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2. *Westward Movement of the Seismic Activity Associated with the Earthquake of July 23, 1982 off Ibaraki Prefecture, Northeastern Honshu, Japan.*

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Abstract

The earthquake of July 23, 1982 (M 7.0) off Ibaraki Prefecture, Northeastern Honshu was accompanied by remarkable foreshock and aftershock activities after the quiet period of seismicity for about 16.5 years since 1966. Three earthquake provinces were specified in the trench side, the transitional and the coastal zones through a systematic westward movement of the aftershock activity.

In the earlier stage of the movement, a seismic activity of a shallow focal depth of less than 30 km took place in the trench side province including major quakes of M 5.9~6.2. An aseismic area of 30~40 km in length, a possible locked portion on the plate boundary, separated the trench side province from the transitional one, where both shallow and the pronounced double-planed deeper origin earthquakes were observed. In the succeeding stage of the westward movement, the seismic activity in the coastal province seemed to be slightly strengthened on the double-planed seismic zone. A penetration of seismic activity as deep as 60~80 km in the east coast of Ibaraki Prefecture was observed coupled with the occurrence of the earthquake of February 27, 1983 (M 6.0) in the south of Ibaraki Prefecture. It can be suggested from these evidences that the westward movement of the aftershock activity were closely related to regional effects of the subduction of the Pacific plate off and in the coast of and in the southern part of Ibaraki Prefecture.

1. Introduction

Based on a preliminary survey of the activity of large earthquakes ($M \geq 6.0$) off the Pacific coast of Japan, UTSU (1974-a) classified seismic regions into several types according to the pattern of earthquake occurrence in space, time and magnitude. He proposed a division of the seismic zone off Ibaraki Prefecture as represented by the two zones, one on the coastal side and the other on the trench side. The former is characterized by large earthqakes of M up to about 7.5 tending to occur in swarms and the latter by a sporadical occurrence of large earthquakes.

A continuation of a quiet seismicity off Ibaraki Prefecture since 1966 was noted by KATO *et al.* (1981) from statistical studies of the rate of earthquake occurrence. UTSU (1980) pointed out the predominant tendency of high frequency earthquake occurrence during the last ten years. NOGUCHI (1982) suggested an increase of stress level in the region on the basis of the results obtained by UTSU (1980). It can be understood in this connection that the earthquake off Ibaraki Prefecture of July 23, 1982 marked a new stage of seismic activity for the release of the strain energy accumulated in the preceding quiescent period since 1966.

The high magnification seismographic network in the Kanto district operated by E. R. I. (Earthquake Research Institute, Tokyo University) detected a microearthquake activity a few months before the occurrence of the main shock on July 23. The activity was followed by a sequence of the foreshocks, the main shock and the aftershocks involving an extraordinarily large area coverage of about 8000 km^2 as compared to the ordinary case for M 7.0.

A westward movement of the seismic activity was observed in the sequence for a several months period after the occurrence of the main shock. Three earthquake provinces in the trench side, the transitional and the coastal zones were specified through a systematic westward movement of the aftershock activity, in which the activities of shallow origin on the trench side was taken over by the activities of deeper origin near the coast.

Both shallow and the pronounced double-planed deeper origin earthquakes were observed in the transitional province as pointed out by KAWAKATSU and SENO (1982) for the regional variation of seismic activities along the Northern Honshu arc. A considerable amount of stress level variation in space and time is suggested from the classification of major earthquakes into the very low, the low and the high frequency earthquakes as defined by UTSU (1980). Considering the seismotectonic environment in the region including the background seismicity, it can be concluded that the westward movement of the aftershock activity was a manifestation of the interactive process between the oceanic plate and the overriding continental lithosphere.

2. Microearthquake observation network system

The microarthquake observation network system in Fig. 1 has been operated by E. R. I. since September 1980. Three component short period seismographs are installed at each of the satellite stations linked by radio or telephone lines to the central recieving station of E.R.I. in Tokyo. Overall frequency characteristics of the seismographs shown in Fig. 2 have a flat responce for the velocity of ground motions in the frequency range of 1~10 Hz. The station coordinates and the

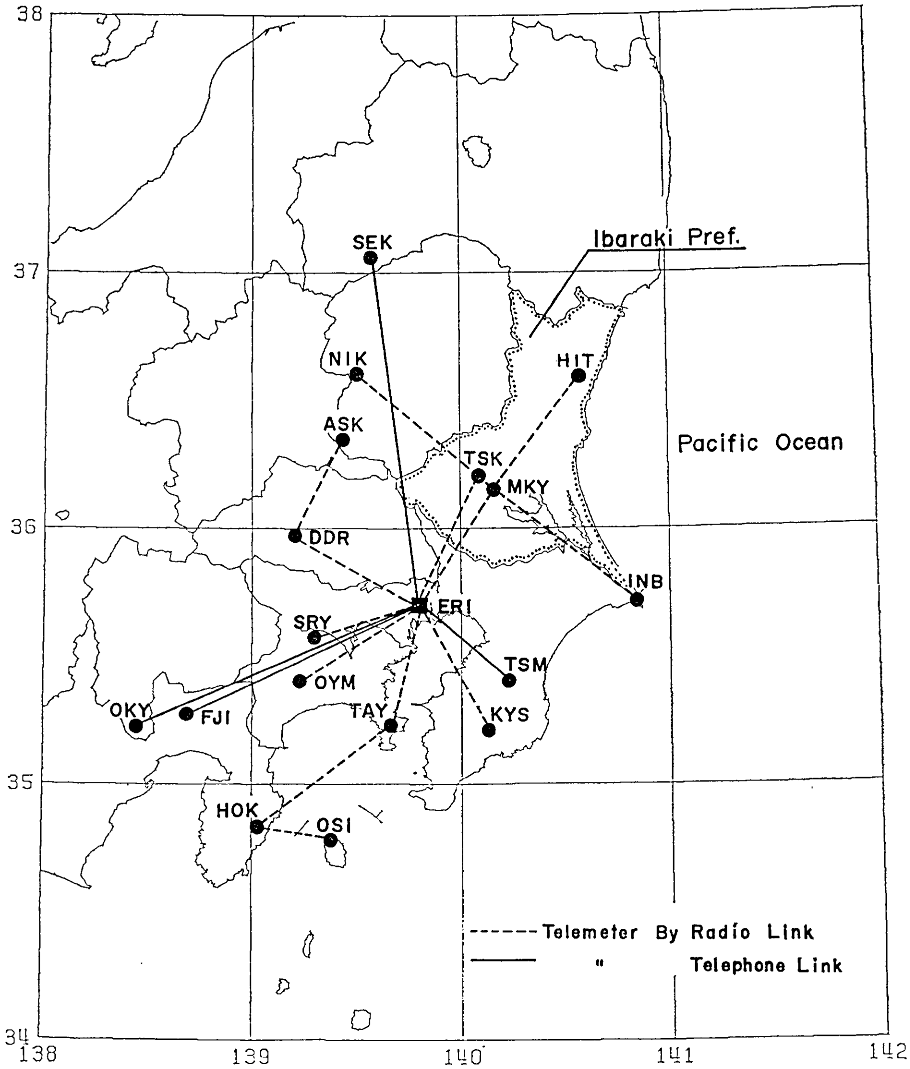


Fig. 1. Microearthquake observation network in the Kanto district operated by E. R. I.. List of the seismographic stations of the network is given in Table 1.

Table 1. List of the seismographic station coordinates and the magnification of seismographs of the network in the Kanto district shown in Fig. 1.

St. Code	Lat.	Long.	Alititude (m)	Magnification at 10 Hz.
ASK	36°.3582	139°.4159	80	293400
DDR	35.9983	139.1933	800	293400
FJI	35.3103	138.6789	1040	73350
HIT	36.6181	140.5873	600	146700
HOK	34.8498	139.0396	890	73350
INB	35.7019	140.8588	60	73350
KYS	35.1976	140.1482	180	146700
MKY	36.1620	140.1333	460	9170
NIK	36.6207	139.4872	1290	146700
OKY	35.2273	138.4211	620	293400
OSI	34.7891	139.3517	20	32890
OYM	35.4200	139.2430	600	100770
SEK	37.0951	139.5762	76	73350
SRY	35.6083	139.2741	250	293400
TAY	35.2147	139.6594	170	36680
TSK	36.2108	140.1097	280	293400
TSM	35.4110	140.2292	50	18340

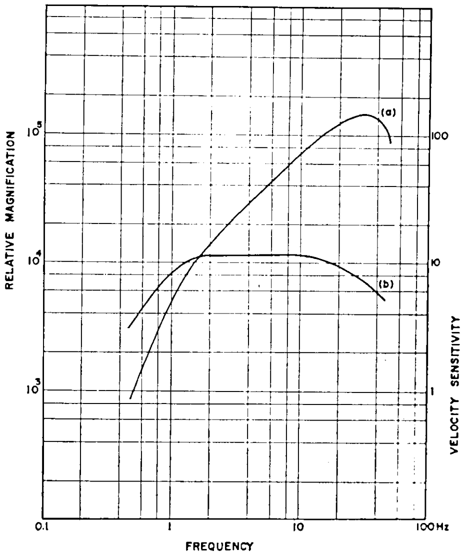


Fig. 2. Overall frequency characteristics of seismographs for (a) relative magnification and (b) sensitivity used for the seismographic network shown in Fig. 1.

magnification at 10 Hz are listed in Table 1.

As a routine work, a preliminary hypocentral determination of microeathquakes in and around the Kanto district has been made automatically by an on-line base system. The preliminary result is re-examined by interpreters to ensure its reliability. The arrival time of the P and S waves at the five stations of HIT (Hitachi), INB (Inubo), TSK (Tsukuba), ASK (Ashikaga) and NIK (Nikko) were exclusively used to have a preferable geometrical distribution of the stations relative to the epicenters off Ibaraki Prefecture. The hypocentral determination by the fixed station combination improves the accuracy of the relative location of hypocenters. The stations of HIT and INB are located in the Pacific coast

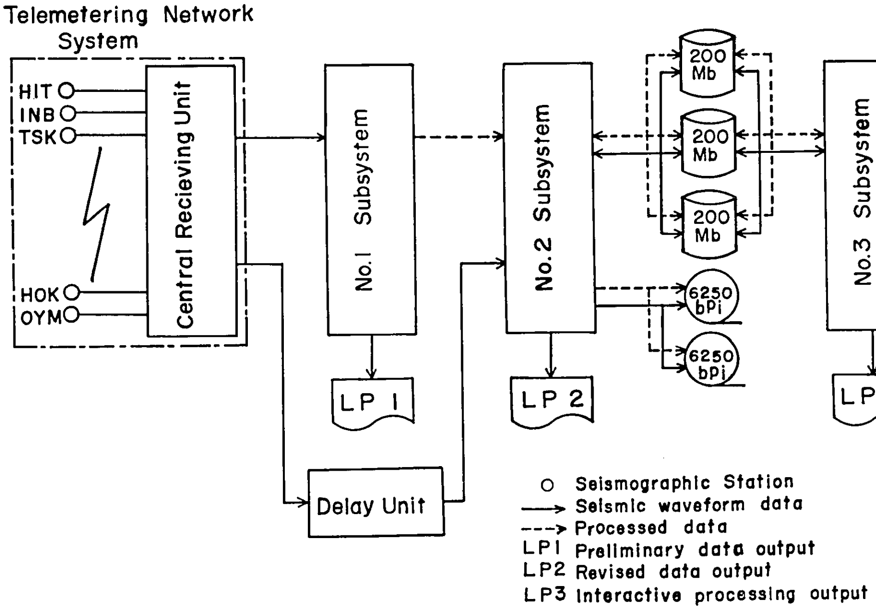


Fig. 3. Schematic block diagram of the data processing system for microearthquake observation. The No. 1, 2 and 3 subsystems are for a preliminary data production, a revised data production and interactive data processings, respectively.

facing to the active seismic region off Ibaraki Prefecture. The other three stations of TSK, ASK and NIK are located on the inland part of the Northern Kanto district.

The data processing system connected with the microearthquake observation network consists of three subsystems closely associated with one another as shown by the schematic block diagram of the system in Fig. 3. The No. 1 subsystem produces preliminary data of the P and S arrival times, hypocentral coordinates and magnitude values to be revised through the processings by the No. 2 subsystem to improve their accuracy and reliability. Seismic signals are recorded on magnetic tapes in a digital form with the processed data including arrival times and hypocentral coordinates. The No. 3 subsystem is available for off-line interactive processing to revise the data produced by the No. 2 subsystem. Examples of seismic waveform data reproduced by the No. 3 subsystem are shown in Fig. 4.

3. Space-time seismicity

3.1. Forerunning microearthquakes

The epicentral distribution of the background seismicity off Ibaraki Prefecture at depths of $20 \sim 40$ km shows a characteristic feature striking

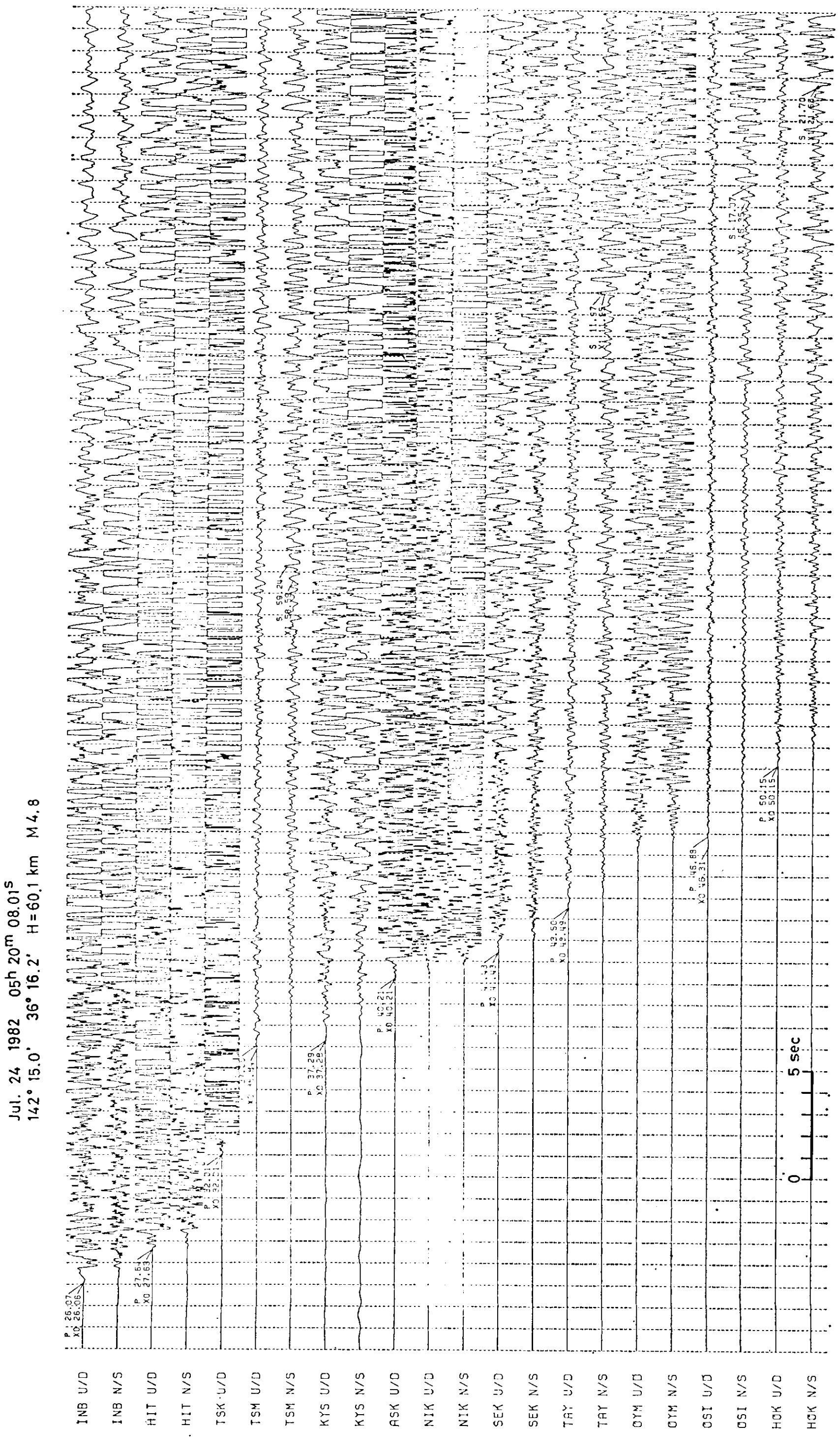

Jul. 24 1982 05h 20m 08.01s
142° 15.0' 36° 16.2' H=60.1 km M4.8
INB U/D
INB N/S
HIT U/D
HIT N/S
TSK U/D
TSM U/D
TSM N/S
KYS U/D
KYS N/S
ASK U/D
NIK U/D
NIK N/S
SEK U/D
SEK N/S
TAY U/D
TAY N/S
OYM U/D
OYM N/S
OSI U/D
OSI N/S
HOK U/D
HOK N/S
0
5 sec

Fig. 4-(a).

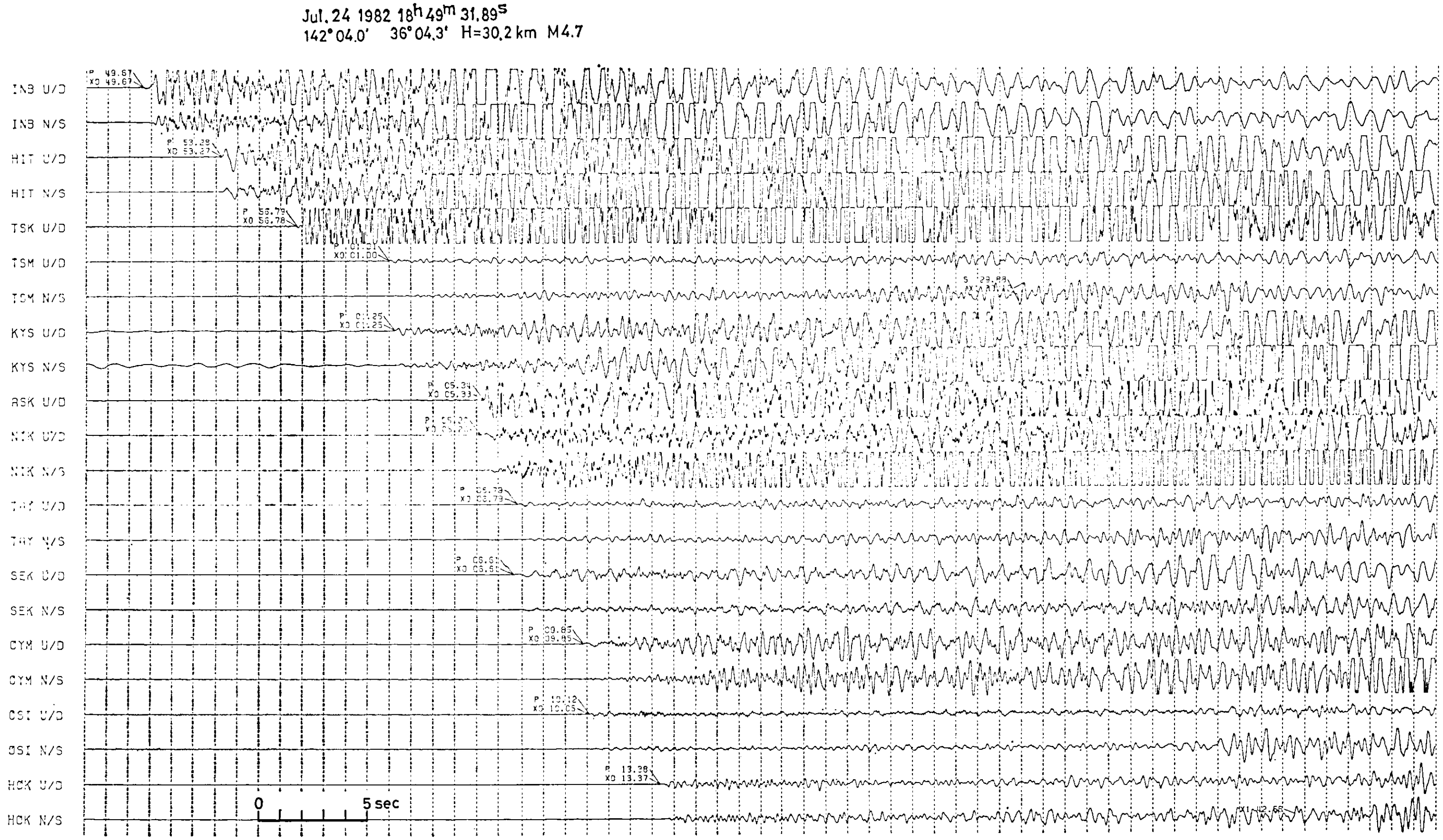


Fig. 4-(b).

Fig. 4. Examples of reproduced seismograms of the earthquakes off Ibaraki Prefecture for vertical (U/D) and north-south (N/S) components. Time pick results by the automatic data processing system (Fig. 3) are indicated by P (preliminary P time pick), X0 (revised P time pick), S (preliminary S time pick) and X1 (revised S time pick). Arrival times are given with a 10 msec accuracy.

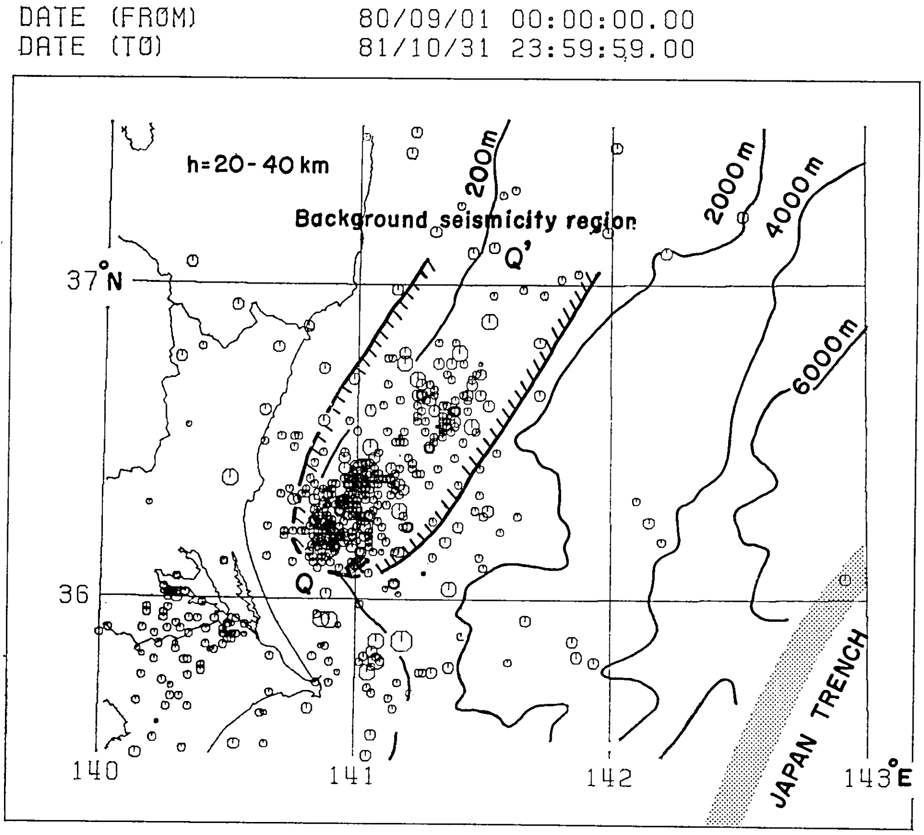


Fig. 5. Epicentral distribution of the background seismicity at depths h of 20～40 km striking in the direction of about N 30°E (QQ') off Ibaraki Prefecture during the period from September, 1980 to October, 1981. Contour lines of bathymetric depth are given for 200, 2000, 4000 and 6000 m.

in the N 30°E direction along QQ' as shown in Fig. 5 nearly parallel to the trench axis. A heavily concentrated epicentral zone at a distance range of about 20～40 km from the coast of Ibaraki Prefecture coincides with the eastern border of the pronounced double-planed hypocentral distribution (Tsumura, 1973; Hasegawa, 1977; Hasegawa *et al.*, 1978), descending beneath Honshu in the direction of about N 70°W with a dip of about 35°. A gradual decrease of the background seismicity towards the trench axis was found with an infrequent occurrence of microearthquakes in the trench side region beyond the line of the bathymetric depth of 2000 m.

During the period from May 1 to July 20, 1982, an isolated epicentral group of microearthquakes of M 2.5～3.7 was located in the area of bathymetric depth of 2000～4000 m near the trench as shown in Fig. 6-(a). The activity was identified as a forerunner preceding

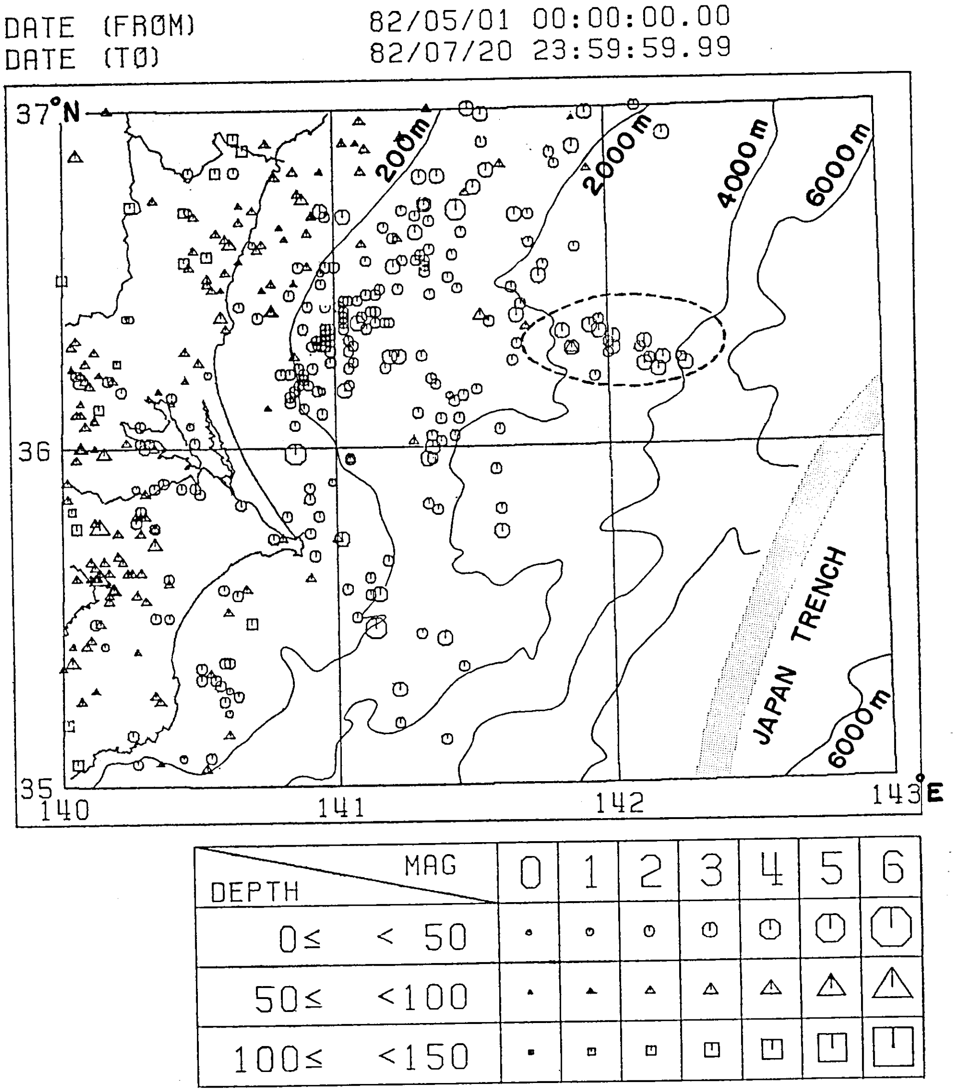


Fig. 6-(a). Epicentral distribution of the forerunning microearthquakes located in the area as enclosed by a dashed line during the period from May 1 to July 20, 1982.

the remarkable foreshoks associated with the main shock on July 23 (M 7.0). Examples of seismograms of the forerunning microearthquakes are shown in Fig. 8-(a).

3.2. Foreshocks

The number of foreshocks and the aftershocks located by the network in the Kanto district (Fig. 1) is shown for every one hour interval in Fig. 7. The foreshock activity started about 2 days before the occurrence of the main shock on July 23 as shown in Fig. 7 in

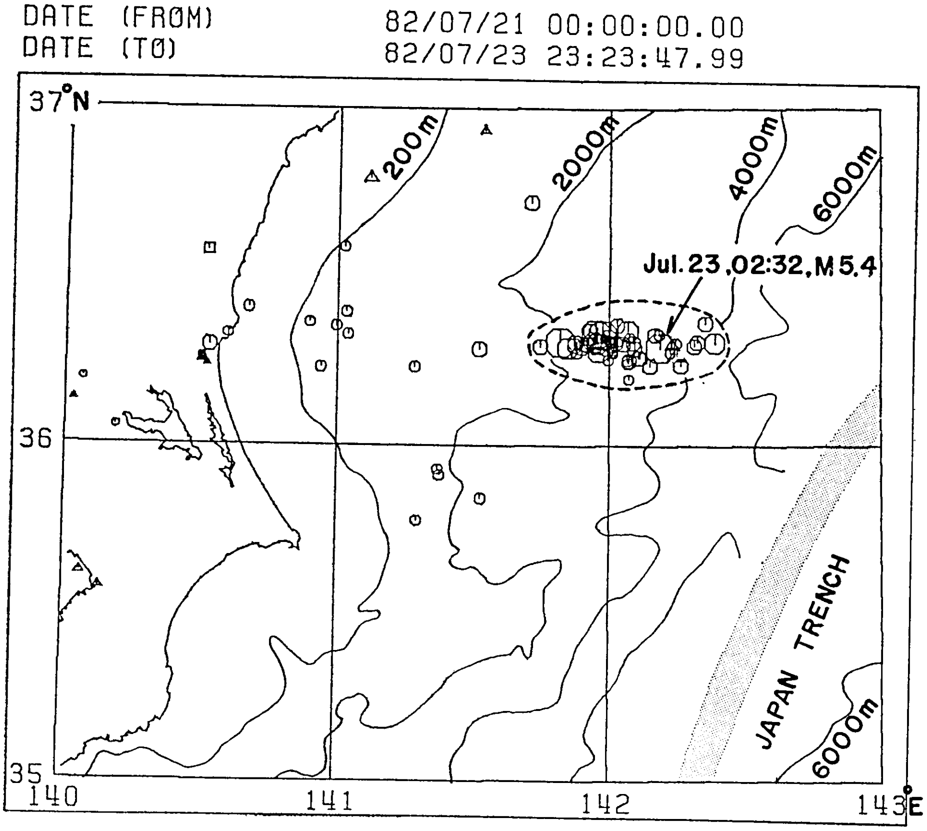


Fig. 6-(b). Epicentral distribution of the foreshocks during the period from 0000 hours July 21 to 2323 hours, July 23, 1982. The largest foreshock (*M* 5.4, focal depth *h* 18 km) took place at 0232 hours, July 23, 1982.

nearly the same area where the forerunning microearthquakes took place. The largest foreshock of *M* 5.4 at 0232 hours, July 23 was followed by the peak of the activity from 0400 hours to 0600 hours, July 23. The activity was on its minimum level from 1300 hours to 1900 hours, July 23. Soon after the recovery from the minimum level, the main shock of *M* 7.0 took place at 2323 hours, July 23. Examples of the seismograms of the foreshocks shown in Fig. 8-(b) can be compared with those of the forerunning microearthquakes in Fig. 8-(a). High frequency components are more predominant in case of the forerunning microearthquakes than in the foreshocks after the occurrence of the largest foreshock. This suggests a stress level drop caused by the occurrence of the largest foreshock though the effect might be limited within a very small area near the epicenter of the largest foreshock.

In addition to the remarkable foreshock activity in the trench

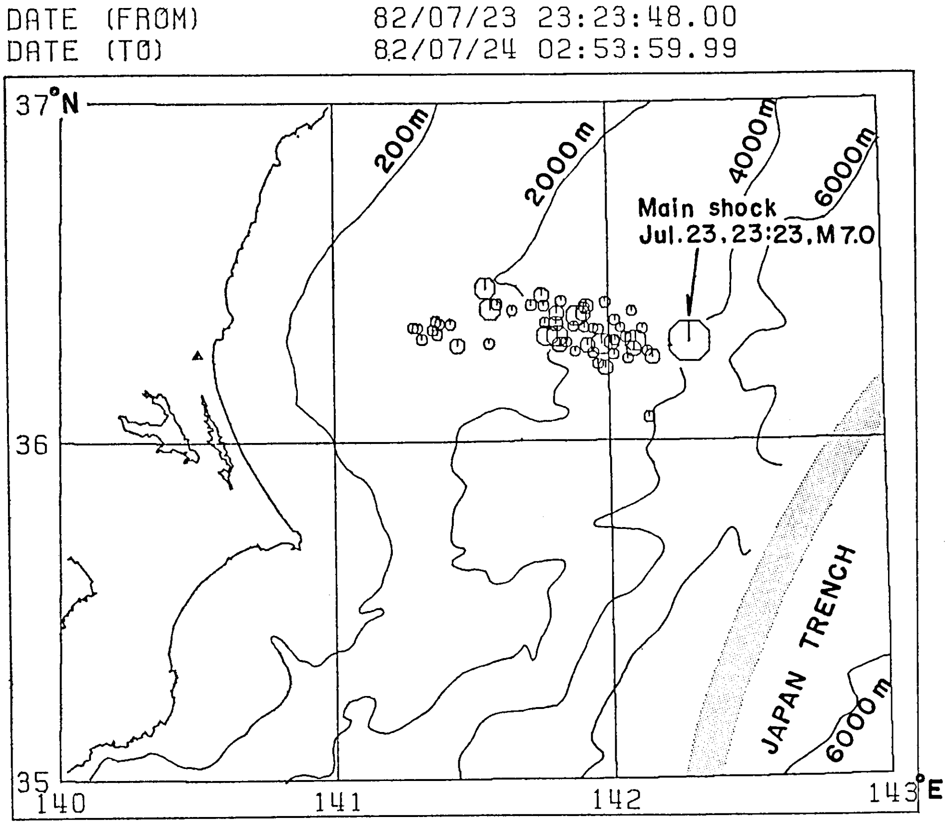


Fig. 6-(c). Epicentral distribution of the main shock (2323 hours, July 23, M 7.0, h 15 km) and the aftershocks during the period from 2323 hours, July 23 to 0253 hours, July 24, 1982 (the first stage of the aftershock sequence).

side area, a coincident seismic activity was detected in the east coast of Ibaraki Prefecture (OKADA *et al.*, 1982). A comparatively strong background seismicity in the coastal area at a distance of more than 100 km from the main shock makes it disputable to identify the activity as a precursory phenemenon associated with the main shock on July 23.

3.3. Main shock

A large earthquake of M 7.0 took place at 2323 hours, July 23, 1982 with the epicenter of 36.29°N, 142.30°E and the focal depth of about 15 km. It shoud be noted that the earthquake was preceded by a 16.5 years period of low seismicity from 1966. The earthquake, the largest of all in the sequence starting from July 22, was identified as the main shock for the successive seismic activity lasting over several months off and in the coast of Ibaraki Prefecture.

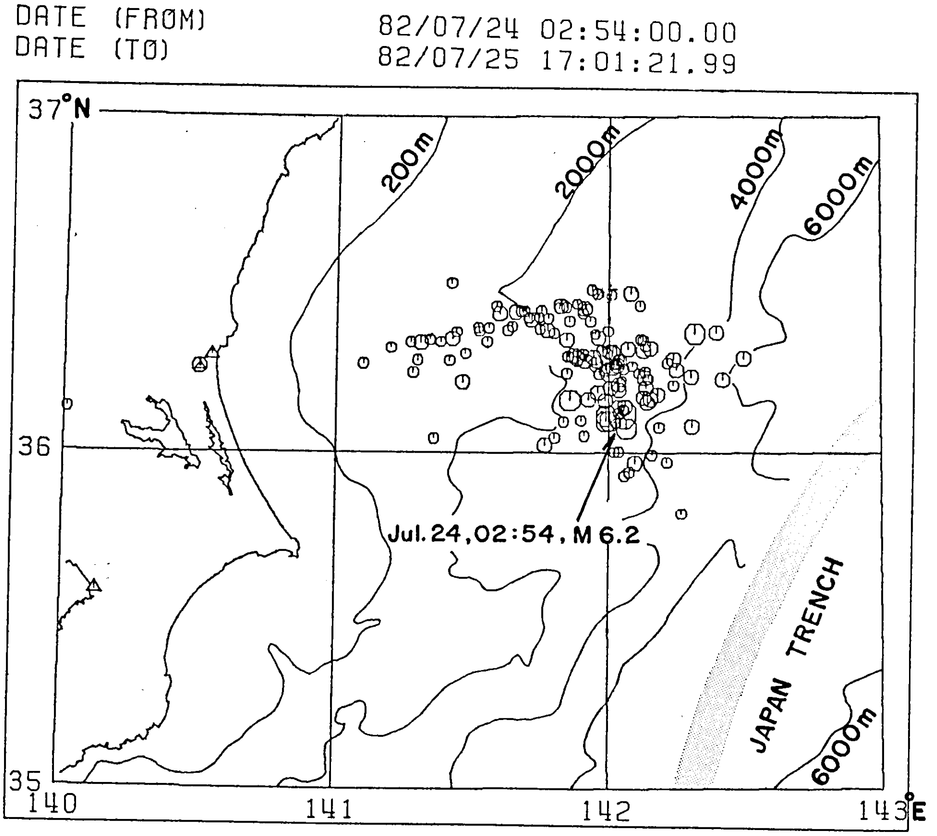


Fig. 6-(d). Epicentral distribution of the aftershocks during the period from 0254 hours, July 24 to 1701 hours, July 25, 1982 (the second stage of the aftershock sequence). The largest aftershock (*M* 6.2, focal depth *h* 23 km) took place at 0254 hours, July 24.

Comparing the hypocentral location of the main shock with the multichannel seismic reflection profiles off the Joban district (SAKURAI *et al.*, 1981), the main shock was located very close to the plate boundary when the hypocenter was projected on the profile perpendicular to the contour lines of equi-bathymetric depths as shown in Fig. 9 (FACULTY OF SCIENCE, TOHOKU UNIV., 1983). A fault plane solution of the main shock from the initial P wave motion at 32 stations indicates a reverse type faulting striking in the direction of N 13°E with a dip angle of 35° as shown in Fig. 10. It shoud be noted that the strike of the fault plane is nearly parallel to that of the trench axis. The dip angle is significantly larger than that of 10~20° as usually observed for shallow earthquakes on the plate boundary off Ibaraki Prefecture (ABE, 1977; KAWAKATSU and SENO, 1982).

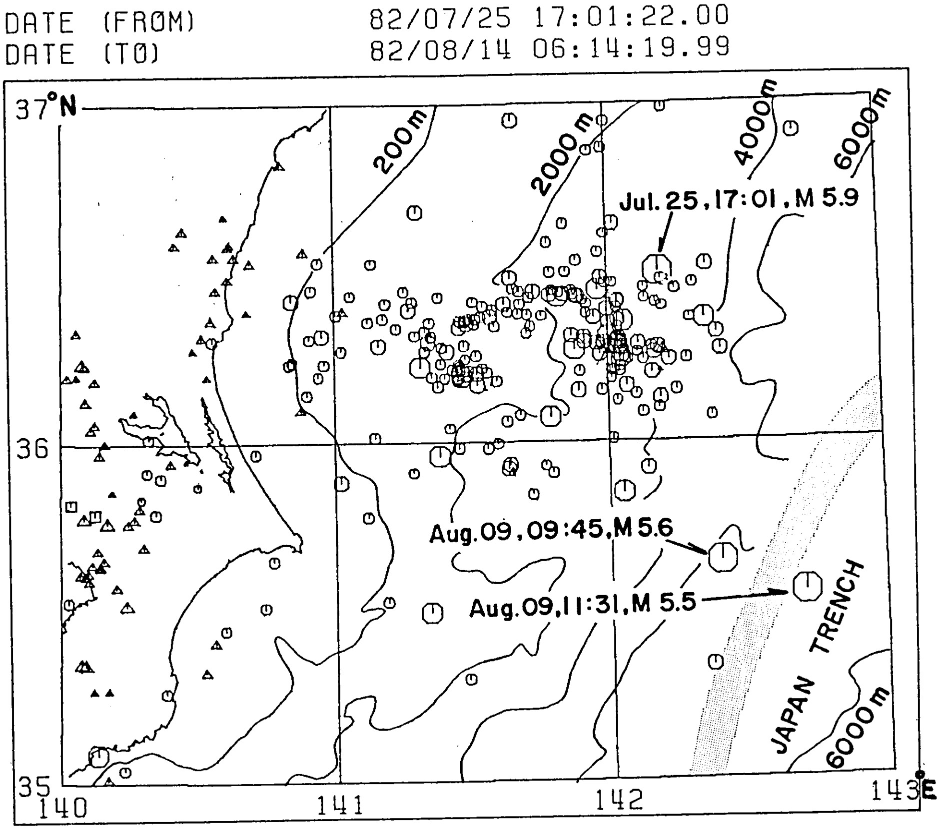


Fig. 6-(e). Epicentral distribution of the aftershocks during the period from 1701 hours, July 25 to 0614 hours, August 14, 1982 (the third stage of the aftershock sequence). Major earthquakes ((i) 1701 hours, July 25, M 5.9, h 10 km; (ii) 0954 hours, August 09, M 5.5, h 26 km; (iii) 0911 hours, August 09, M 5.5, h 18 km) are indicated with an arrow.

3.4. Aftershocks

Epicentral distributions in the six successive stages of the aftershock sequence are shown in Figs. 6-(c)~(h). In the first stage of the aftershock sequence from 2323 hours, July 23 to 0253 hours, July 24, epicenters were mostly distributed in the area with bathymetric depths of 2000~4000 m (Fig. 6-(c)), where the forerunning microearthquakes (Fig. 6-(a)), the foreshocks (Fig. 6-(b)) and the main shock took place. It should be noted that the main shock was located in the eastern extreme of the epicentral area in Fig. 6-(c) indicating a strong tendency of westward extension of the aftershock activity. Focal depths of the aftershocks in the first stage were mostly less than 30 km. In the second stage from 0254 hours, July 24 to 1701 houas, July 25, the largest aftershock of July 24 (M 6.2) and its secondary aftershocks

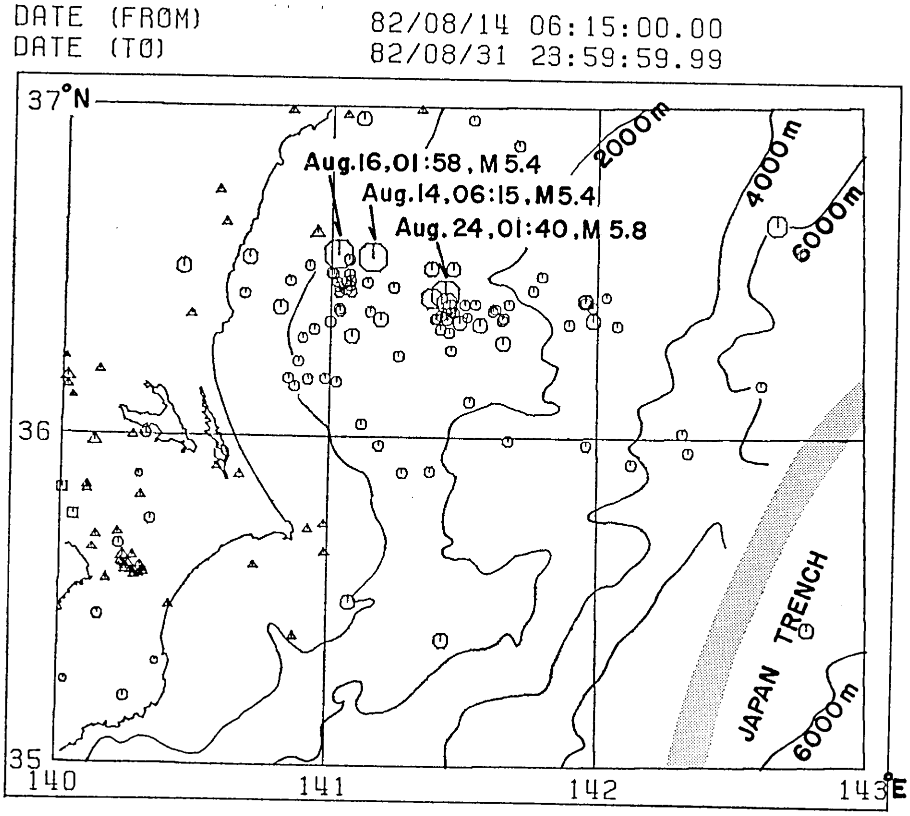


Fig. 6-(f). Epicentral distribution of the aftershocks during the period from 0615 hours, August 14 to 2359 hours, August 31, 1982 (the fourth stage of the aftershock sequence). Major earthquakes ((i) 0615 hours, August 14, M 5.4, h 31 km; (ii) 0158 hours, August 16, M 5.4, h 40 km; (iii) 0140 hours, August 24, M 5.8, h 17 km) are indicated with an arrow.

took place in the area with bathymetric depths of 2000～4000 m. Epicenters were distributed with an lineation extending to the west from the main part of the epicentral area with bathymetric depths of 2000～4000 m. In the third stage from 1701 hours, July 25 to 0614 hours, August 14 (Fig. 6-(e)), the second largest aftershock and its secondary aftershocks took place on the northern border of the main part of the aftershock area. An epicentral area was newly formed several tens of kilometers west from the main part of the aftershock area. The newly formed epicentral area was separated by an aseismic area of 30～40 km in length. Apart from the main part of the aftershock area, two major earthquakes at 0945 hours, August 9 (M 5.6) and at 1131 hours, August 9 (M 5.5) were located in the southeastern margin off Ibaraki Prefecture very close to the trench axis. The

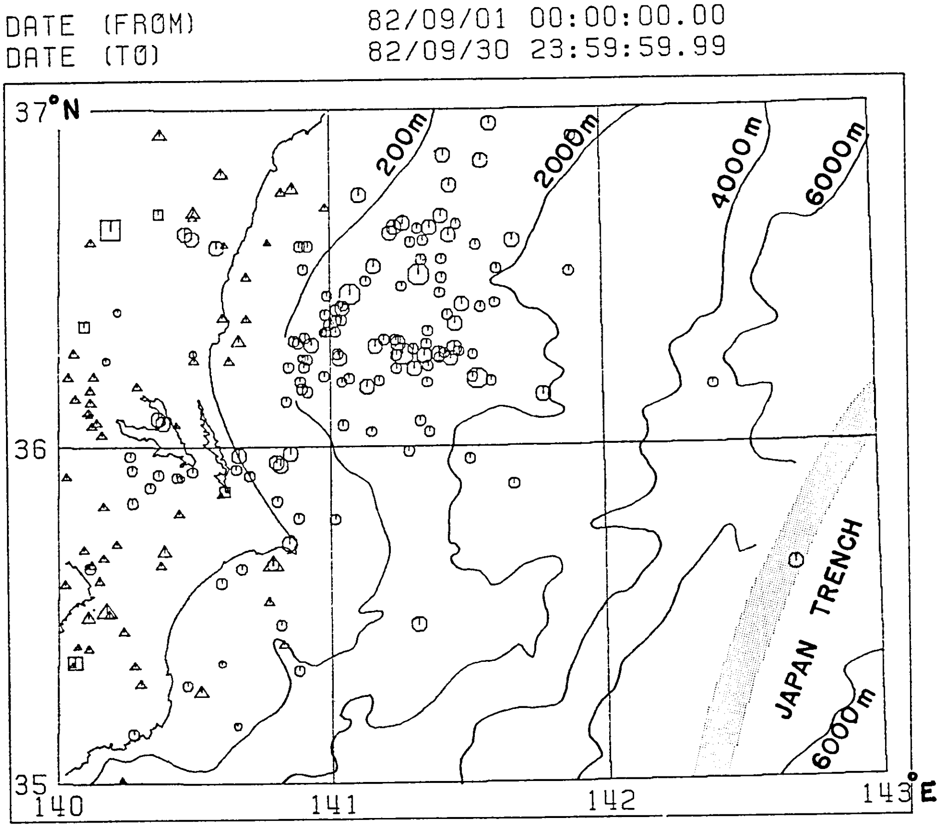


Fig. 6-(g). Epicentral distribution of the aftershocks during the period from September 1 to September 30, 1982 (the fifth stage of the aftershock sequence).

simultaneous activation of seismicity in the various different areas off Ibaraki Prefecture can be noted as one of the characteristics of the aftershock sequence.

In the fourth stage from 0615 hours, August 14 to 2359 hours, August 31, the seismicity in the area near the coast with bathymetric depths of 200～2000 m was apparently activated at depths of 40～50 km, while the seismic activities of a shallow origin in the eastern area with bathymetric depths of 2000～4000 m decreased with a removal of the main part of the epicentral area in the preceding stages of the aftershock sequence. Among the three major earthquakes of August 14 (M 5.4), August 16 (M 5.4) and August 24 (M 5.8) located in the area near the coast, the first and the second earthquakes were of deeper origin with their focal depths of 30～40 km (Fig. 6-(f)). A noticeable activities with M of 3.5～4.5 in the central and eastern part of Tochigi Prefecture may be an indication of the westward movement of the

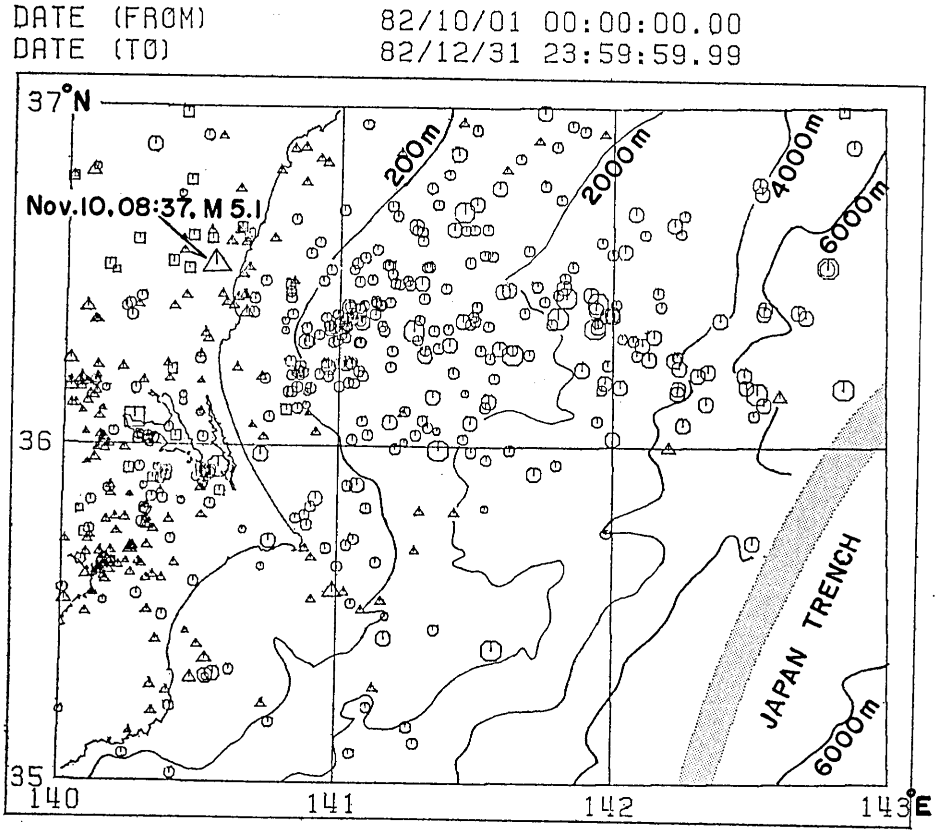


Fig. 6-(h). Epicentral distribution during the period form October 1 to December 31, 1982.

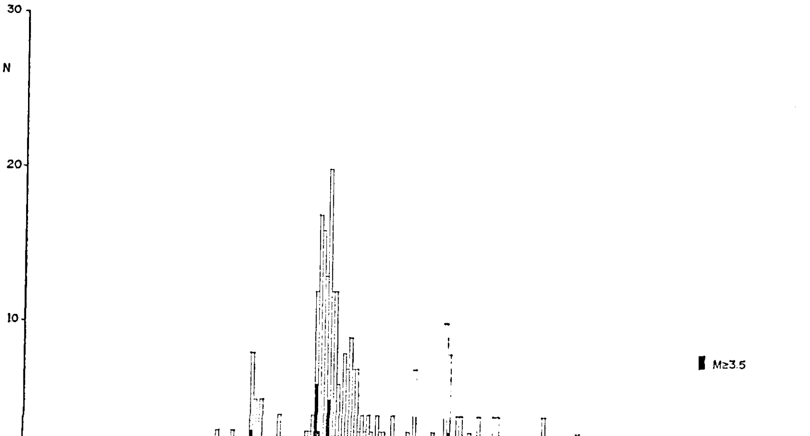


Fig. 7. Hourly variations in the number of the earthquakes N off Ibaraki Prefecture located by the seismic network in the Kanto district as shown in Fig. 1.

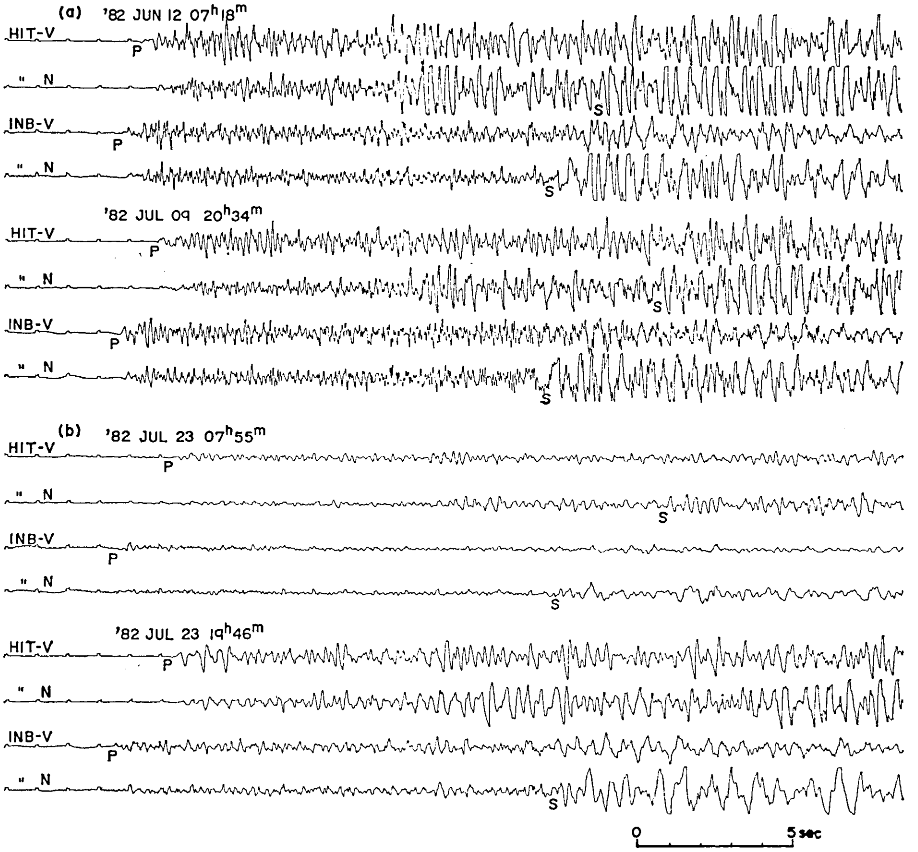


Fig. 8. Examples of seismograms at HIT and INB on a multichannel strip chart record with a paper speed of 10 mm per second for (a) the forerunning microearthquakes and (b) the foreshocks in the area enclosed by a dashed line in Figs. 6-(a) and (b), respectirely. Note that the records of the foreshocks contain less higher frequency components than those of the forerunning microearthquakes.

aftershock activity beyond the shore line of Ibaraki Prefecture. In the sixth stage from October 1 to December 31, 1982 (Fig. 6-(h)), a deeper penetration of the seismic activity as resulted from the westward movement was evidently observed in the occurrence of the earthquake of November 10 (M 5.1) with a focal depth of about 80 km located in the coastal area of Ibaraki Prefecture. In addition to the activity in the coastal area, noticeable earthquakes with M of 4.0~4.3 were detected in the southeastern part of Ibaraki Prefecture.

The main shock of July 23 (M 7.0) and the accompanying major earthquakes were classified into the groups of the very low, the low and the high frequency earthquakes from the relation between the maximum range of perceptibility R and magnitude M as defined by

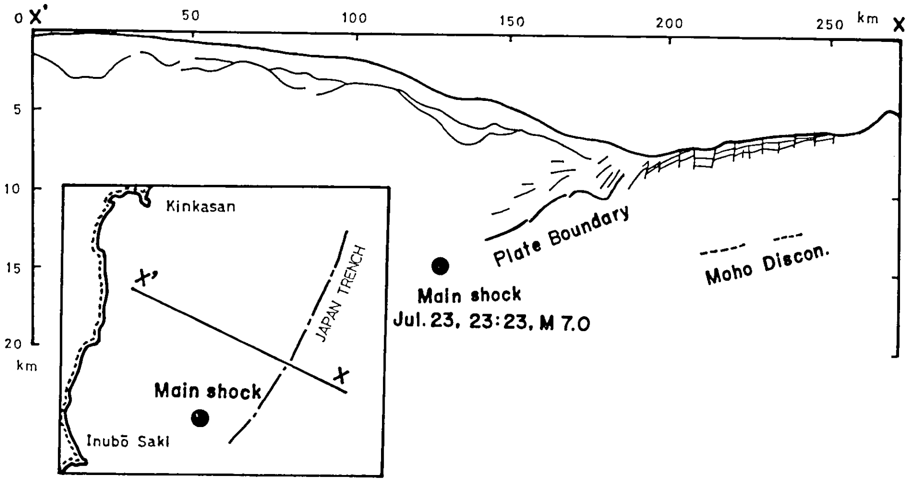


Fig. 9. Interpreted section from multichannel seismic reflection profile off Joban district (after SAKURAI *et al.*, 1981). Location of the main shock of July 23 (M 7.0) is indicated by an solid circle projected on the vertical cross-sectional profile along the line XX' as shown in the inset.

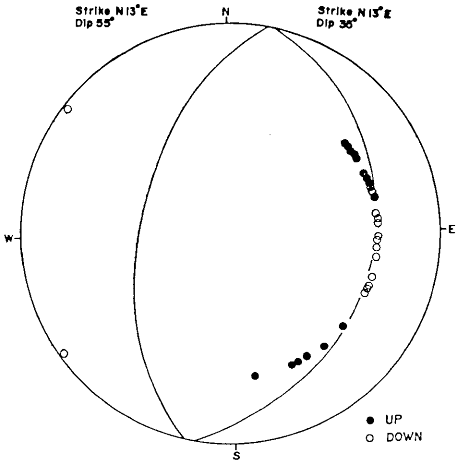
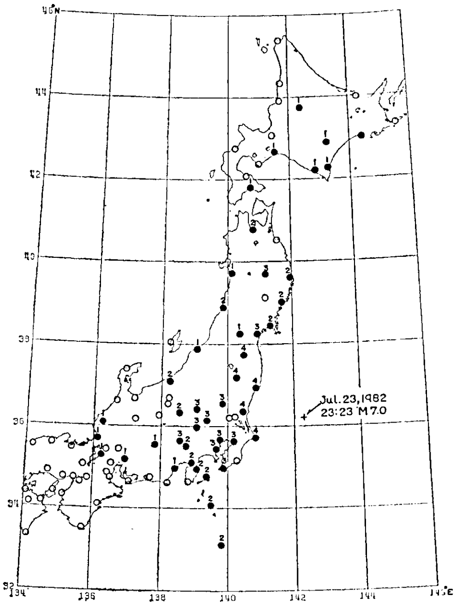
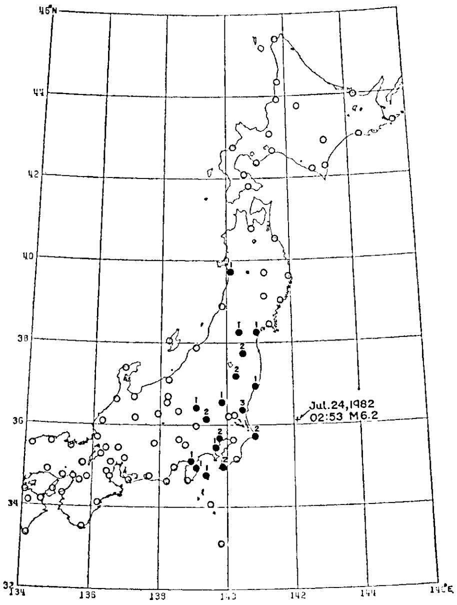


Fig. 10. Fault plane solution of the main shock of July 23 (M 7.0) presented as stereographic projection of the upper hemisphere of the focal sphere.

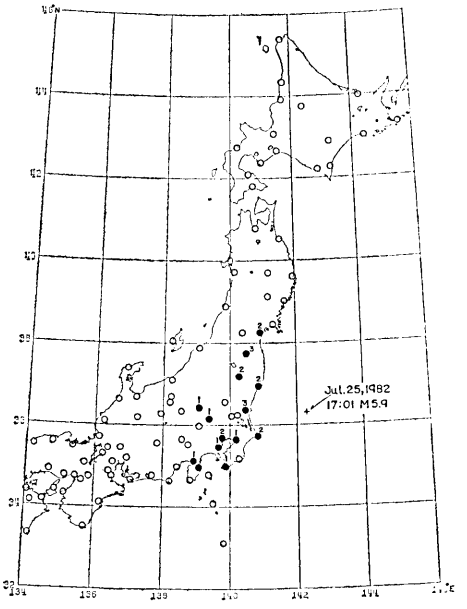
UTSU (1980). The intensity distribution of these earthquakes is shown in Figs. 11-(a)~(f). The main shock of July 23 (M 7.0) with R of 820 km was identified as a high frequency earthquake, while the major aftershocks of July 24 (M 6.2) with R 300 km and of July 25 (M 5.9) with R of 235 km located in the trench side area with bathymetric depths of 2000~4000 m can be identified as a very low frequency and a low frequency earthquakes, respectively. A remarkable difference of the P wave forms between the main shock (M 7.0) of the high frequency earthquake and the largest aftershock (M 6.2) of the very low frequency earthquake is represented by seismograms for these earthquakes recorded at the selected stations on the microearthquake observation network in the Kanto district as shown in Fig. 12. A stress level drop caused by the occurrence of the main shock of July 23 is a possible explanation


46°N
44
42
40
38
36
34
32
134
136
138
140
142
144
146°E
Jul.23,1982
23:23 M7.0

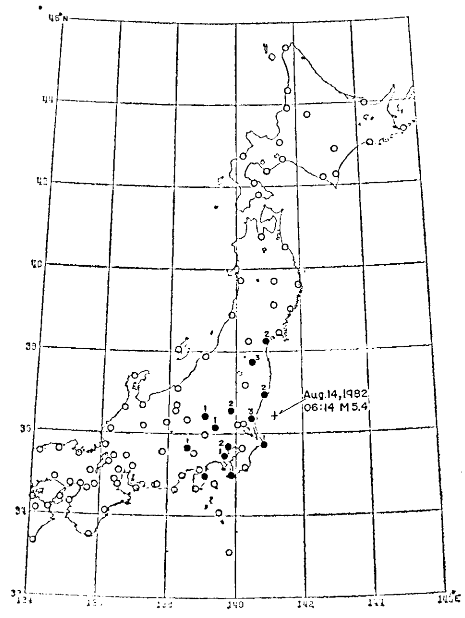
(a)


46°N
44
42
40
38
36
34
32
134
136
138
140
142
144
146°E
Jul.24,1982
02:53 M6.2

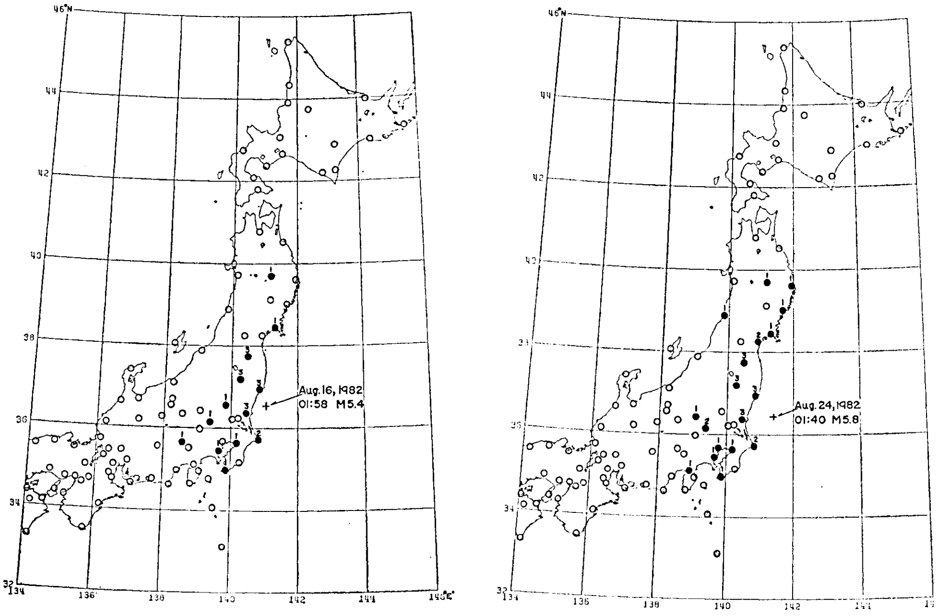
(b)


46°N
44
42
40
38
36
34
32
134
136
138
140
142
144
146°E
Jul.25,1982
17:01 M5.9

(c)


46°N
44
42
40
38
36
34
32
134
136
138
140
142
144
146°E
Aug.14,1982
06:14 M5.4

(d)



(e) (f)

Fig. 11. Intensity distribution of the major earthquakes in the sequence from July 22 to August 31, 1982 off Ibaraki Prefecture. Epicenter is indicated by a cross. At each observational station of J. M. A. (solid circle), the intensity in the J. M. A. scale is given by a numeral. An empty circle indicates a station at which the earthquake was unfelt.

for the lack of high frequency components of the two major aftershocks located in the trench side area with bathymetric depths of 2000~4000 m. The three major earthquake of August 14 (M 5.4) with R of 185 km, August 16 (M 5.4) with R of 195 km and August 24 (M 5.8) with R of 365 km located in the coast side area with bathymetric depths of 200~2000 m were identified as high frequency earthquakes. This suggests a continuation of a high stress level condition after the occurrence of the main shock for a longer period of time in the coast side area than in the trench side area.

The b-value of the foreshocks and the aftershocks in the first and the second stages were obtained from the data of the microearthquake observation in the Kanto district as shown in Fig. 13. A smaller value of b of 0.56 for the foreshocks as compared to that of 0.71 for the aftershocks was found to agree with the results obtained by various authors as exemplified by SUYEHIRO *et al.* (1964) and UTSU (1974-b). No significant difference was found between the b-values for the aftershocks and the background seismicity.

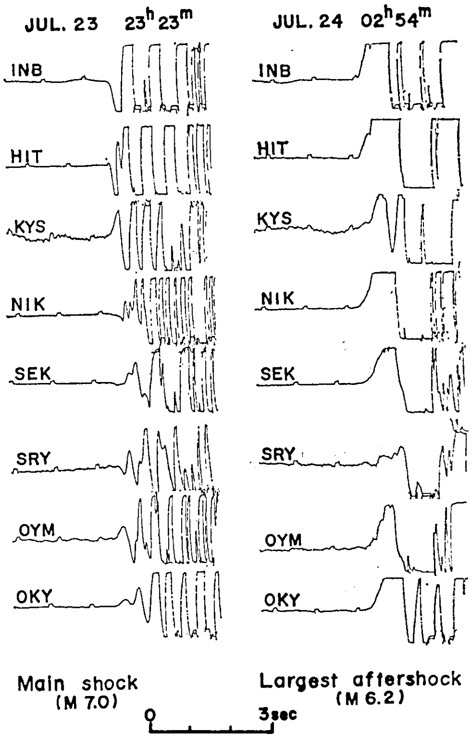


Fig. 12. Comparison of the P wave forms of the main shock of 2323 hours, July 23 (the high frequency earthquake of M 7.0) and the largest aftershock of 0254 hours, July 24 (the very low frequency earthquake of M 6.2) at the stations of the network in the Kanto district as shown in Fig. 1.

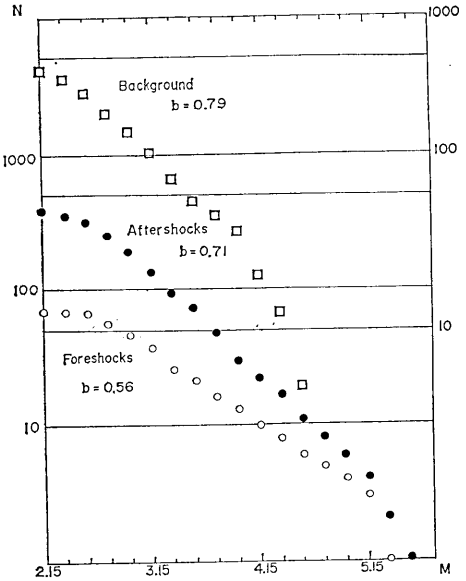


Fig. 13. Magnitude frequency distributions and the corresponding b-values for the foreshocks, the aftershocks and the earthquakes of the background seismicity for the period from September 1980 to October 1981.

4. Occurrence of a large earthquake in the south of Ibaraki Prefecture

A large earthquake with a M 6.0 took place on February 27, 1983 in the south of Ibaraki Prefecture accompanied by foreshock and aftershock activities. The fault plane solution of this large earthquake on Feburuary 27 is shown in Fig. 14 with the location of epicenters of the main shock and the accompanying earthquakes. With a typical reverse type faulting as for the earthquakes occurring in the area, the large earthquake on February 27 was located in the heavily concentrated hypocentral zone of a background seismicity interpreted as being caused by an interaction between the Pacific plate and the Philippine Sea plate as shown in Fig. 15 (MAKI, 1981, NATIONAL RESEARCH

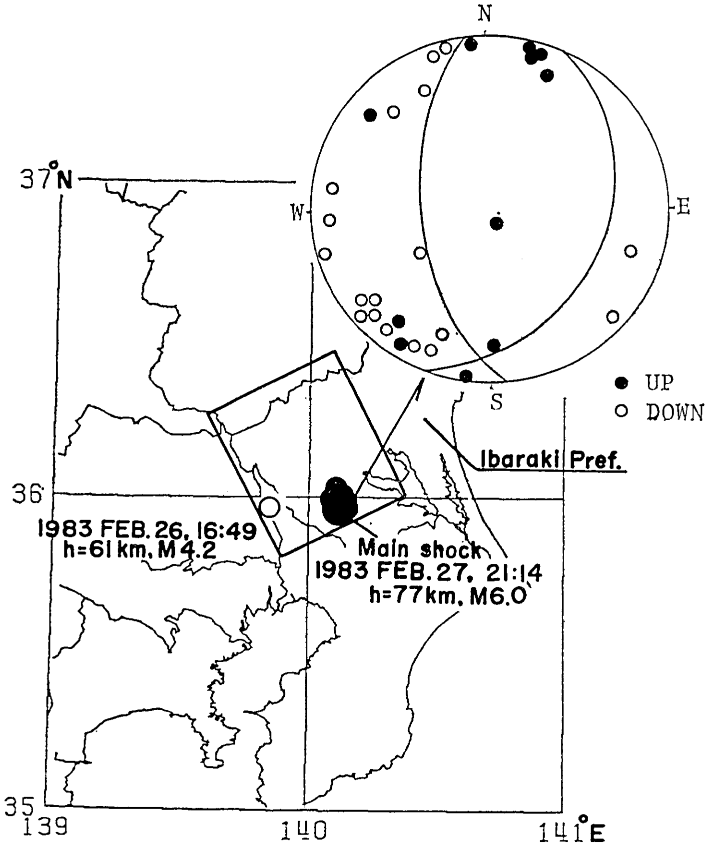


Fig. 14. Epicenters of the earthquakes of February 27, 1983 (*M* 6.0) (large solid circle), foreshock (empty circle) and aftershock (small solid circle) in the south of Ibaraki Prefecture. The fault plane solution of the earthquake on February 27 is presented as stereographic projection of the upper hemisphere of the focal sphere.

Center for Disaster Prevention, 1981). Judging from the space-time relation of the large earthquake of February 27 with the aftershock sequence accompanying the earthquake of July 23, it is highly possible that the large earthquake in the south of Ibaraki Prefecture was triggered by the westward movement of the aftershocks penetrating as deep as 60～80 km.

5. Earthquake provinces

Three earthquake provinces were specified through a systematic westward movement of the aftershock activity as described in the followings.

i) Earthquake province (A): An earthquake province (A) in the

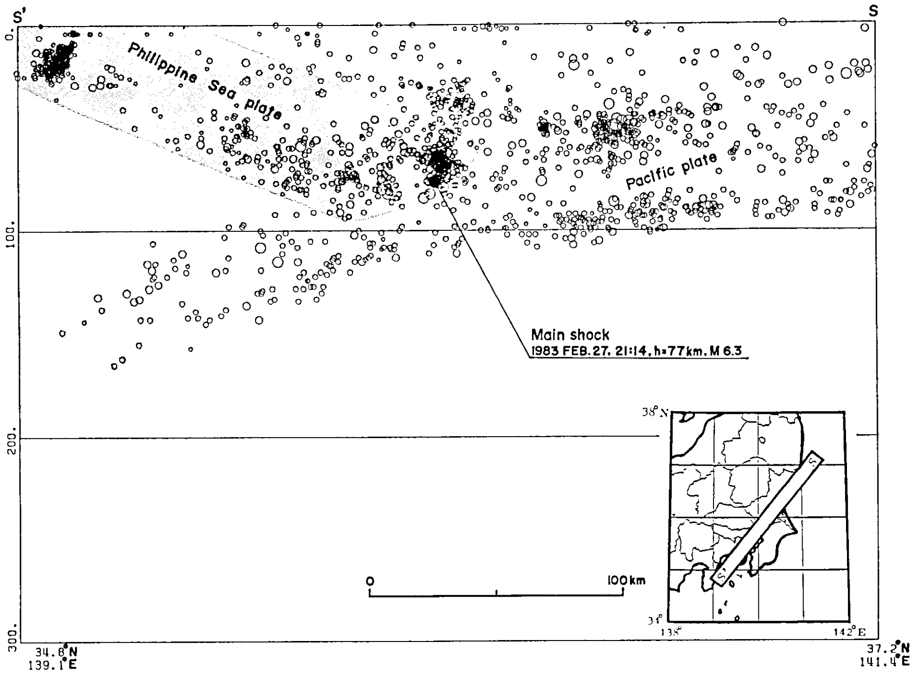


Fig. 15. Hypocentral location of the earthquake on February 27, 1983 (*M* 6.0) (solid circle) projected on the vertical cross sectional profile along SS' in the rectangular area enclosed by a solid line as shown in the inset. The hatched zone indicates the lithosphere of the Philippine Sea plate.

trench side area was specified corresponding to the aftershock activity from July 23 to July 25. In the first and the second stages of the aftershock sequence, epicenters were mostly distributed in the area of bathymetric depths of 2000～4000 m (Figs. 6-(c) and (d)) with focal depths of less than about 30 km (Fig. 16-(b)). An aseismic area (G) as shown in Fig. 16 on the western border of the province (A) was found for the epicentral distribution in the third stage of the aftershock activity from July 25 to August 14.

ii) Earthquake province (B): An earthquake province (B) in the transitional zone was specified corresponding to the aftershock activity from August 14 to September 30. In the fourth and the fifth stages of the aftershock sequence, epicenters were mostly distributed in the area of bathymetric depths of 200～2000 m (Figs. 6-(f) and (g)), where both shallow and pronounced double-planed deeper origin earthquakes were observed (Figs. 17-(a) and (b)). An aseismic area (G) separated the two earthquake provinces of (A) and (B) with a gap of a 30～40 km in length. The seismic activity in the province (B) showed a transitional feature from the shallow earthquakes in the trench side province (A) to the double-planed deep earthquakes in the coastal region.

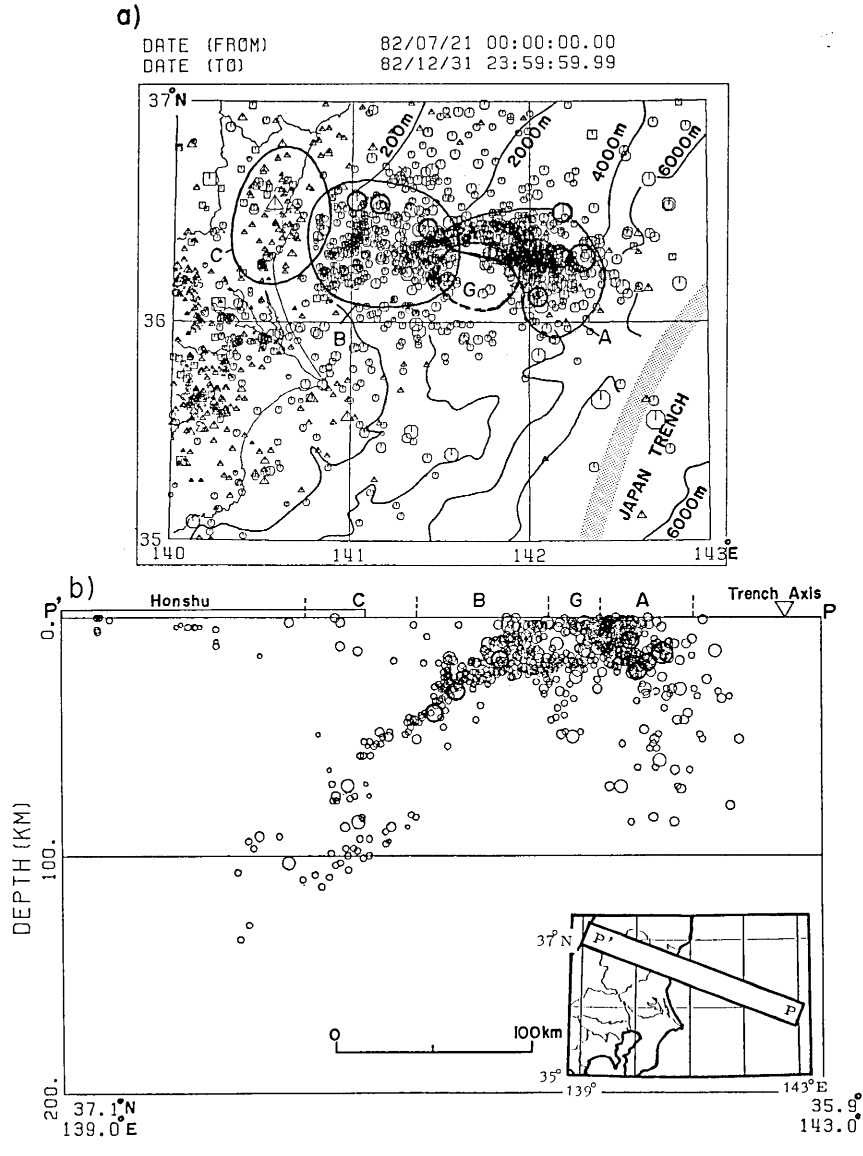


Fig. 16-(a). Epicentral distribution during the period from July 21 to December 31, 1982 and (b) the corresponding vertical cross sectional profile along PP' for the rectangular area enclosed by a solid line as shown in the inset. Major earthquakes in the seismic sequence associated with the earthquake of July 23, 1982 (*M* 7.0) are indicated by large empty circles with a heavy line. The aseismic area (G) separating the earthquake provinces (A) from (B) is enclosed by a dashed line.

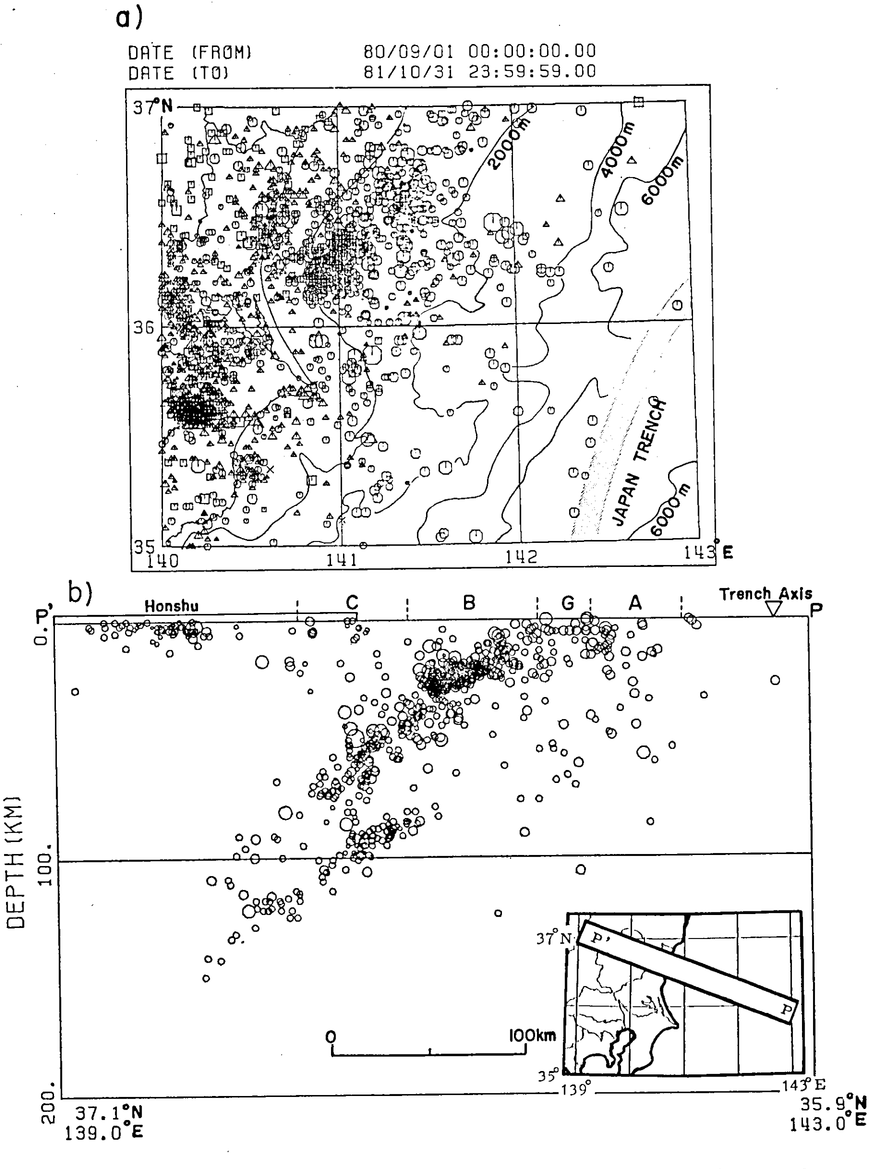


Fig. 17-(a). Epicentral distribution of the background seismicity during the period from September, 1980 to October, 1981 and (b) the corresponding vertical cross sectional profile along the PP' for the rectangular area enclosed by a solid line as shown in the inset. Earthquake provinces and the aseismic area in the text are designated as (A), (B), (C) and (G), respectively.

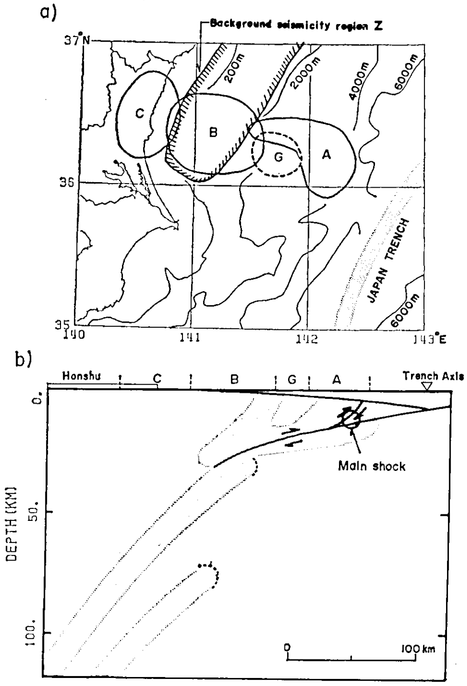


Fig. 18-(a). A schematic illustration of the orderly arrangement of the earthquake provinces (A), (B) and (C), the aseismic area (G) and the region of strong background seismicity Z and (b) the corresponding vertical cross sectional profile from (A) to (C) with an indication of the location of the main shock of July 23, 1982 (*M* 7.0) by an empty circle and seismic zones by hatched area.

iii) Earthquake province (C): An earthquake province (C) of the coastal area was specified corresponding to the aftershock activity from November 1 to December 31. In the sixth stage of the aftershock sequence, a comparatively large number of earthquakes of *M* 4.0~5.1 were located in the coastal and inland areas of Ibaraki Prefecture, though small and microearthquakes were still extensively distributed off Ibaraki Prefecture. The seismic activity in the coastal province were closely related to the double-planed seismic zone dipping to the west at depths of 60~100 km.

A schematic illustration of the arrangement of the earthquake provinces (A), (B) and (C) is shown in Figs. 18-(a) and (b) with an indication of the hypocenters of the main shock of July 23.

6. Westward movement of the aftershock activity

The aftershock sequence accompanying the main shock of July 23, 1982 can be understood in the framework of the westward movement of the aftershock activity. The main shock located on the eastern border of the province (A) is associated with a reverse type faulting with a comparatively large angle of 35° branching from the thrust of a low dip angle on the plate boundary as shematically shown in Fig. 18. The aseismic area (G) located between the provinces (A) and (B) suggests an existence of a locked portion on the interplate boundary preventing successive faultings to the west related to the aftershock activity. The seismic activity in the province (B) was strongly affected for 24~32 days after the main shock occurrence on July 23, related to

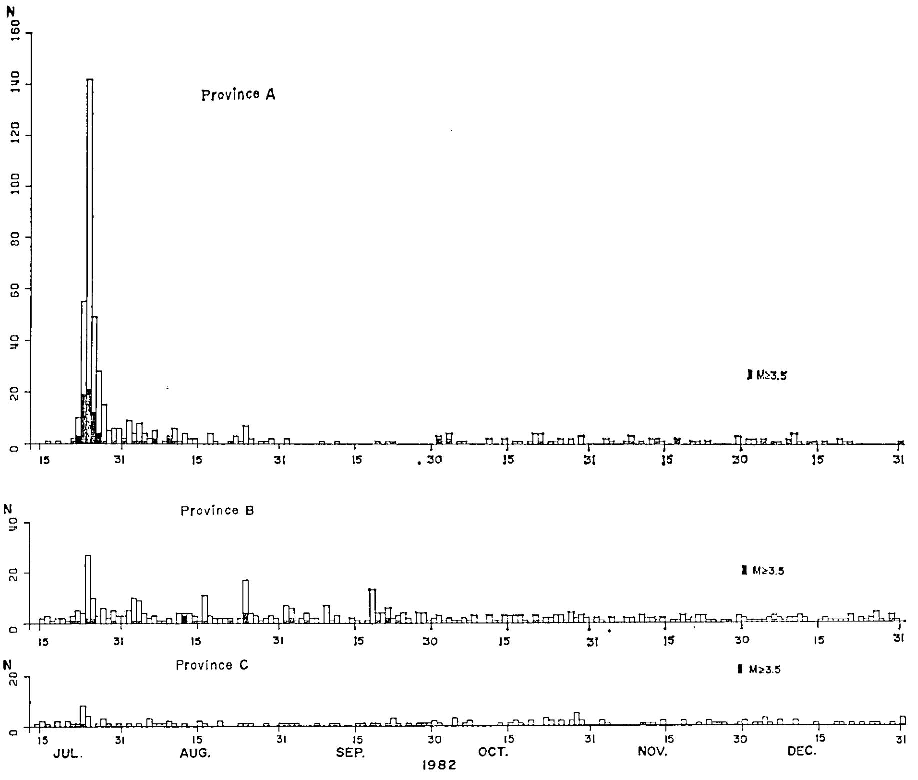


Fig. 19. Daily variations of the number of earthquakes N in the earthquake provinces (A), (B), and (C) located by the microearthquake observation network shown in Fig. 1.

an interaction of the seismic zones at different depth levels as shown in Fig. 18. The seismic activity in the province (C) was slightly activated during the period of more than three months after the main shock occurrence related to the faultings on the upper plane of the double-planed seismic zone.

In the earlier stage of the aftershock sequence when the seismic activity stayed within the province (A), the aftershock area was about 1800 km^2 nearly equal to the value of 1400 km^2 as expected from the empirical formula of $\log S = 1.02\, M_m$-4.0 (UTSU and SEKI, 1955), where S is the aftershock area measured in km^2 and M_m is magnitude of the main shock. Towards the end of the sequence, the aftershock area became as large as 8000 km^2 extending from the province (A) to (C). The temporal variation of the activity in the province (A) was characterized by a typical sequence of foreshocks-main shock-aftershocks, while a swarm type activity was predominant in the province (B) as shown in Fig. 19. Therefore, the abnormally large aftershock area was produced by the westward movement of the seismic activity in

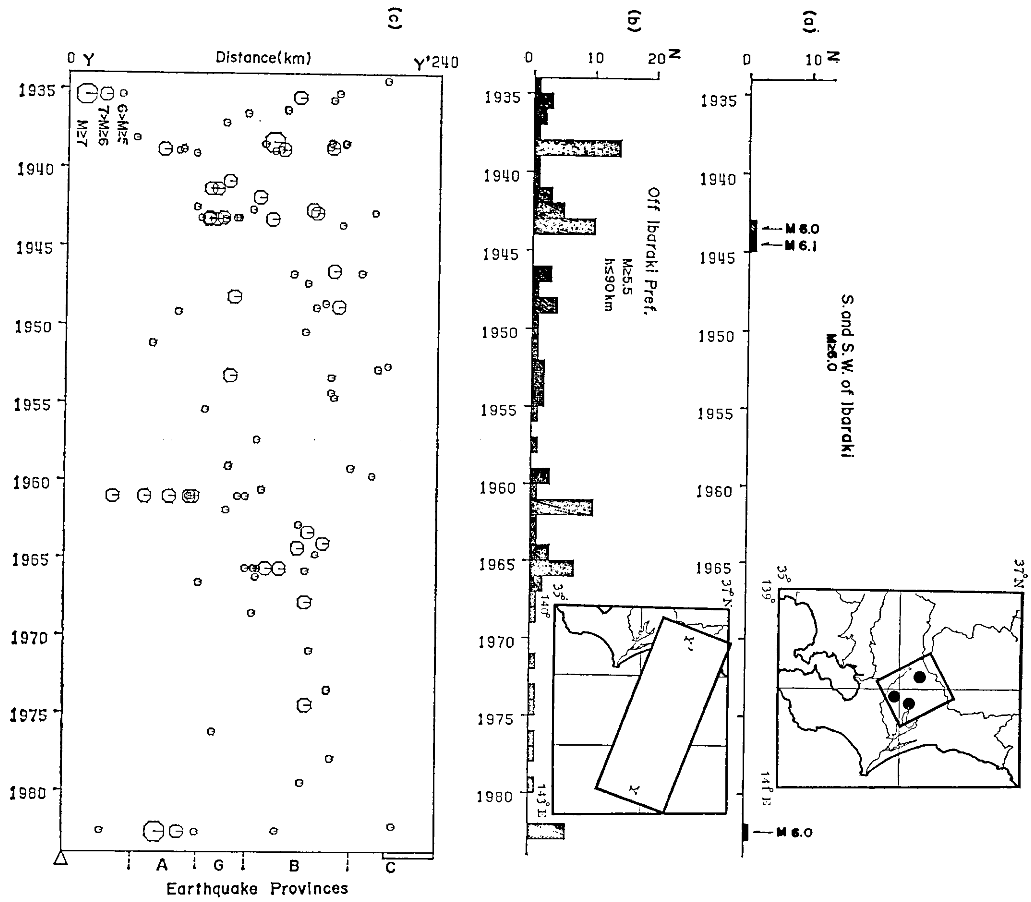


Fig. 20-(a). Annual variations of the number of earthquakes N ($M \geq 6.0$, focal depths $h \leq 90$ km) in the south and the southwest of Ibaraki Prefecture enclosed by a rectangle with an indication of the corresponding earthquakes in the inset, (b) those of N ($M \geq 5.5$, focal depths $h \leq 90$ km) off and in the coast of Ibaraki Prefecture enclosed by a rectangle in the inset and (c) corresponding space-time distribution of the earthquakes as projected on the cross sectional profile along YY' as shown in the inset during the period from 1935 to 1982. Earthquake provinces and the aseismic area in the text are designated as (A), (B), (C) and (G).

which the foreshocksmain shock-aftershocks type of sequence was taken over by a swarm type of sequence.

7. Recurrent mode of seismicity

A continuation of an active period of seismicity for several years has repeatedly been experienced off Ibaraki Prefecture with a succeeding or preceding quiescent period of about 20 years. Looking at the annual variation in the number of earthquakes ($M \geq 5.5$, focal depth

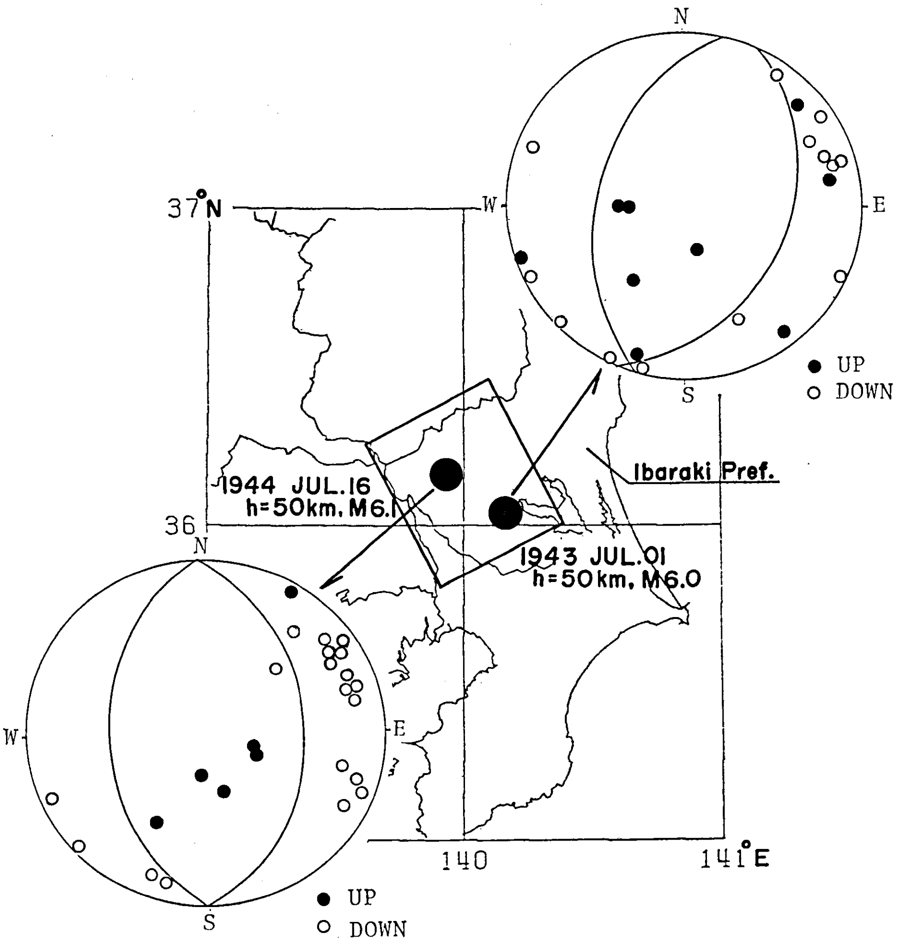


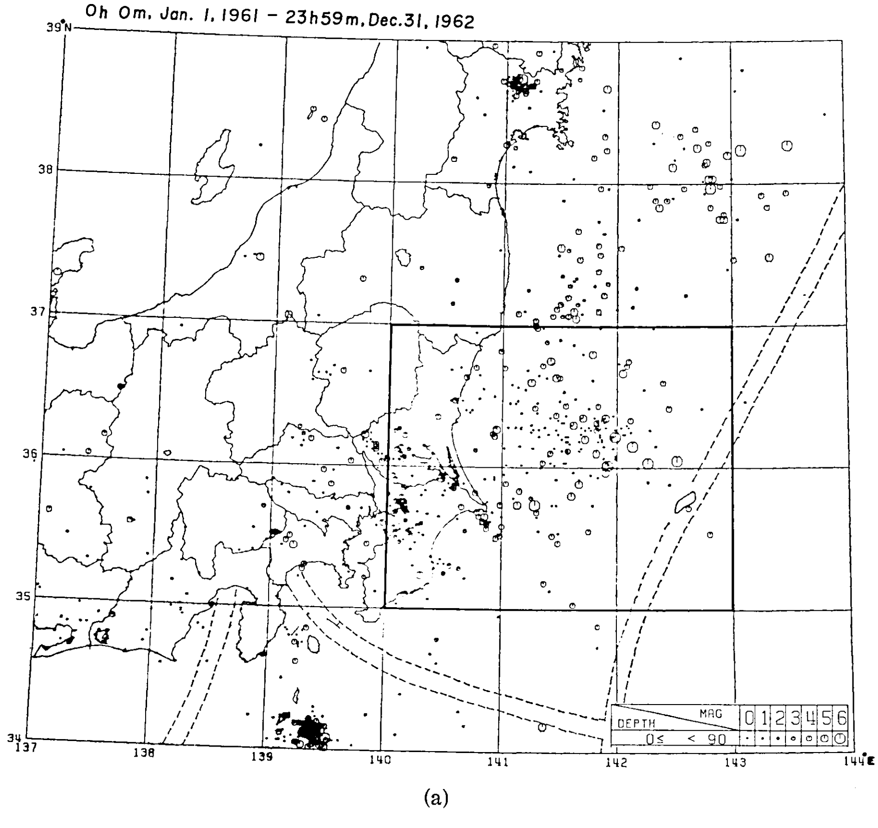
Fig. 21. Epicenters of the earthquakes of July 01, 1943 (M 6.0) and of July 16, 1944 (M 6.1) in the southwest of Ibarki Prefecture (solid circle) and the fault plane solutions of these earthquakes presented as stereographic projection of the upper hemisphere of the focal sphere. These two quakes are counted in the number of earthquakes N as shown in Fig. 20-(a).

$h \leq 90$ km) off Ibaraki Prefecture in Figs. 20-(b), the active periods of seismicity for 1938~1943 and 1961~1965 are identified by a characteristic feature of the two separated peaks marking the beginning and the ending of the active period of seismicity.

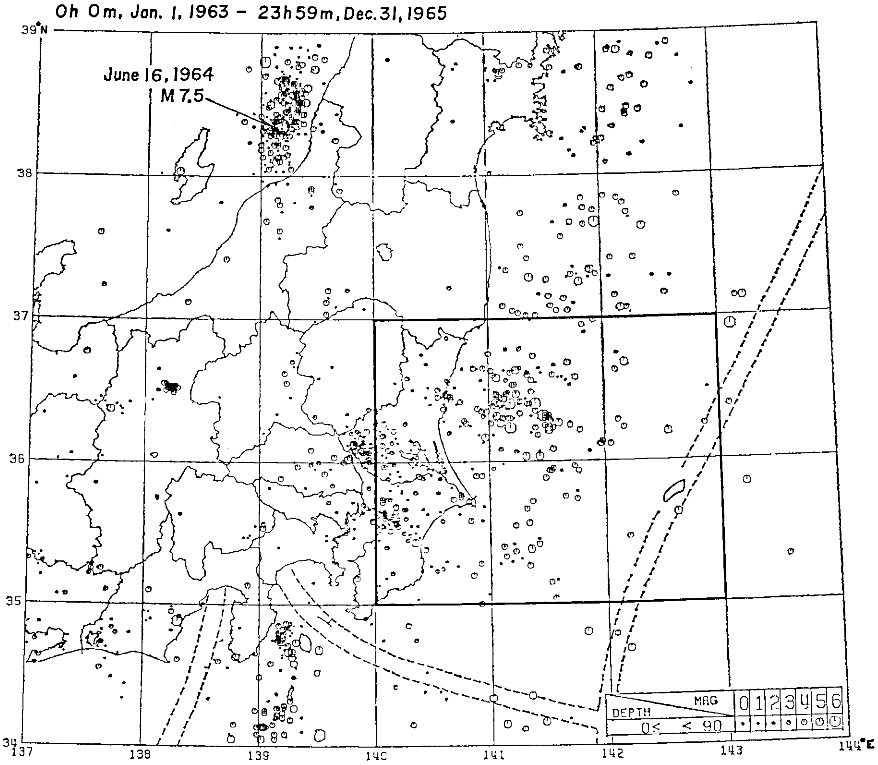
During the active period from 1961 to 1965, the peaks in the number of earthquakes (Fig. 20-(b)) can be correlated with the seismic activities in the two separated areas as shown by the space-time distribution of earthquakes off and in the coast of Ibaraki Prefecture (Fig. 20-(c)). It is noticeable that earthquakes with $M \geq 6.0$ took place successively in 1961 in the trench side area while in 1963~1965 in the coast side area as listed in Table 2 with a gap between the two activated seismic areas. The epicentral distribution in Figs. 21-(a) and (b) presents a regional view of the seismicity in the central part of Honshu during the periods of 1961∼1962 and 1963∼1965. It can be

Table 2. List of the major earthquakes ($M \geq 6.0$) off Ibaraki Prefecture during the period from 1961 to 1965 as shown in Fig. 22-(c).

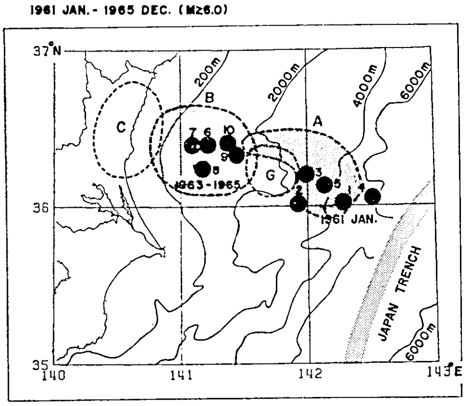
No.	Year	Month	Day	Hour	Min.	Long.	Lat.	Depth (km)	M
1	1961	1	16	16ʰ	20ᵐ	142°27	36°03	40	6.8
2	1961	1	16	20	19	141.92	36.02	20	6.4
3	1961	1	16	21	12	141.98	36.22	20	6.5
4	1961	1	16	23	03	142.52	36.05	40	6.1
5	1961	1	17	00	41	142.13	36.15	40	6.6
6	1963	5	8	19	22	141.18	36.40	40	6.1
7	1964	2	5	20	30	141.07	36.40	40	6.0
8	1964	5	30	23	30	141.18	36.23	40	6.2
9	1965	9	13	01	21	141.47	36.32	40	6.7
10	1965	9	23	07	08	141.40	36.40	40	6.2



(a)



(b)



(c)

Fig. 22-(a). Epicentral distribution ($h \leq 90$ km) in and around the central Honshu during the period from January 1961 to December 1962 and (b) from January to December 1965. (c) The correspnding schematic illustration of big earthquake distribution ($M \geq 6.0$) for 1961~1965 in relation to the earthquake provinces (A), (B) and (C) and the aseismic area (G) off and in the coast of Ibaraki Prefecture as shown in Fig. 18.

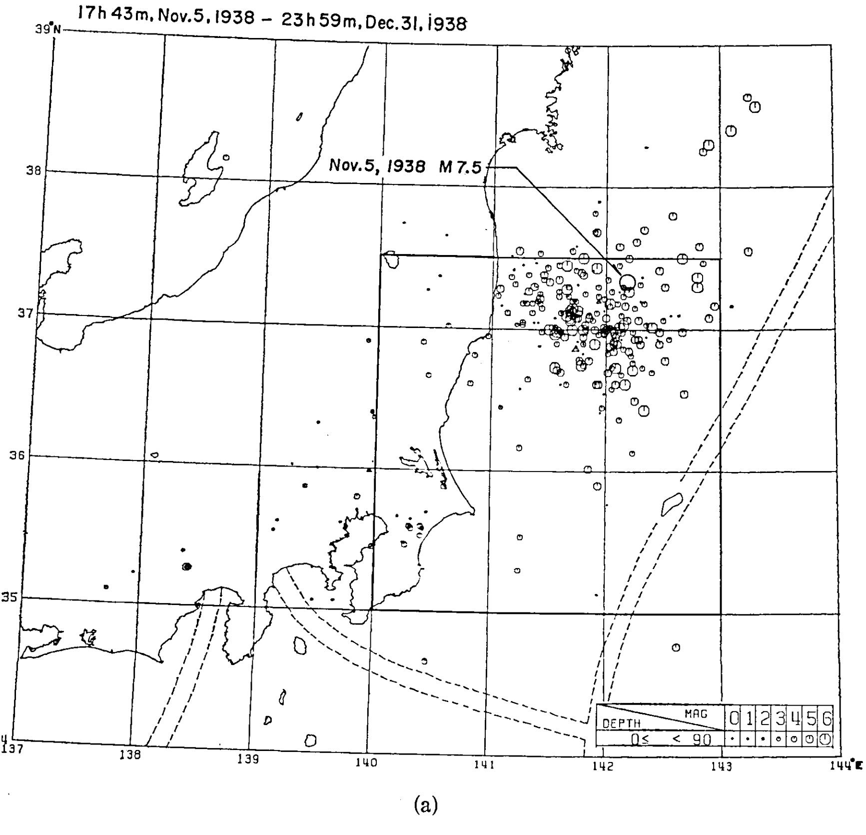
Table 3-(a), (b). List of the major earthquakes ($M \geq 6.0$) off Ibaraki Prefecture during the period from May to December 1938 as shown in Fig. 23-(c) and from March to July, 1943 as shown in Fig. 23-(d).

(a)

No.	Year	Month	Day	Hour	Min.	Long.	Lat.	Depth (km)	*M*
1	1938	5	23	16	18	141°.65	36°.65	0	7.0
2	1938	6	6	01	31	140.40	35.77	50	6.1
3	1938	9	22	03	52	141.02	36.40	30	6.5
4	1938	10	29	22	08	141.15	35.63	0	6.4
5	1938	11	5	17	43	142.18	37.33	30	7.5

(b)

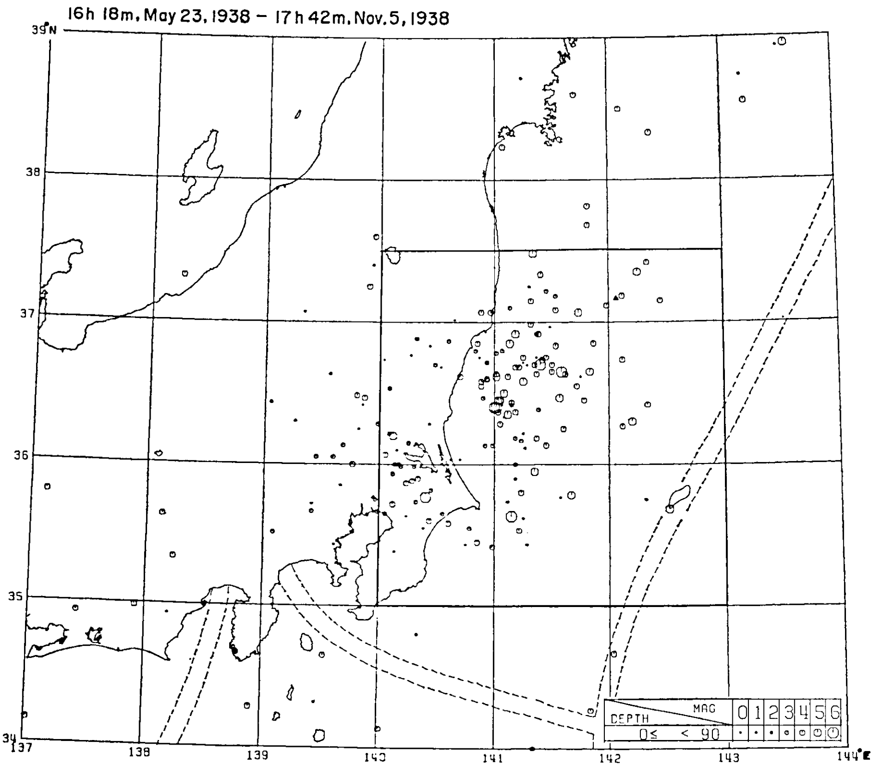
No.	Year	Month	Day	Hour	Min.	Long.	Lat.	Depth (km)	*M*
1	1943	3	14	20	59	141°.87	36°.20	60	6.1
2	1943	3	14	21	43	141.73	36.15	0	6.3
3	1943	4	11	23	46	141.45	36.35	10	6.7
4	1943	4	13	04	43	141.85	36.28	0	6.2
5	1943	4	13	04	50	141.83	36.12	60	6.0



(a)

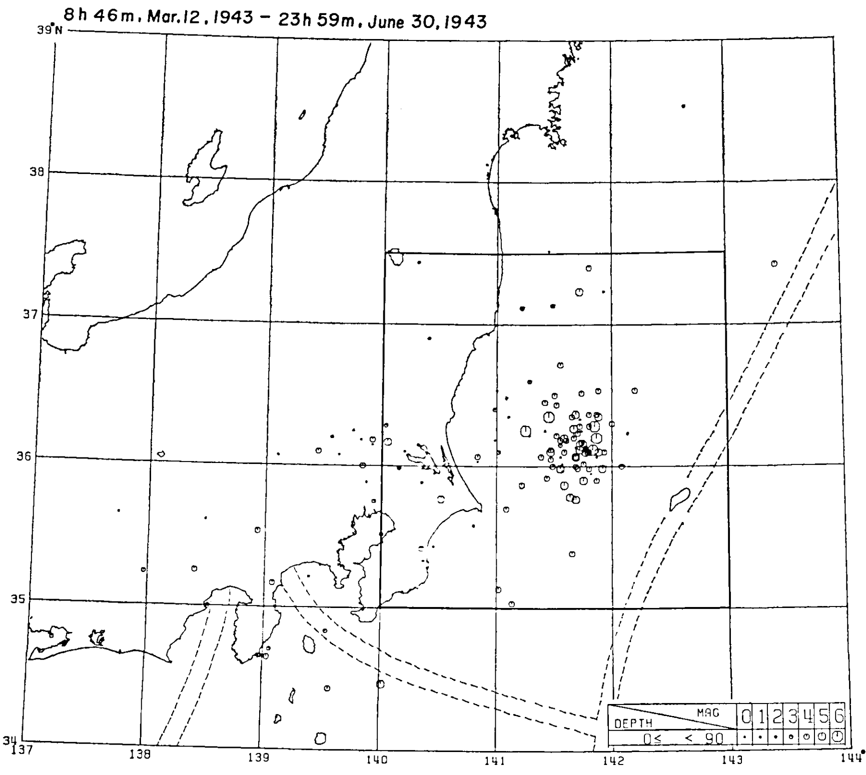
confirmed from the epicentral distribution as given by J. M. A. (JAPAN METEOROLOGICAL AGENCY, 1972) that the earthquakes of M 6.0~7.0 took place in the two separated areas of the trench side and the coast side as observed in 1982. A schematic presentation of the mode of seismicity in Fig. 21-(c) evidently shows that the earthquake provinces (A) and (B) as specified from the activity in 1982 was activated during the period of 1961~1965 separated by the aseisimc area (G). The difference in the time interval required for the shift of the activity from the province (A) to (B) might probably be dependent on the rate of the stress increase in (B) associated with the stress release in (A). A preexisting condition in the aseismic area (G) would take an important role to control the coupling effect of the seismic activities in the two adjacent earthquake provinces.

During the active period from 1938 to 1943, the peak in the number of earthquakes in Fig. 20-(b) can be correlated with the seismic activity in the coast side area, while the peak in 1943 with that in the intermediate area between the coast side and the trench side areas. Epicentral distribution in Figs. 22-(a), (b) and (c) as give by



(b)

J. M. A. (JAPAN METEOROLOGICAL AGENCY, 1982) presents a regional view of the seismicity in the central part of Honshu during the periods from May 1938 to November 1938, from November 1938 to December 1938 and from March to June 1943, in which earthquakes with M 6.0~7.0 occurred successively off Ibaraki Prefecture as listed in Table 3-(a) and (b). The successive occurrence of large earthquakes with M 6.0~7.0 in the coast side area from May to October, 1938 was followed by the M 7.5 Fukushima-Toho-Oki Earthquake of November 5, 1938. The aftershock distribution showed a clear boundary between the two seismic regions off Ibaraki Prefecture and off Fukushima Prefecture as shown in Fig. 22-(b). In the last stage of the activity, large earthquakes occurred successively in the intermediate area between the trench side and the coast side areas as shown in Fig. 22-(c). A schematic presentation of the mode of seismicity in Figs. 22-(d) and (e) shows that the intermediate area remained until as a seismicity gap until large earthquakes fully occupied the area overlapping with the aseismic area (G) as specified from the aftershock activity in 1982. A comparatively long time interval between the beginning of the activity

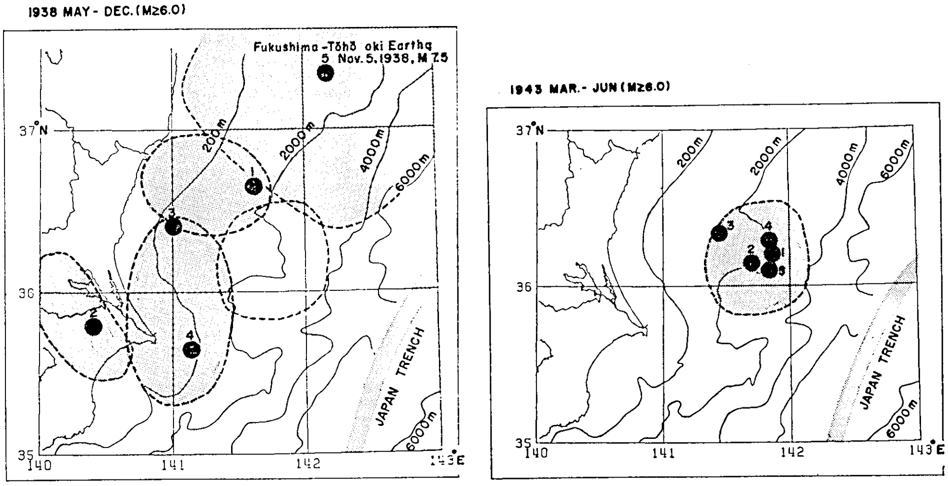


(c)

in 1938 and the final events in 1943 in the area (G) suggests that the strength in (G) was considerably higher than in the surroundings.

From the above considerations of the recurrent nature of the mode of seismicity off Ibaraki Prefecture, it can be suggested that the earthquake provinces as shown in Fig. 18 are potential places to generate earthquakes with *M* 6.0$\sim$7.0 successively by forming epicentral groups separated from neighbouring activities in space-time sequence. The aseismic area (G) as revealed in the repeated seismic sequences may be an indication of an existence of a local barrier preventing successive faultings on the plate boundary. It will be noteworthy in this connection that the no superficial geological faults are found in the area (G) where submarine topography shows a very small inclination to the east as shown in Fig. 23.

An occurrence of large earthquake with *M* 6.0$\sim$6.5 in the south and southwest of Ibaraki Prefecture present a typical example of a regional mode of seismicity coupled with the occurrence of large earthquakes off Ibaraki Prefecture. Succeeding the last stage of the aftershock sequences accompanying the earthquake on July 23, 1982 off Ibaraki Prefecture, a large earthquake with a *M* 6.0 took place on February 27, 1983 in the south of Ibaraki Prefecture. A similar type



(d) (e)

Fig. 23-(a). Epicentral distribution in and around the central Honshu ($h \leq 90$ km) during the period from May 23, 1938 to November 5, 1938, (b) from November 5, 1938 to December 31, 1938 and (c) from March 13, 1943 to June 30, 1943 and (d) the corresponding schematic presentation of big earthquake distribution ($M \geq 6.0$) during the period from May to December 1938 and (e) from March to July, 1943 in relation to the earthquake provinces and the aseismic area (G) off Ibaraki Prefecture as shown in Fig. 18.

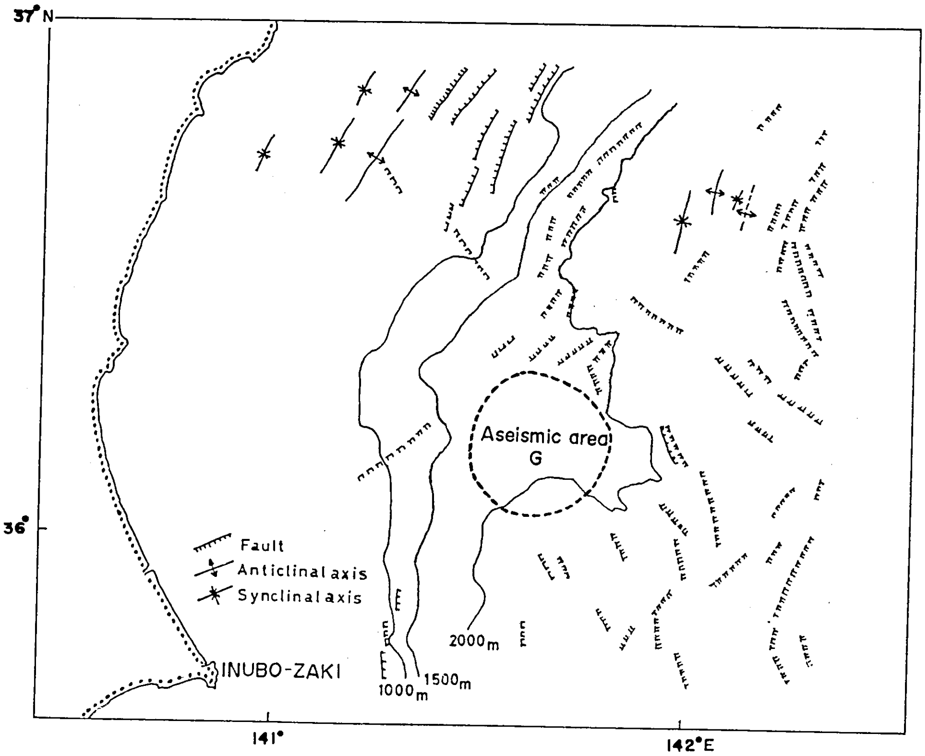


Fig. 24. Submarine topography and geological fault distribution in the south off Joban district (after Hydrographic Department, Maritime Safety Agency, 1980) in relation to the location of the aseismic area (G). Note that no geological faults are found in the aseimic area (G) where the submarine topography shows a very small inclination to the east.

of sequence was found for the activity during the period from 1938 to 1943 off Ibaraki Prefecture coupled the two large earthquakes in the south of Ibaraki Prefecture on July 01, 1943 (M 6.0) and on July 16, 1944 (M 6.1) as shown in Fig. 24 and Fig. 20-(a). Judging from the fault plane solutions of these earthquakes as well as from their hypocentral locations, it is highly possible that the earthquakes were triggered by the occurrence of large earthquakes off Ibaraki Prefecture under the interactive stress system associated with the Pacific and the Philippine Sea plates.

8. Summary and conclusions

i) A systematic space-time sequence was found in the seismic activity accompanying the earthquake of July 23, 1982 (M 7.0) off Ibaraki Prefecture. Three earthquaks provinces were specified in the trench side (A), the transitional (B) and the coastal (C) zones through a westward movement of the aftershock activity.

ii) In the province (A), earthquakes were mostly of shallow origin at depths of less than 30 km including the main shock on July 23. In the transitional province (B), both shallow and deep origin earthquakes were observed. In the province (C), earthquakes were mostly of deeper origin at depths of more than 40 km, where the pronounced double-planed distribution of earthuakes descending to the west was clearly observed.

iii) The earthquake provinces (A) and (B), as revealed in the earlier stages of the westward movement of the seismic activity, were separated by an aseismic area of a 30∼40 km in length. The aseismic area, showing a recurrent nature as found in the sequence during the periods of 1938∼1945, 1961∼1965 and July-Septmber, 1982, possibly related to the existence of a locked portion preventing a successive faulting on the interplate boundary in the process of the westward movement.

iv) A remarkable epicentral lineation striking in the direction of about N 30°E was observed as one of the predominant modes of background seismicity off Ibaraki Prefecture at depth of about 20∼40 km. The transitional province (B) overlapped with the background epicentral area. Both of the shallow and the pronounced double-planed deeper origin earthquakes produced a triple-planed structure of hypocentral distribution in the eastern part of the province (B).

v) Towards the end of the sequence of the westward movement, seismicity in the province (C) were activated remarkably with a penetration of hypocenters as deep as 60∼80 km in the coast of Ibaraki Prefecture accompanied by a noticeable earthquakes of M 4.0∼4.3 in the southern and the southeastern part of Ibaraki Prefecture.

vi) A large earthquake with a M 6.0 occurred on February 27, 1983 in the south of Ibaraki Prefecture. Judging from the location and the focal mechanism of this earthquake, it is highly possible that the earthquak was in close relation to the westward movement of the aftershock activities associated with the earthquake of July 23, 1982 off Ibaraki Prefecture.

vii) It can be concluded from the above consideration that the seismic sequence of the westward movement was closely related to the regional effects of the subduction of the Pacific plate involving a extraordinarily large area covering more than 8000 km^2 as compared to ordinary cases of the aftershock area of an earthquake of M 7.0.

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2. 1982年7月23日茨城県沖地震にともなう地震活動の西方移動について

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1982年7月23日23時23分に発生した茨城県沖地震（M 7.0）は顕著な前震および余震活動をともなった．この活動は1966年以来の約16.5年にわたる静穏期にひきつづいて発生した．関東地方における微小地震観測網によりとらえたこの活動の特徴は次のようである．

i) 海溝寄りから茨城県沿岸部にかけて余震活動がひろがったが，この余震活動の時空間分布から余震域を3つの地震区A), B)およびC)に分けることができる．余震活動はこれらの地震区を東から西へと移動した．

ii) 余震活動の初期には東側，海溝寄りの地震区A)でM 5.9〜6.2を含む余震が発生しそれらの震源の深さは大部分のものが30km以浅であった．本震はこの海溝寄りの地震区の東端に位置し震源の深さは約15kmと推定される．

iii) 海溝寄りの地震区A)はその西隣りの地震区B)と長さ30〜40kmの低地震活動域により分離されている．この低地震活動域は断層面の摩擦の大きい部分に対応する可能性がある．地震区B)ではM 5.4〜5.8を含む余震が発生し，それらの震源の深さは30km以浅のものとより深いものとがある．後者は沈みこむ太平洋プレートに対応する2層構造の震源に属する．

iv) 余震活動の終期には茨城県東岸での活動の高まりが見られその震源の深さは60〜80kmであり2層構造の上面の地震活動の活発化を示唆する．

v) 1983年2月27日，茨城県南部の地震（M 6.0）は上記の経過からみてこの茨城県沖地震と連鎖して発生した可能性が高い．茨城県沖地震(1982年7月23日，M 7.0)およびその余震活動が太平洋プレートとユーラシア・プレートとの相互作用によるものと考えられるが，この茨城県南部の地震は太平洋プレートとフィリピン海プレートとの相互作用によるものと考えられる．

vi) 以上から今回の茨城県沖地震にともなう余震活動の西方移動は3つのプレート間の相互作用を反映した一連の現象であると推察される．