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著者	Umino Norihito, Hasegawa Akira, Takagi Akio
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The Relationship between Seismicity Patterns and Fracture Zones beneath Northeastern Japan

NORIHITO UMINO[1], AKIRA HASEGAWA
and AKIO TAKAGI[2]

Observation Center for Prediction of Earthquakes and Volcanic Eruptions
Faculty of Science, Tohoku University, Aoba-ku Sendai 980

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Abstract: Using microearthquake data of the Tohoku University seismic network during the period from April, 1975 to April, 1988, we examine the seismicity pattern and tectonics beneath the northeastern Japan arc. Most of the high seismicity regions along the plate boundary correspond to the rupture areas of previous large interplate earthquakes ($M \geq 7.0$) and are bounded by the landward extensions of the fracture zones in the Pacific plate. The high seismicity regions and the rupture areas of large interplate earthquakes suggest strong mechanical coupling between the Pacific plate and the overriding Eurasian plate.

Five intraplate earthquakes are located in and around the fracture zones far east off the Japan trench. Some of them have the suggestive focal mechanism of lateral movement of the Pacific plate across the fracture zone. Beneath the landward extension of the fracture zone occurred a large intermediate-depth earthquake (M 6.5; h=177 km), with a hinge fault type mechanism. This suggests continuation of the fracture zone through the subducted Pacific plate beneath northeastern Japan.

Within one month preceding the occurrence of the 1983 Japan Sea earthquake (M 7.7), earthquake swarms occurred in the vicinity of the fracture zones and near the landward extensions of the fracture zones. Preceding the occurrence of large earthquakes, tectonic stresses would change over a wide area and would cause such earthquake swarms near the fracture zones.

1. Introduction

The subduction zone beneath northeastern Japan is one of the world's most active seismic regions. Not only many large interplate earthquakes occur between the subducting Pacific plate and the overriding Eurasian plate, but also many intraplate earthquakes occur in the double-planed deep seismic zone beneath northeastern Japan (*e.g.* Hasegawa *et al.*, 1978). The interplate seismicity is related to the mechanical coupling between the subducting plate and the overriding one (Kanamori, 1971; Ruff and Kanamori, 1980).

Nakayama (1987) discussed the seismo-tectonic implication of the aseismic front (Yoshii, 1975) based on the focal mechanism distribution and the epicenter distribution of microearthquakes by using Tohoku University seismic network data. Figure 1 shows

[1] Fellow at Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington DC 20015 (1988-1989).

[2] Now at Faculty of Science, Kagoshima University, Kagoshima 890.

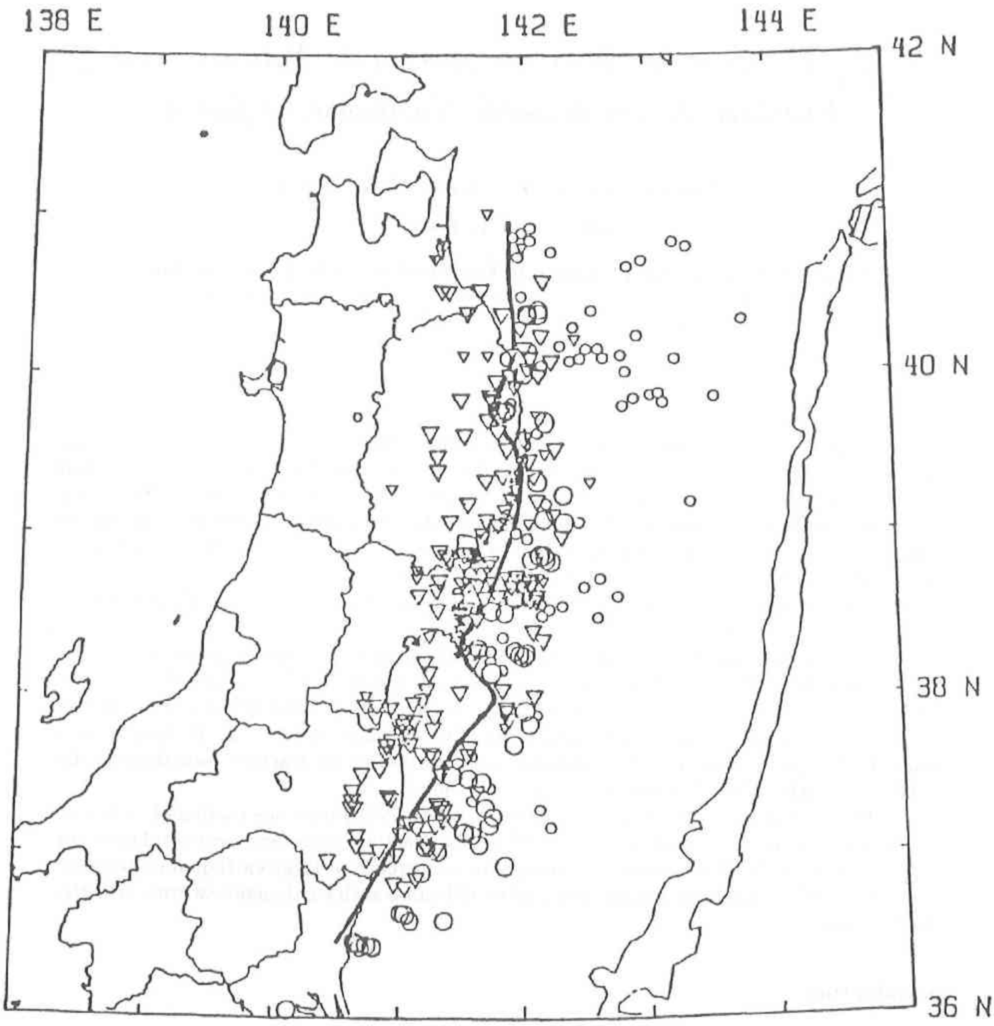

Fig. 1 Distibution of fault mechanisms of earthquakes which occurred in the upper seismic plane of the double-planed deep seismic zone beneath northeastern Japan (Nakayama, 1987). Open circles and open triangles denote low-angle thrust fault events and down-dip compressional events, respectively. Thick solid line shows the western margin of the region where low-angle thrust fault events occur.

the focal mechanism distribution of earthquakes which occurred in the upper plane of the double-planed deep seismic zone beneath northeastern Japan. Open circles denote the epicenters of low-angle thrust fault events, and open triangles denote the epicenters of down-dip compressional events. Small symbols and large symbols refer to studies by Umino and Hasegawa (1982) and Nakayama (1987), respectively. The western margin of the distribution of low-angle thrust fault events shown by the thick line is nearly coincident with the western margin of the high seismicity regions (Fig. 3), for which regions the mechanical coupling between the Pacific plate and the overriding plate is thought to be relatively strong.

Hasegawa and Takagi (1987) showed that the rupture areas of large shallow earthquakes beneath the Pacific Ocean in and around the northeastern Japan subduction zone are bounded by the landward extensions of the fracture zones estimated from the offsets of magnetic anomaly lineations by Hilde *et al.* (1976). Figure 2 shows the rupture

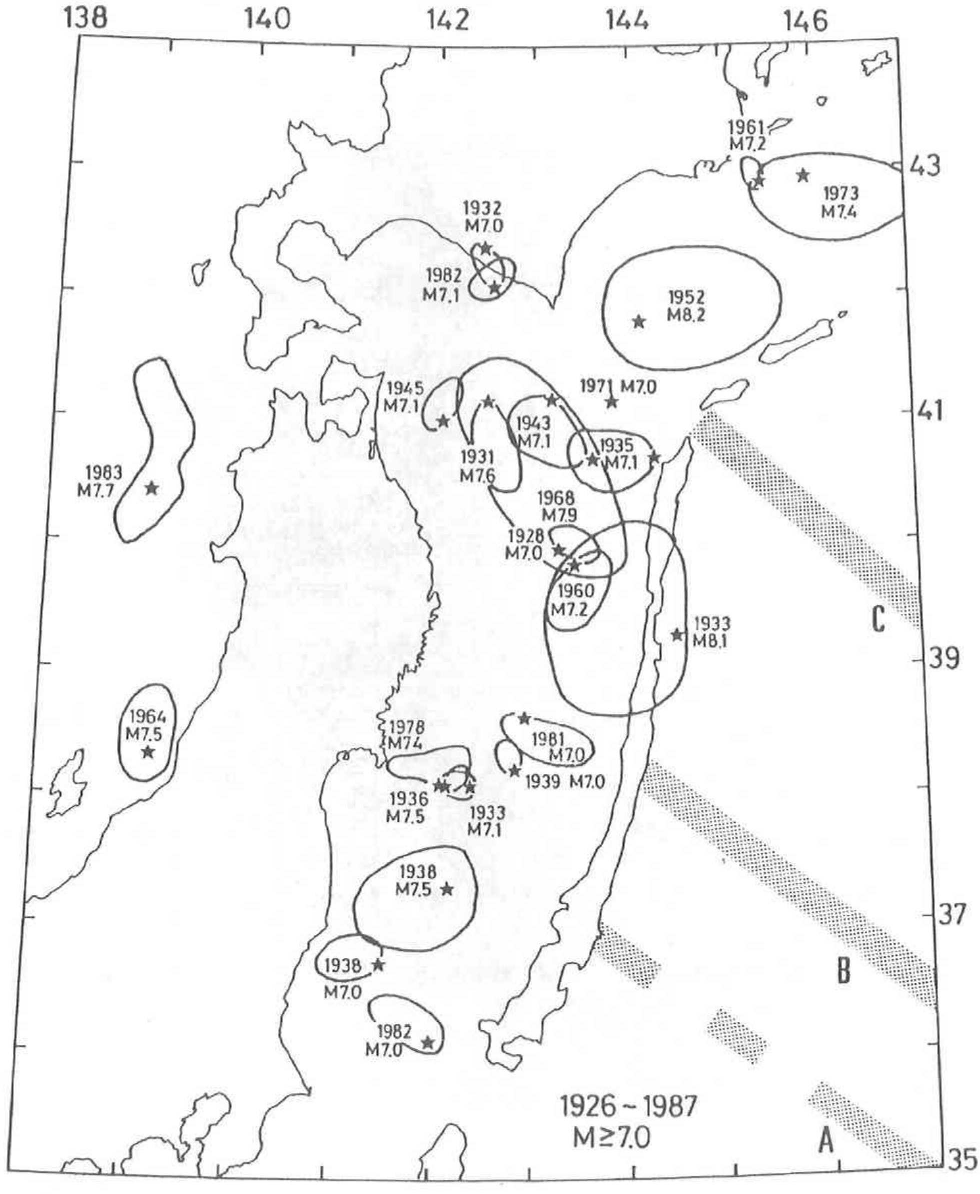

Fig. 2 Distribution of rupture areas of large shallow eathquakes ($h \leq 60$ km) with magntiude 7 or greater (1926-1987). Stars denote epicenters of the main shocks The fracture zones (Hilde *et al.*, 1976) are shown by shaded areas A, B and C.

areas of shallow large earthquakes ($M \geq 7.0$; $h \leq 60$ km) in and around northeastern Japan during the period from 1926 to 1987. The rupture area is determined by the 24-hour aftershock area as determined from the Japan Meteorological Agency (JMA) network data (1926-1975) and from the Tohoku University network data (1976-1987). Although the distribution of the rupture areas is slightly different from that shown by Nagumo (1973), which is defined by the one-month aftershock area, some of the rupture areas are still bounded by the landward extensions of the fracture zones A-C shown by

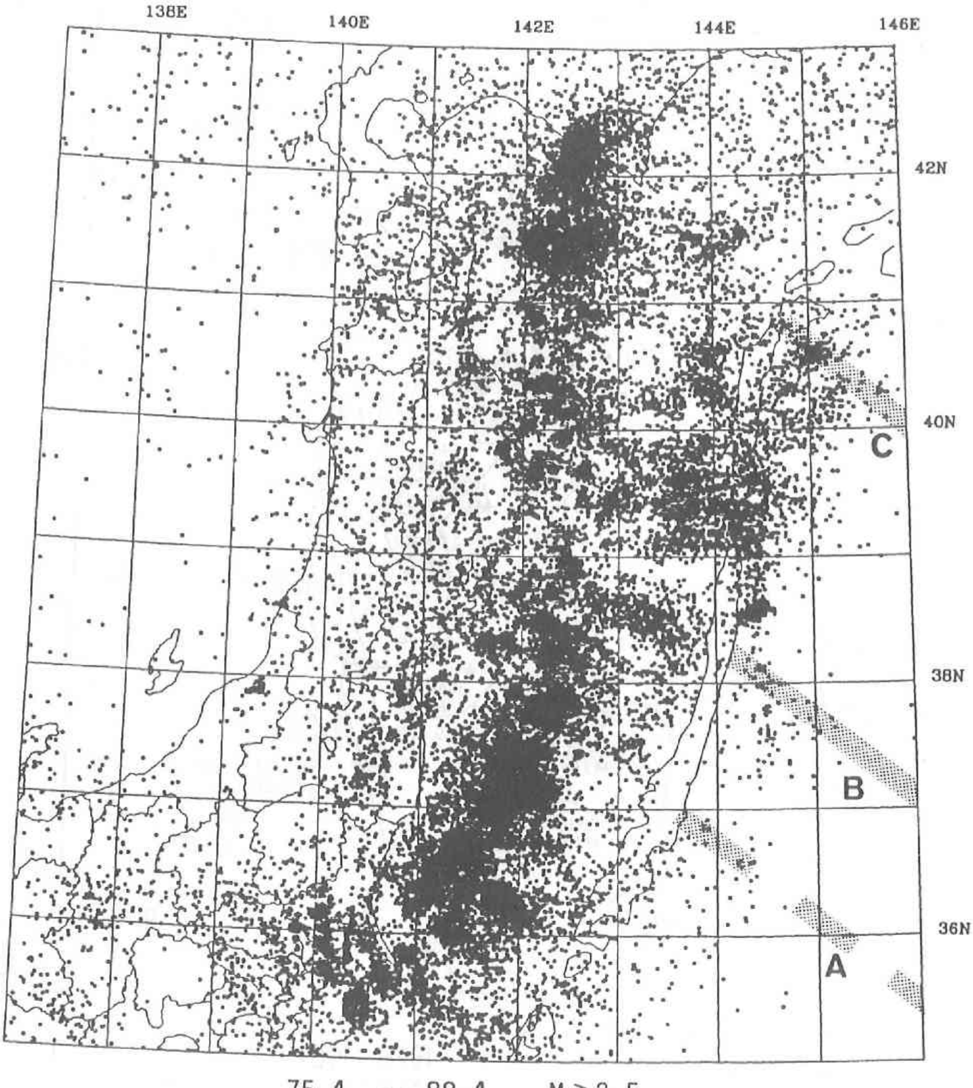

Fig. 3 Epicenter distribution of earthquakes ($M \geq 2.5$) which occurred at the plate boundary between the Pacific plate and the Eurasian plate and in the Pacific plate. All the epicenters are shown by small circles with no distinction for magnitude. Shaded areas denote the fracture zones in the Pacific plate (Hilde *et al.*, 1976).

the shaded areas. Sizes of rupture areas and magnitudes of main shocks are larger in northern part than those in southern part of northeastern Japan. The distribution of the rupture areas and the main shock magnitudes of large interplate earthquakes suggests a change in the strength of mechanical coupling along the plate boundary across the subducted fracture zones.

2. Seismicity of Interplate Earthquakes

Figure 3 shows the epicenter distribution of earthquakes ($M \geq 2.5$) related to the subduction of the Pacific plate. From the seismic network data of Tohoku University for the period from April, 1975 to April, 1988, the hypocenters of these earthquakes are located in the Pacific plate and along the plate boundary between the subducting Pacific plate and the overriding Eurasian plate. Hypocenters of earthquakes which occurred inland northeastern Japan ($h \leq 40$ km) and in the Japan Sea area are excluded in this figure. The western margin of the active seismic region, the aseismic front (Yoshii, 1975), is nearly parallel with the Japan trench, but is doglegged at 100 to 150 kilometer intervals. The seismicity pattern of these interplate earthquakes changes across the landward extensions of the fracture zone (Hilde *et al.*, 1976). For example, the trend of the high seismicity area off Ibaraki Prefecture and off Fukushima Prefecture, 36°N to 37.5°N, changes its strike from northeast to north at the landward extension of the fracture zone A. There is a triangular aseismic region near the Japan trench at the landward extension of the fracture zone B. At the landward extension of the fracture zone C, there is a marked change in the rate of seismicity. The variation of distribution of these interplate earthquakes is consonant with the aftershock area patterns of large earthquakes (Fig. 2) : both phenomena suggest that the Pacific plate is separated into several segments by the subducted fracture zones beneath northeastern Japan. The strength of mechanical coupling along the plate boundary changes from segment to segment.

Although aftershocks of four large earthquakes which occurred after April, 1975 are included in Fig. 3, we can see some correspondence between the rupture areas of large shallow earthquakes (Fig. 2) and the high seismicity areas along the plate boundary (Fig. 3). The highest seismicity region off Fukushima Prefecture corresponds with the rupture area of the 1938 Fukushima-oki earthquake (M 7.5). Within the rupture area of the 1933 Sanriku-oki earthquake (M 8.1), many microearthquakes and small earthquakes are located. The high seismicity regions within the rupture area of the 1968 Tokachi-oki earthquake (M 7.9) correspond to the locations of its subevents with high stress drop (Mori and Shimazaki, 1984). The low seismicity region, however, corresponds to the vicinity of the epicenter of the 1968 Tokachi-oki earthquake.

3. Intraplate Earthquakes Occurring Far East off the Japan Trench

From the Tohoku University network data, five earthquakes are located far east off the Japan trench for the period from April, 1975 to April, 1988. The epicenters of these earthquakes are shown by large solid circles in Fig. 4 and are listed in Table 1. All of

Table 1. List of Earthquakes Which Occurred Far East off the Japan Trench.

Date	Lat(°N)	Lon(°E)	h(km)	M[1]	N[2]
1977-4- 2 23:11 43.05	37.868	149.452	132	4.1	9
1983-1-24 17:44 34.12	37.994	149.175	93	4.6	19
1985-8-21 15:49 6.29	37.549	150.184	25	5.1	31
1986-8-27 23:22 41.03	37.540	145.984	128	3.5	16
1987-8-23 05:27 34.31	37.311	146.165	25	4.2	26

[1] Magnitude of earthquake
[2] Number of stations

the five earthquakes occurred in and near the fracture zones B and C shown by the shaded areas.

The epicenters of these five earthquakes are located with an accuracy of a few tens of kilometers, because Hasegawa *et al.* (1988) showed that the locations of in-water explosions in this region are determined within 40 km accuracy by using the Tohoku University network data. The depths of the earthquakes are less well controlled than the epicenters and are distributed from 25 km to 132 km. The depths are estimated as 25 km deep in the case of the events detected at many stations (Table 1). The focal depth of the event on August 21, 1985 is estimated as 22 km by using pwP and pwwP phase data (Kishio *et al.*, 1985; Ishikawa *et al.*, 1986). These five earthquakes should have occurred in shallower portion of the Pacific plate.

Distributions of polarities of the P wave first motions are projected on the lower focal hemisphere of the equal area projection (Fig. 5). Because of the one-sided distribution of polarity data, focal mechanism solutions are not determined. By supposing that these events have a strike-slip fault mechanism, we can determine one nodal plane with strike almost parallel with that of the fracture zone (Fig. 4). It appears that these intraplate earthquakes are related to the fracture zones in the Pacific plate, although the left lateral motion of the focal mechanism solution is opposite to the motion deduced from the offsets of magnetic anomaly lineations (Hilde *et al.*, 1976).

The epicenters of earthquakes shallower than 150 km are shown by small solid circles in Fig. 4. A number of earthquakes are located seaward of the Japan trench, bounded by the fracture zones B and C, but the seaward seismicity is lower south of the fracture zone B. The outer rise of the Japan trench is more developed north of the fracture zone B, as indicated by variations in ocean depths. The mechanical coupling along the plate boundary in the northern part is stronger than that in the southern part.

4. Intermediate-Depth Earthquake (M 6.5) near Subducted Fracture Zone

A number of intermediate-depth earthquakes occur in the Wadati-Benioff zone beneath northeastern Japan, but few large intermediate-depth ones occur in this area. Figure 6 shows the epicenter distribution of large intermediate-depth earthquakes ($h \geq$ 70 km) with magnitude 6 or greater. Hexagons and stars denote the epicenters deter-

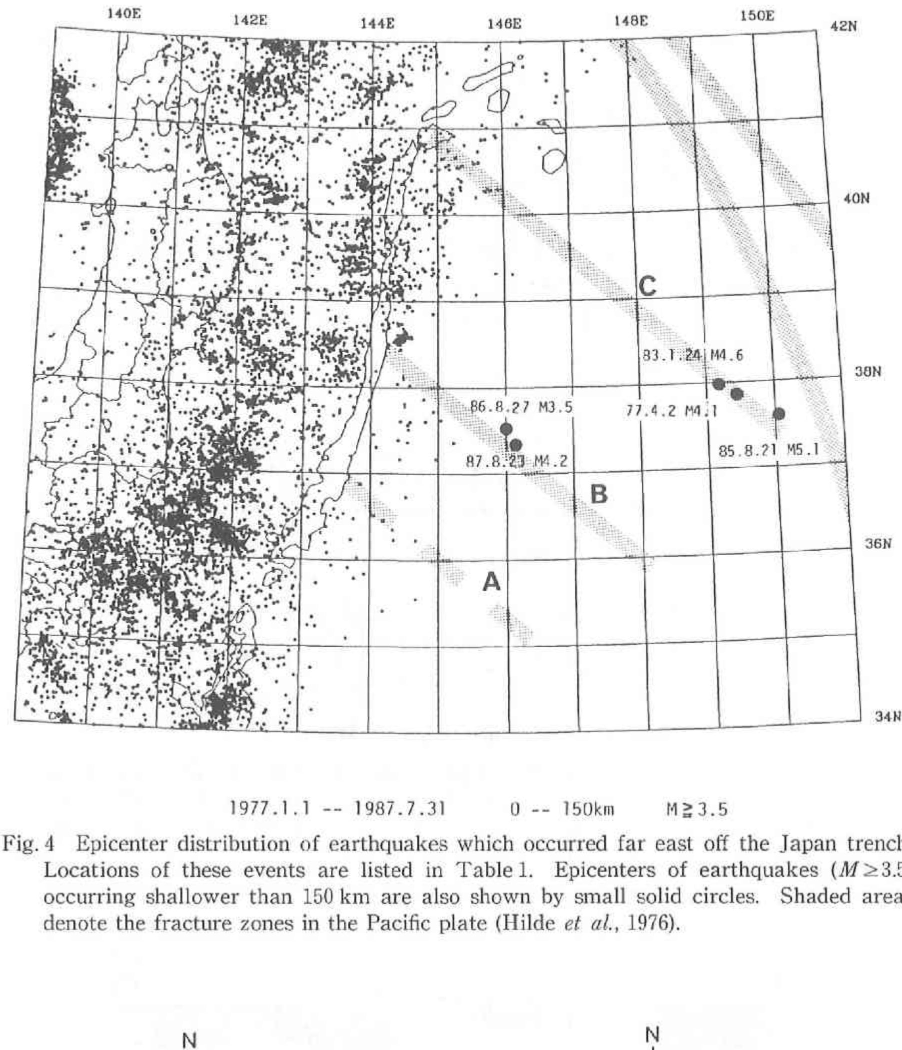

Fig. 4 Epicenter distribution of earthquakes which occurred far east off the Japan trench. Locations of these events are listed in Table 1. Epicenters of earthquakes ($M \geq 3.5$) occurring shallower than 150 km are also shown by small solid circles. Shaded areas denote the fracture zones in the Pacific plate (Hilde *et al.*, 1976).

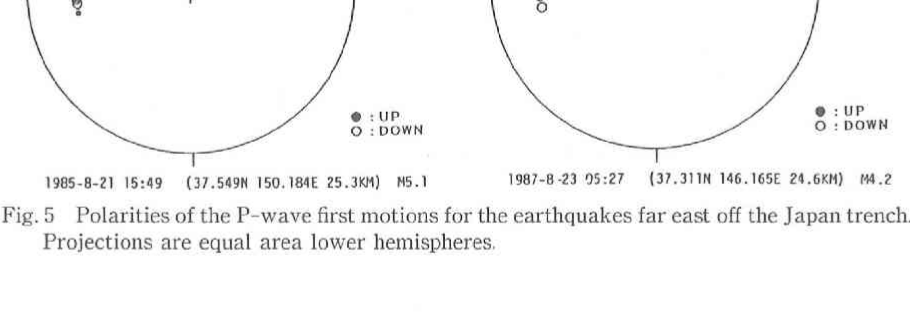

Fig. 5 Polarities of the P-wave first motions for the earthquakes far east off the Japan trench. Projections are equal area lower hemispheres.

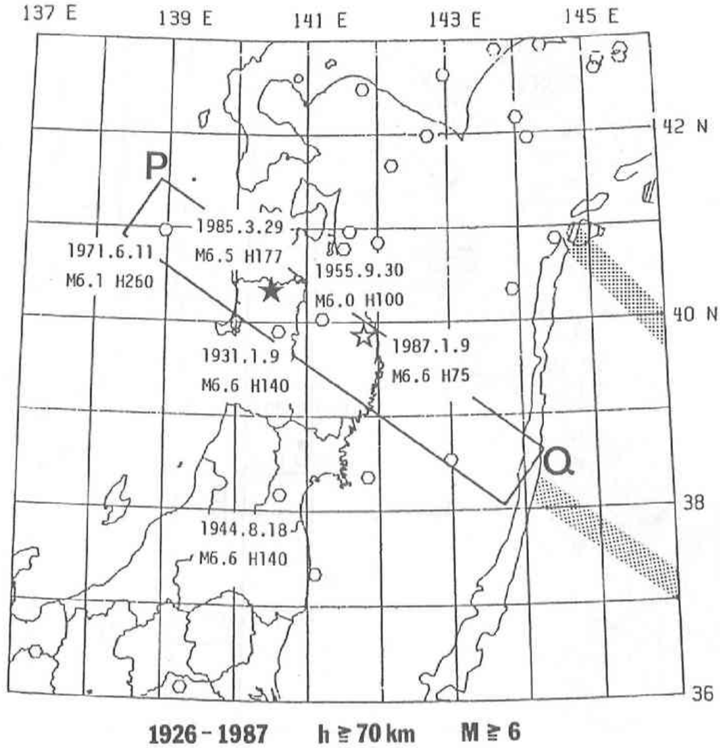

Fig. 6 Distribution of large intermediate-depth earthquakes ($M \geq 6.0$; $h \geq 70$ km) during the period from 1926 to 1987. Hexagons denote epicenters of events before 1976 (determined by the JMA network), and stars denote epicenters of events after 1976. Region PQ is the position of the cross section shown in Fig. 7.

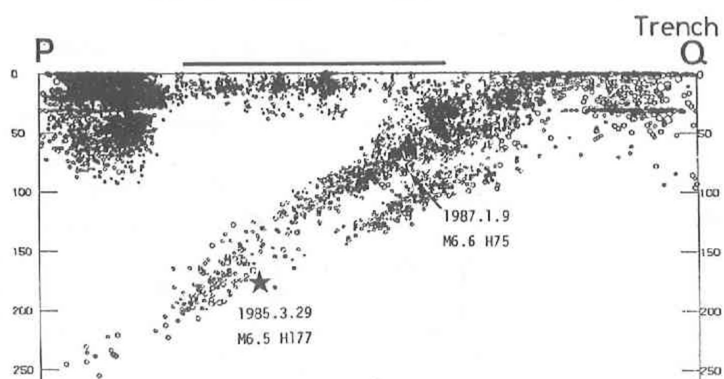

Fig. 7 Vertical cross section of seismicity from the Tohoku University network. Location of the cross section is shown in Fig. 6

mined by the JMA network (1926-1975) and by the Tohoku University network (1976-1987), respectively. The large earthquakes seem to be aligned within the region PQ which is nearly parallel with the direction of the relative plate motion between the Pacific plate and the Eurasian plate (Minster and Jorden, 1978). The region PQ is also located in the landward extension of the fracture zone B.

The vertical cross section of the earthquakes occurring in the region PQ is shown in Fig. 7. Hexagons denote the hypocenters of earthquakes determined by the Tohoku University network during the period from April, 1975 to January, 1987. Two large intermediate-depth earthquakes are shown by stars and the land area of northeastern Japan is shown by a thick line. The shallower event (M 6.6 ; h=75 km), January 9, 1987, is located in the upper plane of the double-planed deep seismic zone, and is characterized by down-dip compression (Umino *et al.*, 1987).

The deeper event (M 6.5 ; h=177 km), March 29, 1985, is located near the lower plane of the double-planed deep seismic zone. The epicenter of the earthquake is thought to be well controlled, because this event occurred beneath the region within the seismic network of Tohoku University. No aftershocks of this event are located by the Tohoku University network. Frohlich (1987) revealed that events between 100 km and 450 km depth had less aftershock activities than shallower or deeper ones. Furthermore, few earthquakes occur in the vicinity of this large event.

The focal mechanism solution of the earthquake (M 6.5 ; h=177 km) is projected on the lower focal hemisphere in equal area projection (Fig. 8). This event has neither down-dip compressional nor down-dip extensional focal mechanism, the predomonant focal mechanism in the double-planed deep seismic zone beneath northeastern Japan (*e.g.* Hasegawa *et al.*, 1978 ; Umino and Hasegawa, 1982), but has a hinge fault type mechanism which suggests a vertical offset of the Pacific plate across the subducted fracture

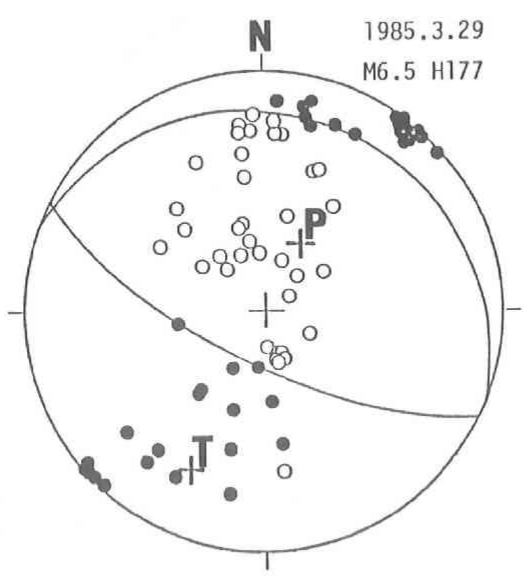

Fig. 8 Focal mechanism solution of the intermediate-depth eathquake (March 29, 1985 ; M 6.5) projected on the lower focal hemisphere by equal area projection method.

zone beneath northeastern Japan. Similar hinge fault mechanism earthquake (*M* 7.7; h=100 km) suggesting vertical offset of the subducted plate was also observed on December 6, 1978 in islandward extension of the fracture zone in the Kurile subduction zone (Sudo and Sasatani, 1979; Brüstle and Müller, 1987).

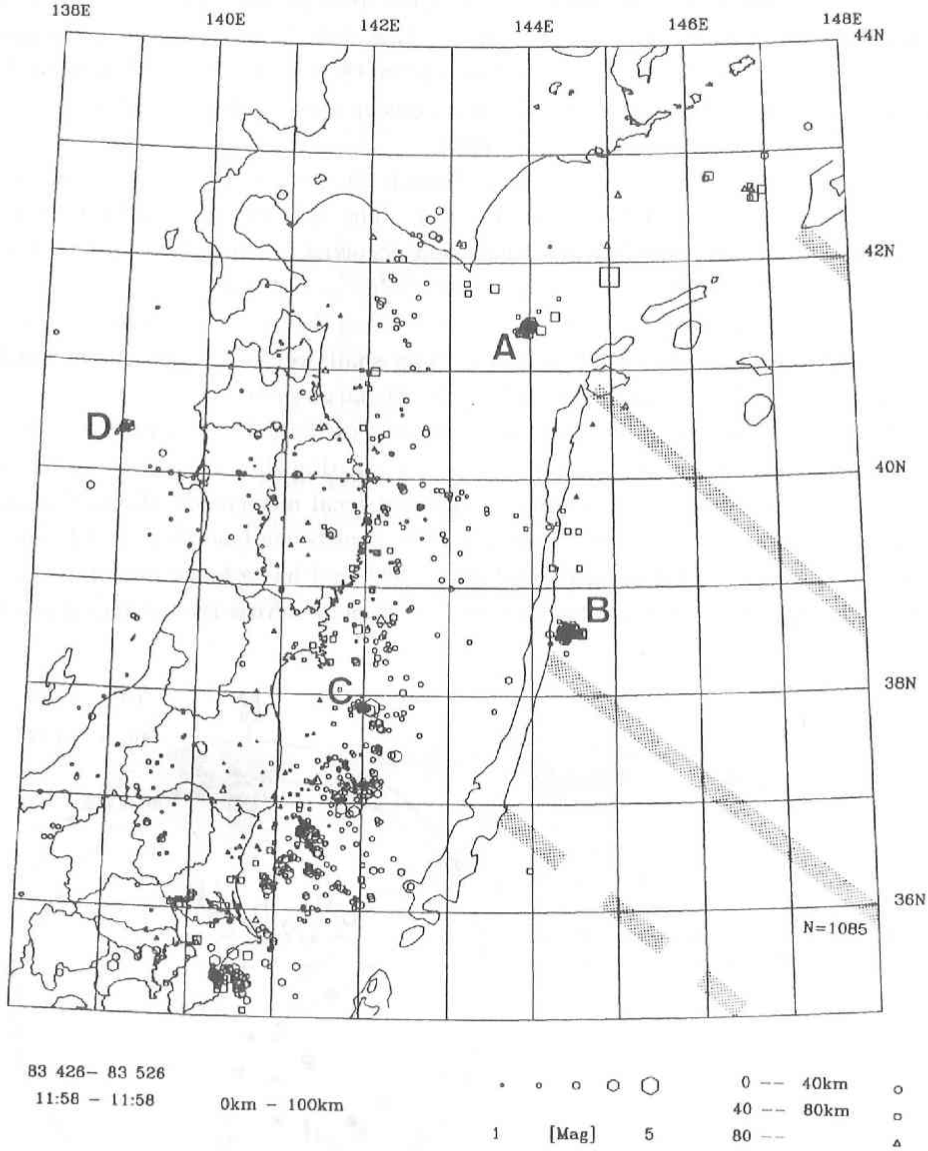

Fig. 9 Epicenter distribution of earthquakes in the month before the 1983 Japan Sea earthquake (*M* 7.7). Labels A-D denote the earthquake swarms preceding the occurrence of the main shock.

5. Earthquake Swarms Preceding the 1983 Japan Sea Earthquake (*M* 7.7)

The 1983 Japan Sea earthquake (*M* 7.7), the largest event in the last decade in northeastern Japan, occurred on the eastern margin of the Japan Basin on May 26, 1983 (Fig. 2). The largest foreshock (*M* 5.0; May 14, 1983) occurred in the vicinity of the main shock hypocenter and 22 other foreshocks were located by the Tohoku University network. The foreshocks can be classified into two groups: one with high peak-fre-

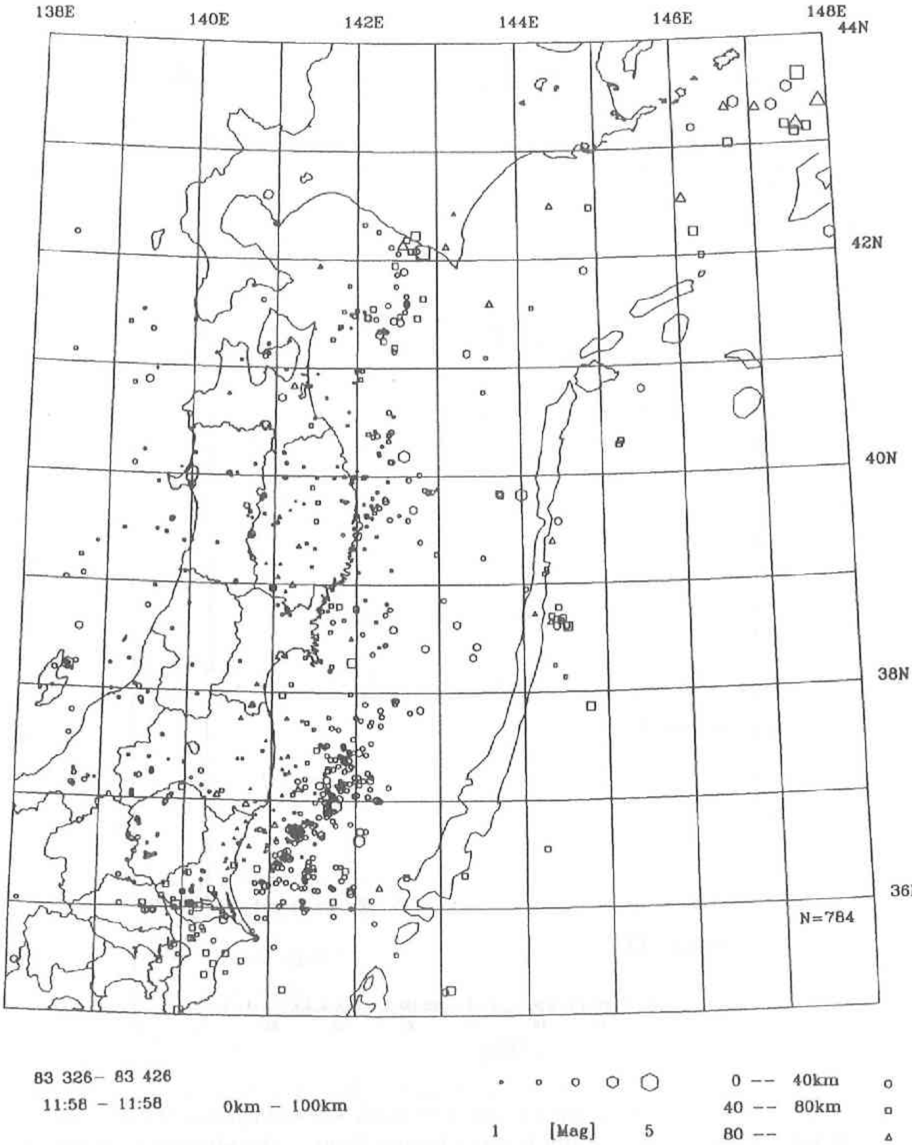

Fig. 10 Epicenter distribution of earthquakes during March 26 to April 26, 1983.

quency and the other with low peak-frequency, within each group, the events have very similar wave forms (Hasegawa *et al.*, 1985 ; Takagi, 1985 ; Umino *et al.*, 1985).

In addition to these foreshocks, three earthquake swarms were observed in and around northeastern Japan preceding the 1983 Japan Sea earthquake. Figure 9 shows the epicenter distribution of earthquakes ($h \leq 100$ km) in the month preceding the 1983 event. We can see four active earthquake swarms labeled A-D. Number of events in each swarm A, B and C is 49, 129 and 53, respectively. All these earthquake swarms occur in the vicinity of the fracture zones or near the landward extensions of the fracture zones, except for D which is the foreshock activity mentioned above. The epicenter

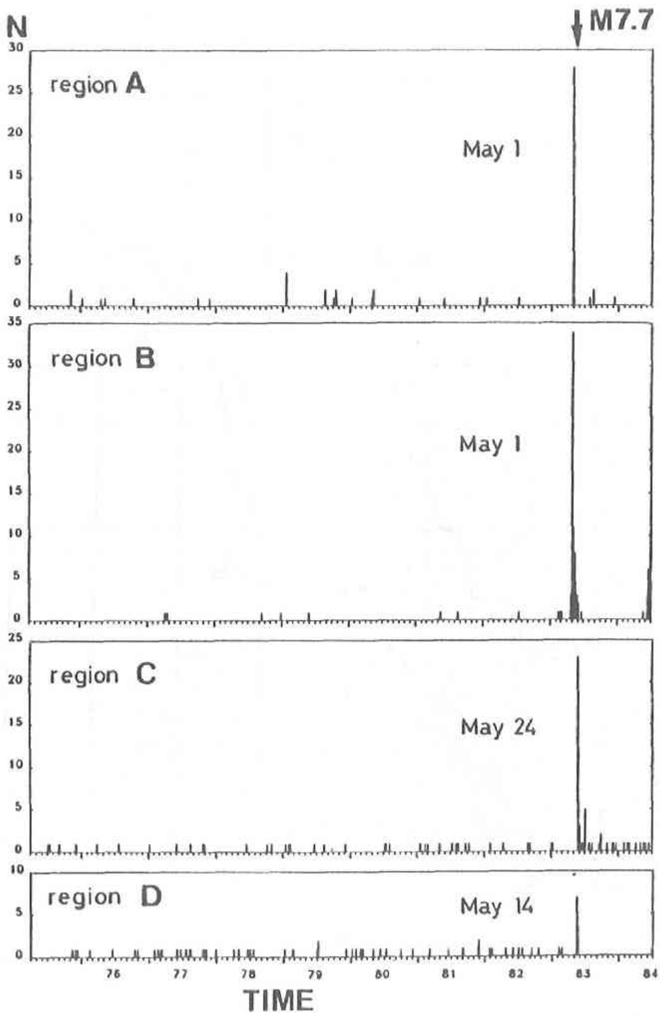

Fig. 11 Distribution of daily number of earthquakes. Regions A to D are shown in Fig. 9. The arrow denotes the occurrence of the 1983 Japan Sea earthquake (M 7.7). The start date for each earthquake swarm is given in each figure. The aftershocks of the 1983 Japan Sea earthquake in region D are excluded.

distribution of earthquakes ($h \leq 100$ km) for one month earlier (March 26–April 26) shows no remarkable swarms (Fig. 10).

Figure 11 shows the daily frequency of earthquakes within the regions A–D shown in Fig. 9. The aftershocks of the 1983 Japan Sea earthquake in region D are excluded from this figure. The arrow denotes the occurrence of the main shock. The date when the earthquake swarm started is shown in each figure. Only one dominant earthquake swarm occurs in each region during the eight years preceding the 1983 event, and all start within one month before the main shock. Swarms A and C became inactive before the main shock, but B continued about 11 days after the main shock.

These earthquake swarms A–C occurred near the fracture zones or the landward extensions of the fracture zones, which would be most sensitive to the change in tectonic stress caused by the subduction of Pacific plate. Preceding the occurrence of large earthquakes such as the 1983 Japan Sea earthquake, tectonic stresses would change over a wide area. Precursory earthquake swarms were also observed beneath northern Tokyo Bay area, preceding some felt earthquakes (seismic intensity three or greater) which occurred in the Kanto District, central Japan (National Research Center for Disaster Prevention, 1982).

6. Conclusions

Beneath northeastern Japan, the subducted Pacific plate is separated into several segments bounded by the landward extensions of the fracture zones (Hilde *et al.*, 1976). The strength of mechanical coupling along the plate boundary changes from segment to segment, since the seismicity of microeathquakes, the size of rupture area and the magnitude of large interplate earthquakes change across the landward extensions of the fracture zones.

The particular large intermediate-depth earthquake (M 6.5; $h=177$ km) with a hinge fault mechanism suggests that the fracture zones continue in the deeper part of the subducted Pacific plate beneath northeastern Japan. Three earthquake swarms occurred in the vicinity of the fracture zones preceding the 1983 Japan Sea earthquake. The intraplate earthquakes far east off the Japan trench and the seismicity in seaward region of the Japan trench are related to the fracture zones in the Pacific plate. The vicinity of the fracture zones will be most affected by the change in tectonic stresses.

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