．

(3)　S 波についてのスペクトル解析から求めた Corner frequency は $M=1.8-3.0$ の間で略一定であり，Corner frequency から求めた震源の大きさは約 200 m の値を示す．

震源分布，及びそれらの地震の震源の大きさを考慮すると，これらの地震はおそらく同じ断層面上で繰返し発生し，特に約 50m の範囲内に分布する4組の地震群は同じ断層面上で Stick-slip 型の地震として発生したものと推定される．