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Triple Seismic Zone and the Regional Variation of Seismicity along the Northern Honshu Arc

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The regional variation of seismicity along the northern Honshu arc, Japan, is studied using accurate focal depths and focal mechanism types. We use focal depths determined from pP-P time intervals reported in the ISC bulletins. For submarine earthquakes, depths are corrected by considering the pP phase reported in the bulletins as the pwP phase (the reflection from the ocean surface). Out of more than 600 well-located earthquakes selected from the ISC bulletins, we determine the types of the focal mechanisms of 184 events using P wave first motion data. Based on historical seismicity of great and large earthquakes, we divide the zone of thrust type earthquakes at the plate interface into two regions: the shallow thrust zone (0–40 km), where great earthquakes ($M_s \sim 8.0$) occur, and the deep thrust zone (40–60 km), where large earthquakes ($M_s \sim 7.4$) occur. The activity of great or large earthquakes shows a variation along the arc; in some regions, both the shallow and deep thrust zones are active, and in other regions, only one of the thrust zones is active. The seismicity of recent moderate size earthquakes ($m_b > 4$) combined with the focal mechanism type shows a variation along the arc, which reflects the variation of the activity of great or large earthquakes. Where large earthquakes do not occur in the deep thrust zone, neither thrust type nor down-dip compression/tension type events occur in and beneath the deep thrust zone. Where large earthquakes do occur in the deep thrust zone, we find a number of thrust type earthquakes. Further, in the latter case, in some regions, the down-dip compression and tension type events of the double seismic zones extend seaward just beneath the deep thrust zone and form a triple-planed structure of seismicity (the triple seismic zone). This study confirms the hypothesis of previous workers (Seno and Pongsawat, 1981) on the causal relation between the strong seismic coupling of two converging plates at the deep thrust zone and extension of the double seismic zone; i.e., the presence or absence of activity within the slab beneath the deep seismic zone occurs when the deep thrust zone has a strong or weak coupling, respectively. Here, the weak coupling could be interpreted as either aseismic slip or as low stress buildup since the last large event occurred at the deep thrust zone. Triple seismic zones are found offshore of Miyagi prefecture, where the deep thrust zone has been broken recently in 1978, and offshore of Fukushima prefecture. We expect a future large earthquake at the deep thrust zone offshore of Fukushima prefecture because the presence of the triple seismic zone suggests stress has been accumulating and 40 years have passed since the deep thrust zone was ruptured in 1938.

INTRODUCTION

The discovery of the double seismic zone beneath trench-island arc systems, revealed by detailed analyses of seismicity [*Tsumura,* 1973; *Veith,* 1974; *Umino and Hasegawa,* 1975; *Hasegawa et al.,* 1978] has become a new aspect of our understanding of the subduction processes [*Engdahl and Scholz,* 1977; *Isacks and Barazangi,* 1977; *Goto and Hamaguchi,* 1978; *Sleep,* 1979; *Yoshii,* 1979a; *Fujita and Kanamori,* 1981; *House and Jacob,* 1982]. Similarly, a detailed analysis of the spatial and temporal distribution of earthquakes with focal mechanism solutions and accurate hypocentral locations has potential to contribute to our understanding of subduction processes (*i.e.*, the stress state in the slab, rheological properties of the upper mantle at the subduction zone, the occurrence of large earthquakes, etc.) and consequently to the prediction of future large earthquakes.

Most work on the double seismic zone mainly treats intermediate or deep events (>70 km). The results of these studies have helped in understanding the stress state within the descending slabs and the rheological properties of the upper mantle around and within the slabs. They do not, however, properly reveal the nature of the seismic coupling at the interface of two converging plates and its effects on the seismic activity and the stress state within the slabs. Difficulties arise because for shallower offshore earthquakes, hypocentral locations (especially focal depths) are scattered and less reliable even for the data of local networks, and focal mechanism solutions are available only for major ($m_b > 5.5$) earthquakes. In this paper, our main concern is the seismic activity at the uppermost part of the double seismic zone and at the deeper (40–60 km) part of the interface of two converging plates. A causal relation between these activities will be shown. Through this, we obtain information on the seismic coupling at the plate interface and the forces which act on the slab at the uppermost edge of the Wadati-Benioff zone.

Recently, *Seno and Pongsawat* [1981] and *T. Seno*

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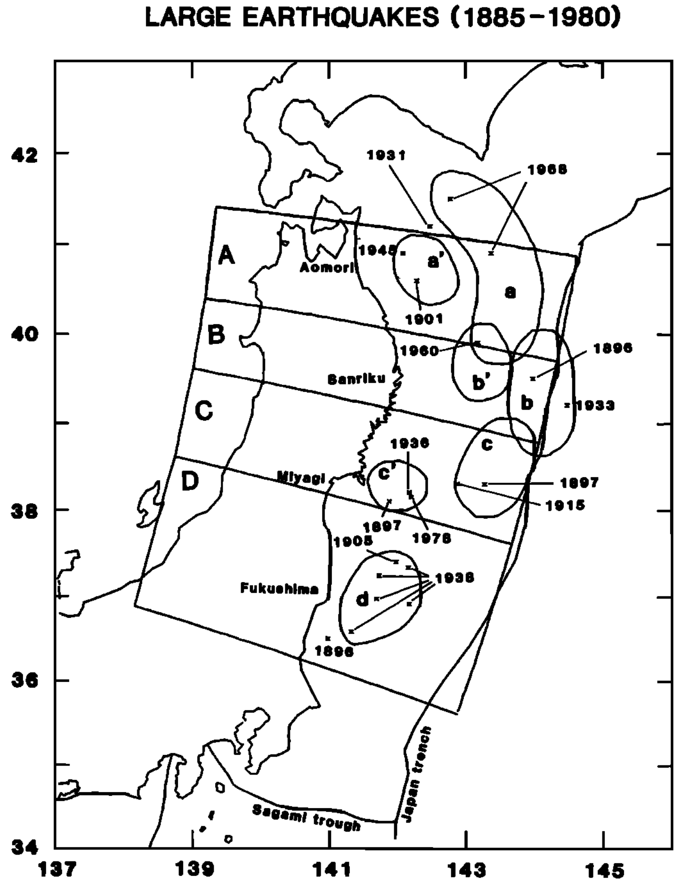

Fig. 1. Summary of large offshore earthquakes along the Japan trench (1885-1980). The subduction zone is divided into four segments from the occurrence of these events. Enclosed areas correspond to the rupture zones of 1968 (a), 1901 (a'), 1933 (b), 1960 (b'), 1897 (c), 1978 (c'), and 1938 (d) earthquakes.

(unpublished manuscript, 1982) made a detailed cross section of the seismicity and determined focal mechanisms for events prior to the occurrence of and in the vicinity of the Miyagi-Oki $M_s=7.5$ earthquake of 1978, northern Honshu, Japan. They studied the occurrence of moderate size earthquakes around the interface of two converging plates (30–150 km depth) to determine the pattern of seismicity which might be related to the occurrence of the large earthquake. They used earthquakes with focal depths determined from depth phases and decided the types of focal mechanism by using a method which allows a larger number of earthquakes with $m_b>4.0$ to be analyzed. They found a triple-planed structure of seismicity which we here call a triple seismic zone, at the seaward edge of the double seismic zone, where the double seismic zone extends seaward beyond the aseismic front and overlaps with the zone of low-angle thrust type earthquakes at the interface of two converging plates. They related this to the stress concentration around the focal region of the Miyagi-Oki earthquake prior to its occurrence.

In the present paper, we extend their work in space to distinguish the regional and temporal variation of seismicity along the subduction zone of the northern Honshu arc, Japan. We divide the subduction zone into four regions from the pattern of occurrence of historical great and large earthquakes. The differences in the seismicity of each region will be illustrated in terms of the pattern of occurrence of both large and intermediate size earthquakes. We will propose to separate the zone of low-angle thrust earthquakes at the plate interface into two: the shallow thrust zone (0–40 km), where great earthquakes ($M_s \sim 8.0$) occur, and the deep thrust zone (40–60 km), where large earthquakes ($M_s \sim 7.4$) occur. The regional variation of seismic activity at the seaward edge of the double seismic zone is discussed with regard to its relation to the coupling at the deep thrust zone. Another triple seismic zone is found in the region offshore of Fukushima prefecture immediately to the south of the region where *Seno and Pongsawat* [1981] found the triple seismic zone. The possibility of a future large earthquake in this region will be discussed on the basis of the seismic coupling at the deep thrust zone and historical seismicity data.

HISTORICAL SEISMICITY

Historical and recent seismicity along the Japan trench represents typical subduction seismicity. Although it is typical, we can find a great variety of modes of seismicity. Historically, great ($M_s \geqslant 7.8$) or large ($M_s \geqslant 7.4$) earthquakes have recurred, but occurrence of these events has never been uniform over the entire length of the arc. In this section, we summarize the historical seismicity for great and large earthquakes. We will relate characteristics of the historical seismicity data to the recent seismicity and focal mechanisms during the past few decades along the Japan trench in the later section.

From the local intensity distribution and many other sources of information including the reports from the seismological bulletins of the Central Meteorological Observatory (formerly Japan Meteorological Agency, JMA), *Utsu* [1979b, 1982] recompiled the epicentral location and magnitude of all earthquakes, $M>6$ (in the rest of the paper M denotes a magnitude determined with respect to JMA magnitude), which occurred around Japan from 1885 to 1925. Combining his data with other earthquake catalogues (JMA, ISS, ISC, PDE, *Gutenberg and Richter* [1954], *Geller and Kanamori* [1977], and *Abe* [1981]), we have a very good record of seismicity of large earthquakes around Japan for about the last 100 years (1885–1980). Figure 1 shows the seismicity of large ($M_s \geqslant 7.4$) earthquakes along the Japan trench during this period, and they are also listed in Table 1. The closed areas represent the focal regions of large earthquakes. From the pattern of occurrence of these earthquakes, we divide the subduction zone along the Japan trench into four sections, A, B, C, and D as seen in Figure 1. Because the subduction of the Philippine Sea plate along the Sagami Trough (Figure 1) makes seismicity complex at the southernmost part of the arc, we do not include the region south of region D in this study. Also, the region north of region A, where the Kuril arc meets the northern Honshu arc, is not included in this study for similar reasons.

TABLE 1. Large Earthquakes (1885-1980)

Year	Latitude, °N	Longitude, °E	Region	Magnitude	
				M_j	M_s
1896	36.5	141.	D	6.6	7.4^a
1896	39.5	144.	B	6.8	8.6^b
1897	38.1	141.9	C	7.4	-
1897	38.3	143.3	C	7.7^c	-
1901	40.6	142.3	A	7.4	-
1905	37.4	141.8^c	D	7.0	7.8
1915	38.3	142.9	C	7.5	7.6
1931	41.2	142.5	A	7.6	7.7
1933	39.2	144.5^d	B	8.1	8.5
1936	38.15	142.13	C	7.5	7.2
1938	36.58	141.34^e	D	7.0	7.6
1938	36.97	141.71^e	D	7.5	7.7
1938	37.24	141.75^e	D	7.3	7.7
1938	37.33	142.18^e	D	7.4	7.6
1938	36.91	142.19^e	D	6.9	7.0
1945	41.00	142.07	A	7.1	7.1
1960	39.9	143.2	B	7.2	7.7
1968	40.9	143.4	A	7.9	8.1
1968	41.5	142.8	A	7.5	7.7
1978	38.15	142.22^f	C	7.4	7.5

Epicentral locations are obtained from *Utsu* [1979b], JMA, ISS, and ISC for the periods 1885-1925, 1926-1954, 1954-1963, and 1964-1980, respectively. M_j represents JMA magnitude; for the events before 1925, they are obtained from *Utsu* [1979b]. M_s denotes surface wave magnitude of *Abe* [1981].

[a] *Utsu* [1980].
[b] Tsunami magnitude (M_t) [*Abe*, 1979].
[c] *Utsu* [1982].
[d] *Kanamori* [1971].
[e] *Abe and Tsuji* [1976].
[f] *Seno et al.* [1980].

Region A

The 1968 M_s=8.1 Tokachi-Oki earthquake, which is a great thrust type event [*Kanamori,* 1971a] occurred offshore of Aomori prefecture in this region. The rupture zone is shown in Figure 1 as the enclosed area 'a' (the 2-day aftershock area based on preliminary determination of epicenter (PDE) data). Studies of historical earthquakes [*Utsu,* 1974; *Usami,* 1975; *Hatori,* 1975] show that similar events have occurred in this zone very regularly since 1677: 1677, 1763, 1853, and 1968. Thus great earthquakes have been occurring in this zone every ~80–100 years. In zone 'a'', immediately landward of zone 'a', relatively smaller but still large (M_s~7.4) events occur often, *e.g.*, in 1901 and 1945. Zone 'a'' is the rupture area of the 1901, M=7.4, earthquake determined from tsunami data [*Hatori,* 1975].

Region B

The 1896, M_t=8.6 (tsunami magnitude; *Abe* [1979]), earthquake caused a great disaster along the coast by its tsunami. This event is a low-frequency tsunami earthquake; the magnitude determined from intensity distribution is only about 6.8 [*Utsu,* 1979b], although this event has a seismic moment comparable to that of great earthquakes [*Kanamori,* 1972]. The 1933 M_s=8.5 Sanriku earthquake, which may have broken the entire lithosphere by normal faulting [*Kanamori,* 1971b], occurred on the seaward edge of this region (zone 'b'). In 1960 a large earthquake (M_s=7.7) occurred west of the previous two great events. The aftershock area (zone 'b'') overlaps with the rupture zone of the 1968 earthquake. *Utsu* [1974] suggested that there had been a possible overestimation of magnitude for this event. Both the size of the rupture area and the size of the generated tsunami show that this event is smaller than the two great earthquakes which occurred in the adjacent regions: 1968 in region A and 1897 in region C. Two historical tsunamigenic earthquakes (869 and 1611) have been located in zone 'b' [*Utsu,* 1974; *Usami,* 1975; *Hatori,* 1975]; however, the nature of faulting and precise locations are not well known.

Therefore, region B is anomalous in the activity of great or large earthquakes; although the 1896 earthquake can be a thrust event, this region lacks typical great thrust type earthquakes at least for the past 200 years. The occurrence of the great normal fault type event and the tsunami event suggests that the plate interface in this region is not coupled strongly. This is also supported by the activity of smaller magnitude events, as will be shown later.

Region C

Zone 'c' is the rupture area of the 1897 M=7.7 earthquake determined from tsunami data [*Hatori,* 1975; *Aida,* 1977]. Historical data suggest that a similar event occurred in 1793 [*Hatori,* 1975; *Aida,* 1977; *Seno,* 1979]. From tsunami analysis, *Aida* [1977] estimated the minimum seismic moments of these two earthquakes to be 5.6×10^{27} and 6.3×10^{27} dyne-cm, respectively, corresponding to a magnitude M_w [*Kanamori,* 1977] of 7.8. This zone is known as a seismic gap and as a possible site of a near-future large earthquake [*Seno,* 1979; *Utsu,* 1979a]. The smaller events often occur landward of this zone. In particular, the rupture zone of the 1978 Miyagi-Oki earthquake (zone 'c''), which represents thrust faulting at the relatively deeper (30–60 km) interface of the two plates [*Seno et al.,* 1980], has experienced large earthquakes (M_s~7.4) about every 40 years at least since 1835: 1835, 1897, 1936, and 1978. Thus, the activity for great and large earthquakes in this region is similar to that in region A; great earthquakes recur in a far offshore area, and landward of this area large earthquakes occur more frequently.

Region D

A series of five large earthquakes occurred in 1938; M_s ranges from 7.0 to 7.7. Three of these are of thrust type and two are of normal fault type [*Abe,* 1977]. The rupture zone of this series of earthquakes [*Abe,* 1977], which is indicated by 'd' in Figure 1, is located more landward than those of great thrust type events in regions A and C. The 1905 $M_s = 7.8$ event is located in the rupture zone of the 1938 events by *Utsu* [1979b]. This event and the 1896 $M_s = 7.4$ event have characteristics of low-frequency earthquakes [*Utsu,* 1980] because magnitudes determined from the data recorded in Japan are much smaller than those determined at the teleseismic stations [*Utsu,* 1979b]. No historical earthquake is known to have occurred in the farther offshore area in this region.

Deep and Shallow Thrust Zones

As mentioned earlier, the pattern of occurrence of great and large earthquakes changes from region to region. Although we have to note that the interpretation of the data (especially the rupture zone) for historical earthquakes is biased by the data of recent large events for which many pieces of information are available, the regional variation of seismicity of large events along the northern Honshu arc can be summarized as follows: (1) decrease of great earthquake activity from north to south, (2) the rupture zones of great earthquakes are located on the landward side of the trench (the zones 'a' and 'c'), (3) frequent occurrence of large events (M_s~7.4) near the coast (the zones 'a'', 'c'' and 'd'), and (4) absence of great thrust type earthquakes and occurrence of a great normal fault earthquake and a great tsunami earthquake in region B.

From the above observation, we propose here to divide the zone of thrust type earthquakes into two parts: the shallow thrust zone where great (M_s~8.0) earthquakes occur, and the deep thrust zone, which is located more landward and where large (M_s~7.4) earthquakes occur. The cross section of seismicity of recent moderate size earthquakes, which will be shown in a later section, defines the depth range of these two zones as 0–40 km and 40–60 km, respectively.

We will show next that the pattern of occurrence of recent smaller size earthquakes also changes from region to region, reflecting the above-mentioned regional variation of the pattern of occurrence of great and large earthquakes. The nature of the shallow and deep thrust zones and the double seismic zone will be discussed in detail in a later section in conjunction with the recent seismicity and mechanism type.

METHOD OF ANALYSIS

Data

The earthquakes are selected from the International Seismology Center (ISC) bulletins for the period of 1964–June, 1978, and satisfy the following conditions: (1) events have focal depths which are determined by the pP phase, and (2) events have not less than 20 P wave arrival time observations.

For the events deeper than 50 km, those whose depths have a standard error of not more than 5.0 km are also included. For the period 1964-1975, data are selected from *Yoshii*'s file, EQ1, which includes events with the above conditions [*Yoshii,* 1979b]. For the period 1976-June, 1978, we list events from the ISC bulletins. For region C we incorporate the results by *Seno and Pongsawat* [1981] and *T. Seno* (unpublished manuscript, 1982); thus the time period treated is terminated at the occurrence of the June 12, 1978, Miyagi-Oki earthquake, as in their study. It should be noted that region C of this study is not exactly identical with the region they studied. With the above procedure we obtain more than 600 earthquakes with minimum magnitude m_b~4.0.

For submarine earthquakes, following *Yoshii* [1979a], we correct the depth determined from the pP phase by ISC by taking account of the effect of the ocean water layer. This is because the pwP phase (water reflection) is very likely to be misidentified as the pP phase [*Fujita et al.*, 1981] for these shallow submarine earthquakes. This will be discussed in more detail in a later section.

Focal Mechanism

For earthquakes which occurred in region D and are big enough ($m_b > 5.4$), we determine their focal mechanisms by the conventional method; the initial motions of P wave and polarization angles of the initial half cycles of S waves are read from film chips of the long-period records at World-Wide Standard Seismographic Network (WWSSN) stations. When the long-period data are insufficient, first motions of short-period P waves are used as supplements. P wave data recorded at the JMA stations which are reported in the ISC bulletins are added to the WWSSN data. The earthquakes for which we determined new nodal plane solutions are summarized in Table 2, and their focal mechanisms are shown in the appendix. In this table, we also include mechanisms which were already determined from long-period data by previous workers.

In other regions, focal mechanisms for major events are compiled from previous studies [*Yoshii*, 1979a, b; *Kanamori*, 1971a; *Sasatani*, 1971; *Stauder and Mualchin,* 1976; *Seno and Pongsawat,* 1981]. Some of these were revised by *Seno and Kroeger* [*1982*] using body wave synthetics, and we use their results for those events. Some of the focal mechanism solutions obtained by *Nakajima* [1974] are used in regions A and B, although they were obtained from short-period first motion data.

TABLE 2. Solutions of Focal Mechanism for Earthquakes Off Fukushima Prefecture During 1964-1978

Solution	Date	Latitude, °N	Longitude, °E	Depth, km	m_b	A		B		P		T	
						$\phi°$	$\delta°$	$\phi°$	$\delta°$	AZ°	PL°	AZ°	PL°
1	Feb. 5, 1964	36.47	141.02	51	5.6	124	74	304	16	124	29	304	61
2	May 30, 1964	36.23	141.29	36	5.7	108	80	288	10	108	35	288	55
3[a]	Sept. 17, 1965	36.35	141.38	31	6.1	129	69	309	21	129	24	309	66
4	Sept. 22, 1965	36.44	141.37	42	5.8	113	78	293	12	113	33	293	57
5	Nov. 14, 1965	36.61	141.08	39	5.5	113	70	293	20	113	25	293	65
6	April 3, 1966	36.66	141.06	44	5.6	131	70	311	20	131	25	311	65
7	Nov. 4, 1967	37.39	141.71	39	5.5	112	82	292	08	112	37	292	53
8	Nov. 19, 1967	36.47	141.17	39	5.7	106	78	286	12	106	33	286	57
9	Aug. 8, 1968	36.40	141.50	31	5.5	107	76	287	14	107	31	287	59
10	April 9, 1969	36.84	139.77	109	5.5	235	40	338	80	7	24	123	43
11	July 20, 1973	36.45	141.05	46	5.8	113	70	293	20	113	25	293	65
12	Aug. 23, 1973	37.22	142.18	32	5.6	92	72	331	33	121	16	229	46
13[b]	May 5, 1974	37.78	141.77	41	5.7	116	70	285	20	113	24	303	65
14[c]	July 8, 1974	36.44	141.17	40	6.0	120	66	327	27	128	20	277	67
15[b]	April 8, 1975	37.75	141.75	42	5.7	108	70	285	20	107	24	289	64
16	Aug. 14, 1975	37.13	141.11	60	5.5	105	70	285	20	105	25	285	65
17	Dec. 16, 1977	36.65	141.07	45	5.6	115	60	295	30	115	15	295	75

Depth is pP-P depth corrected for water layer (see text).

[a] Solution after *Sasatani* [1971].

[b] Solution after *Seno and Pongsawat* [1981].

[c] Solution after *Yoshii* [1979b].

The earthquakes ($m_b < 5.5$) for which we could not produce reliable nodal plane solutions from long-period data were classified according to the type of faulting, using the following method of *Seno and Pongsawat* [1981]. Assuming that there exist only three types of faulting, low-angle thrusting, down-dip compression, and down-dip tension, we classify the events into one of the above three types which is consistent with the P wave first motion data reported in the ISC bulletins. We use P wave first motion data of JMA stations whose epicentral distances are less than 450 km, for which large amplitudes of first motions are expected. Although the first motion data in the ISC bulletins are often found to be inconsistent for teleseismic stations, they are reliable and consistent for local stations (see Figure 2). Figure 3 shows examples of the classification of focal mechanism types (see also Figure 5 of *Seno and Pongsawat* [1981]). For this analysis we use only those events which are located more than 140 km landward of the trench axis. This is because the hypocentral locations of the events distant from the coast are less reliable, and this could cause a serious error in the computation of the take-off angles. It is also difficult to determine the type of the mechanism for these shallower earthquakes since most of the rays travel horizontally westward and they cover only the edge of a focal sphere plot. The take-off angles are computed by assuming a spherically symmetric, layered earth model with crustal structure obtained by seismic refraction studies [*Yoshii*, 1979a; *Asano et al.*, 1979]. We take into account the possible errors in depth determinations in the computation of the take-off angles. The focal mechanism types are determined for 184 earthquakes in all.

For the earthquakes which cannot be classified definitely into one of the above three types, we provided a further weak classification. Those events which can be consistent with either two of the three types are classified into another category (see Table 3 and Figure 3). Although the above procedure reduces the minimum magnitude to be analyzed down to about $m_b = 4.0$, there still remain earthquakes which cannot be allocated to any of the above groups.

Results

The results of the analysis are shown in Figures 4-7. The symbols 'D', 'C', and 'T' represent thrust type, down-dip compression and down-dip tension type events, respectively. The larger symbols correspond to those events of which the nodal plane solutions are obtained from long-period records. The other symbols, 'A', 'B', and 'E' are summarized in Table 3. The cross marks are the earthquakes which could not be classified into any group.

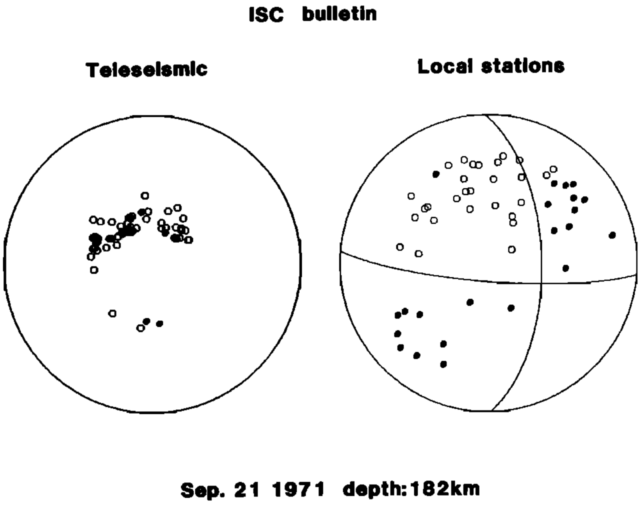

Fig. 2. Comparison of first motion data reported in the ISC bulletin for a typical event. (left) Teleseismic stations. (right) Local stations whose epicentral distances are less than 450 km. Note that the teleseismic data are totally inconsistent, while the local data are self-consistent and enable us to determine a focal mechanism type.

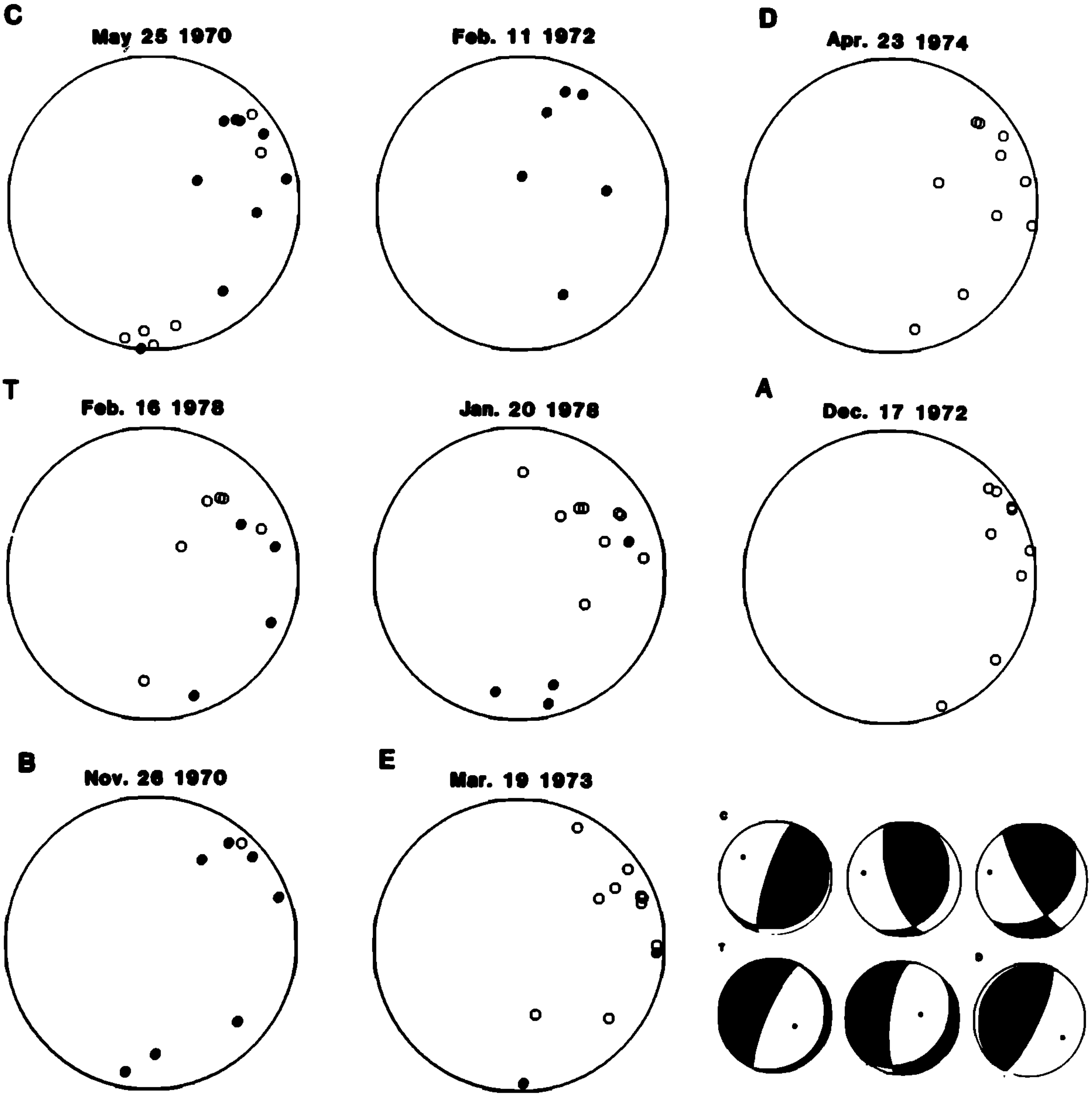

Fig. 3. Examples of the classification of focal mechanism types. C, T, and D denote the events classified into down-dip compression, down-dip tension, and thrust types, respectively. For A, B, and E, see Table 3. Possible focal mechanism diagrams of the above three types are shown at the bottom right.

Map Views

Map views of the entire result and of each type of event are shown in Figures 4 and 5, respectively. The landward edge of thrust type events, *i.e.*, 'D' type events (Figure 5a), is parallel to the trench axis and almost identical to the 'aseismic front', proposed by *Yoshii* [1975]. *Yoshii* [1975] proposed that the thrust type events did not occur landward of the aseismic front. Thus our results support this. Further, we note that the edge of 'D' type events is indented seaward in region B, where no large earthquake is known in historical time (Figure 1). Type 'A' ('D' or 'C' type) events also show the same feature (Figure 5b) and this suggests that most of type 'A' events are actually of thrust type. The map view of compression ('C') type events (Figure 5c) also shows a variation of activity; they extend seaward of the aseismic front in regions C and D. We also note that the activity beneath the land area of region C is very low. It is not proper to draw much of a conclusion from the map view of tension ('T') type events because the activity of this type of event is not as high as other types of events; however, it seems worthy to note that there occurred a number of events in the offshore area well beyond the aseismic front (see Figure 5a for the location). Although *Yoshii* [1979a] proposed that the aseismic front may

TABLE 3. Summary of Symbols.

Symbol	Mechanism
D	low-angle thrust
C	down-dip compression
T	down-dip tension
A	D or C
B	C or T
E	T or D

mark the edge of the double seismic zone along the northern Honshu arc, we can see that this is clearly not true from Figure 5.

Cross Sections

To draw the cross sections, the center of the small circle of the Japan trench was located at (40.15°N, 111.00°E) which was determined by a least squares fit to the trench axis between 41°N and 36°N. Figure 6 shows a cross section of seismicity and mechanism type in each region. In Figure 7, only those earthquakes which could be classified into one of the three main types are plotted as a cross section.

In region A, the overall seismicity is very active with a slight indication of the double seismic zone deeper than 60 km (Figure 6a). 'D' type events are distributed from the shallow zone near the trench to the 60 km depth. Although we can find some seismicity immediately below the deep thrust zone, it is much less active than that seen in regions C and D. Most events belonging to this activity did not provide the information on the type of mechanism. It should be noted that region A and the northern part of region B have experienced the great 1968 Tokachi-Oki earthquake, which is the only great earthquake within the time period of this study. Therefore many shallow events should be considered as the aftershocks of that event. However, the plot without those aftershocks does not basically change the pattern in Figures 6a and 7a.

Region B shows an interesting feature: the presence of a seismic gap at the deep thrust zone, while activity in the shallow thrust zone is rather high. The same feature can also be noticed in the map views of 'D' and 'A' type events (Figures 5a and 5b). The double seismic zone can be seen here as in other regions; however, it does not extend seaward beneath the deep thrust zone. Both the seismicity at the deep thrust zone and immediately beneath the zone is very low in this region. The nature of this gap will be discussed in detail later.

In region C, the double seismic zone which is characterized by 'C' and 'T' type events, extends immediately beneath the deep thrust zone and forms a triple seismic zone (Figures 6c and 7c). The 1978 $M_s = 7.5$ Miyagi-Oki earthquake occurred in the deep thrust zone of region C. The time period treated in this study is just until the occurrence of this large event. *Seno and Pongsawat* [1981] suggested that the triple seismic zone was one of the precursory phenomena. The activity in the shallow thrust zone is low, which may reflect the gap in the activity prior to a great earthquake in this region; the region has been monitored as one of the possible areas of near-future occurrences of great earthquakes [*Seno*, 1979; *Utsu*, 1979a]. The other prominent feature is the lesser activity in the deeper part (>100 km) of the double seismic zone in region C compared with other regions (Figures 5c, 6c, and 7c).

Region D is characterized by the presence of a triple seismic zone and less activity in the shallow thrust zone. It should be noted that the high density of distribution of the earthquakes in the cross section (Figure 6d) is primarily because the width of this zone is about twice as large as those of other regions.

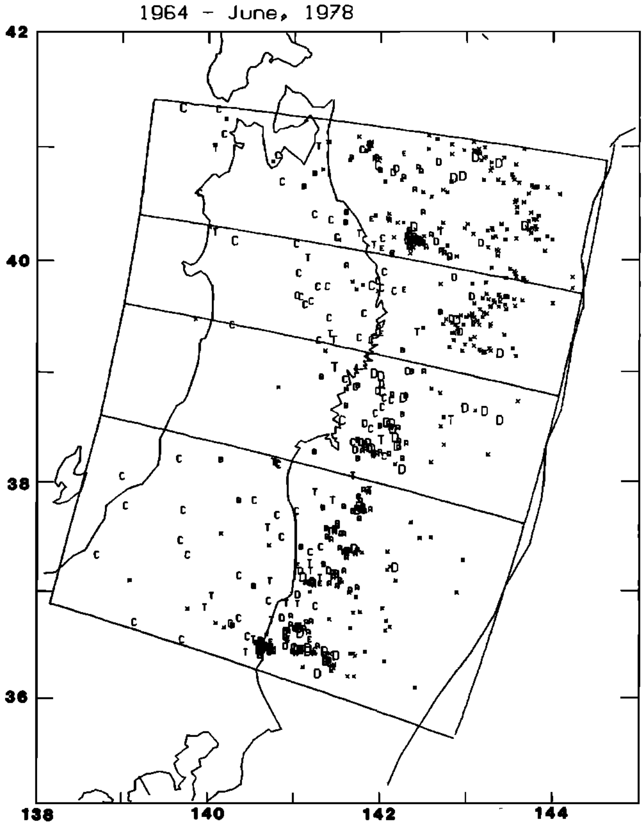

Fig. 4. Map view of the well-located earthquakes with focal mechanism types. Symbols are summarized in Table 3. The larger symbols correspond to those events of which the nodal plane solutions are obtained from long-period records.

Discussion

Depth Phases

It has been noticed that for submarine events, pP phases reported in the ISC bulletins are often actually pwP phases, the reflection from the ocean surface [*Mendiguren*, 1971; *Yoshii*, 1979a, b; *Hong and Fujita*, 1981; *Fujita et al.*, 1981]. Detailed studies of body wave synthetics with the local structure around the earthquake source [*Seno and Kroeger*, 1982; *G.C. Kroeger and R.J. Geller*, unpublished manuscript, 1982] indicate that the reflection from the ocean surface (pwP phase) can be as large as that from the ocean bottom, *i.e.*, pP phase. Since for shallow events, the arrival of the pP phase is much closer to the direct P phase and the amplitude is often smaller than that of the pwP phase, it is very likely that the pwP phases are misidentified as pP phases in the ISC bulletins. Thus *Yoshii*'s [1979a, b] method of depth correction used in this study seems to be proper. *Fujita et al.* [1981] showed that correcting the depth using pwP phases reduces the error to less than 10 and 15 km for large and moderate size events, respectively, from the analysis at the Aleutian trench. Since it is known that reported hypocentral locations determined by the standard method have a better resolution along the Japan trench than in the Aleutian trench [*Barazangi and Isacks*, 1979], our depth correction gives more accurate focal depths than those which *Fujita et al.* [1981] reported. *Seno and*

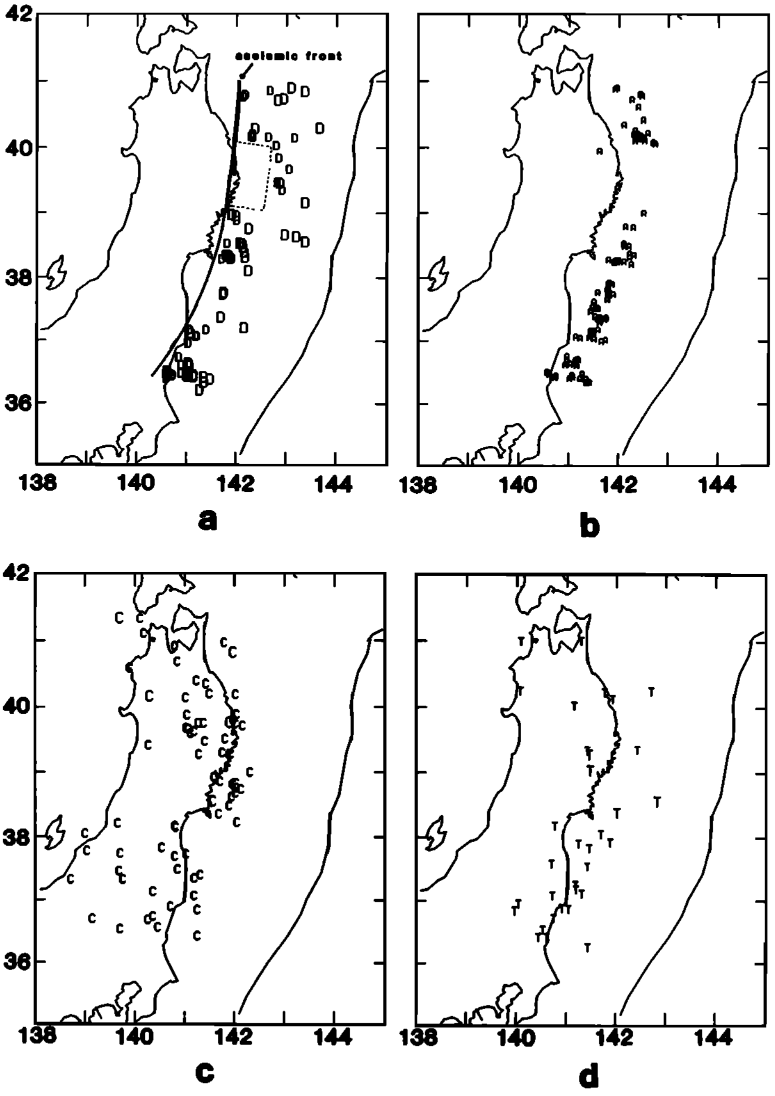

Fig. 5. The events of each type are plotted in separate map views. (a) Thrust type. (b) Type 'A'. (c) Down-dip compression. (d) Down-dip tension. The line in Figure 5a represents the aseismic front. Note the gap in 'D' and 'A' type event activity in region B in Figures 5a and 5b, respectively. Figure 5c shows the lack of type 'C' events in the western half of region C.

Kroeger [1982] determined precise focal depths for six moderate size events in the region studied using synthetic seismograms. For five of them, the corrected pP-P depth was in agreement with the depth determined by the synthetics within 4 km.

Triple Seismic Zone

The triple seismic zone is defined as the zone where the double seismic zone extends seaward of the aseismic front and overlaps with the zone of thrust type events at the interface of two converging plates [*Seno and Pongsawat,* 1981]. As shown in the last section, triple seismic zones were found in both regions C and D. The upper zone of the double seismic zone is characterized by down-dip compression type ('C' type) events and the lower zone by the down-dip tension type ('T' type) events. There is a separation of about 10 km between the thrust zone and 'C' type events in Figures 7c and 7d. However, there is a possibility that the separation between the thrust zone and the zone of down-dip compression type events is caused by the inhomogeneity of the selection of earthquakes at a depth of 50 km. As described earlier, we used mainly the earthquakes whose depths are determined from pP-P time difference with water depth corrections. These depths are often shallower than those determined routinely. For the events deeper than 50 km, we included the events determined routinely and having a small standard error in depth. However, if the accuracy is not good enough, this variation of focal depth determination could cause an artificial separation of one zone. Figure 3 of *Seno and Pongsawat* [1981] suggests this possibility because this figure demonstrates that the depths of the events at the deep thrust zone are mostly determined by depth phases and in contrast, those of down-dip compression type events are mostly from the routine determination.

In order to examine whether the apparent separation of the deep thrust zone and the 'C' type zone is true, we relocated the events in the region D which compose the

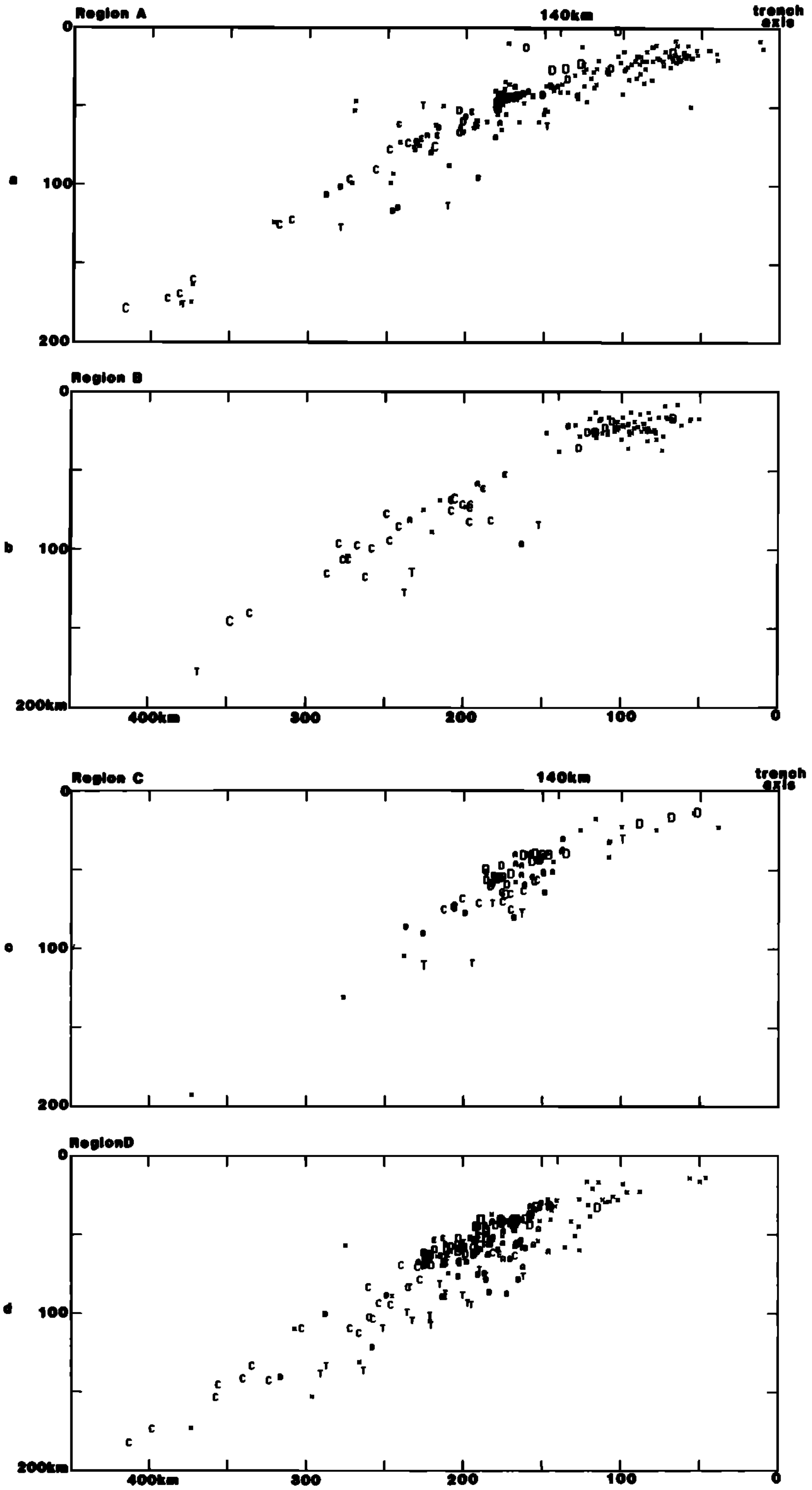

Fig. 6. Cross sections of each region. Double seismic zones are seen in each region. The seismicity just beneath the deep thrust zones in regions C and D are much more active than in the other regions. The gap in region B is clearly seen in Figure 6b.

triple seismic zone, by using a master event relocation technique. As the master events we selected six earthquakes which are relatively large ($m_b > 5.4$) and are expected to be better located. Then we relocated each event relative to the one of these six earthquakes which is the closest to the event. This is because relative relocation methods such as the master event technique or the joint hypocenter determination technique seem to work properly for only events which have nearly equal distances from the center of the arc at subduction zones [*Fujita et al.*, 1981]. Figure 8 shows the result in a cross section. Large symbols denote the earthquakes chosen as master events and medium size symbols represent those relocated. The down-dip compression type events are still

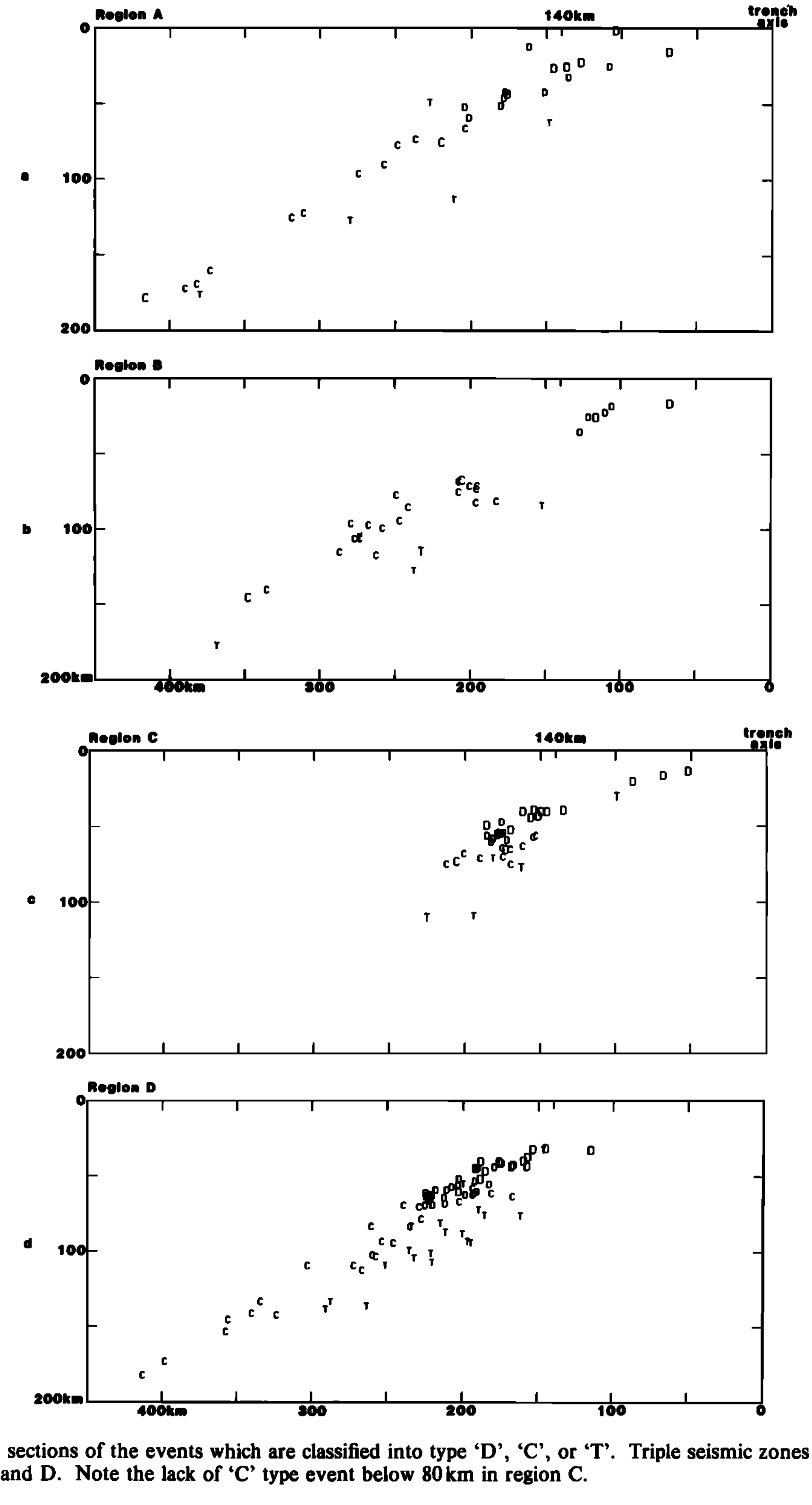

Fig. 7. Cross sections of the events which are classified into type 'D', 'C', or 'T'. Triple seismic zones are seen in the regions C and D. Note the lack of 'C' type event below 80 km in region C.

located about 10 km beneath the thrust type events. Although this does not completely dismiss the possibility of the depth bias, within the resolution of the data this result should be considered as negative evidence for such a bias.

Figure 9 is the cross section of all the events which are classified into one of the three main types. This clearly shows the presence of the double seismic zone and the triple seismic zone at the seaward edge of the double seismic zone.

Seno and Pongsawat [1981] and *T. Seno* (unpublished manuscript, 1982) speculated that the triple seismic zone was caused by a stress disturbance within the slab beneath the deep thrust zone prior to the occurrence of a large thrust event. Because the stress distribution within the slab is more or less continuous, we can expect that the

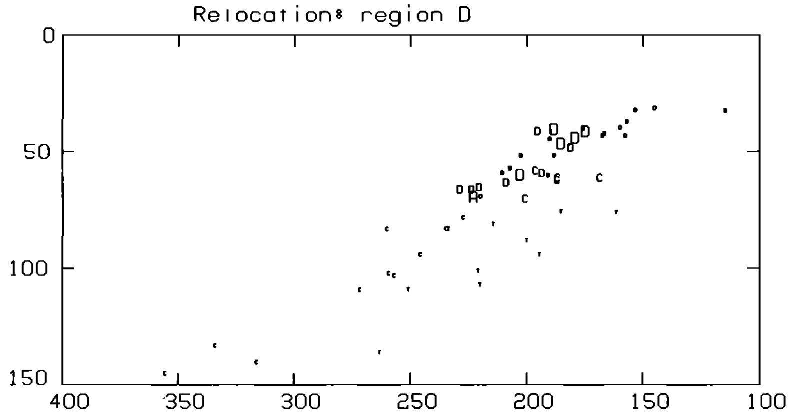

Fig. 8. Master event relocation of the events at the triple seismic zone in the region D. The six large symbols denote the master events, and medium size symbols are those which are relocated. The vertical separation of 'D' and 'C' type events at the deep thrust zone is seen.

similar stress pattern which can be seen in the double seismic zone continues seaward of the double seismic zone. However, because the stress there is less than the critical stress above which earthquakes can happen, we will not see any continuation of the double seismic zone. At the plate interface of the deep thrust zone where large earthquakes recur, a coupling between the plates at the rupture zone would produce a gradual stress buildup there which would approach the strength of the zone just prior to the occurrence of the large event. This stress buildup would also load the slab near the rupture zone and disturb the preexisting stress pattern, which could result in earthquakes within the slab farther seaward of the double seismic zone and beneath the deep thrust zone, resulting in a triple seismic zone.

Although we have not calculated the stress pattern within the slab which would be caused by coupling at the plate interface and although the stress within the descending slab may be very complex, we note here that the normal component of the force transmitted through the interface is in the sense to enlarge the unbending of the oceanic plate. In order to discuss the stress more precisely, we need to include modeling the stress responsible for the double seismic zone itself. *Goto and Hamaguchi* [1980], who proposed that the double seismic zone could be explained by thermal stresses caused by the temperature difference between the asthenosphere and the slab, made a calculation using a finite element method to include the coupling at the thrust zone. The zone of down-dip compression extends farther upward beneath the thrust zone when the upper boundary of the descending slab is held fixed in the depth range of 0–100 km in space. This partially supports our proposal that the triple seismic zone results from the stress buildup at the deep thrust zone.

We note here that in region B, we can see neither activity at the deep thrust zone nor a double seismic zone beneath the deep thrust zone. Historical seismicity data

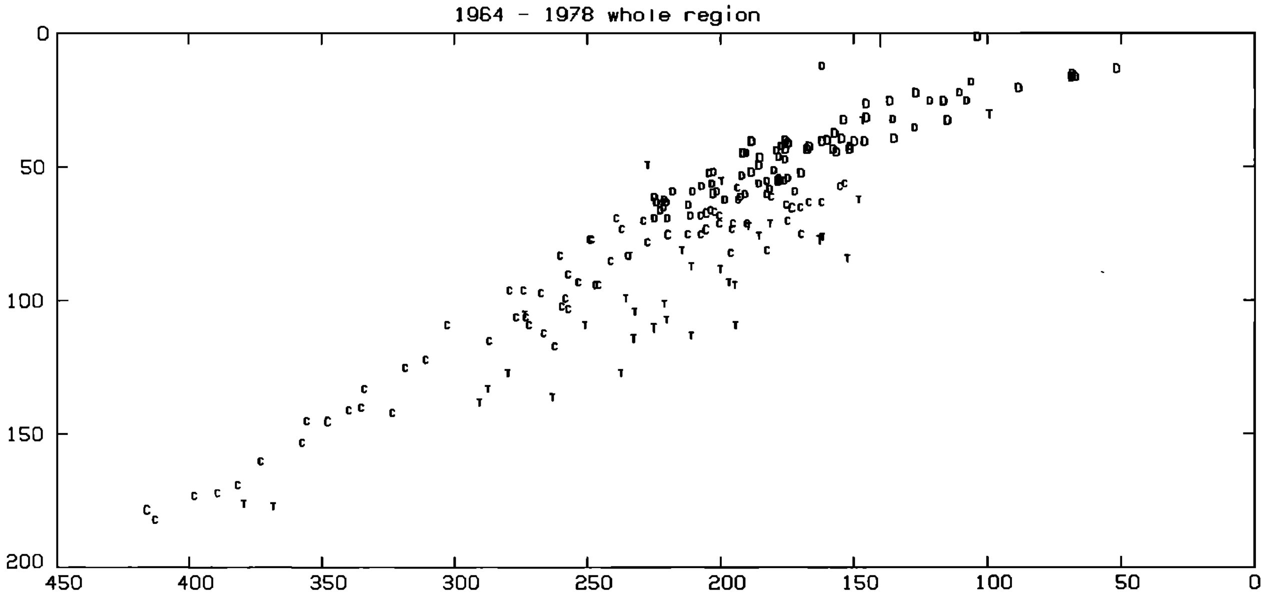

Fig. 9. Cross section of the whole arc. Only those events which are classified into type 'D,' 'C,' or 'T' are plotted. Overall features of subduction seismicity are seen clearly; the shallow and deep thrust zone, the double seismic zone, and the triple seismic zone which is an overlap of the double seismic zone and the deep thrust zone.

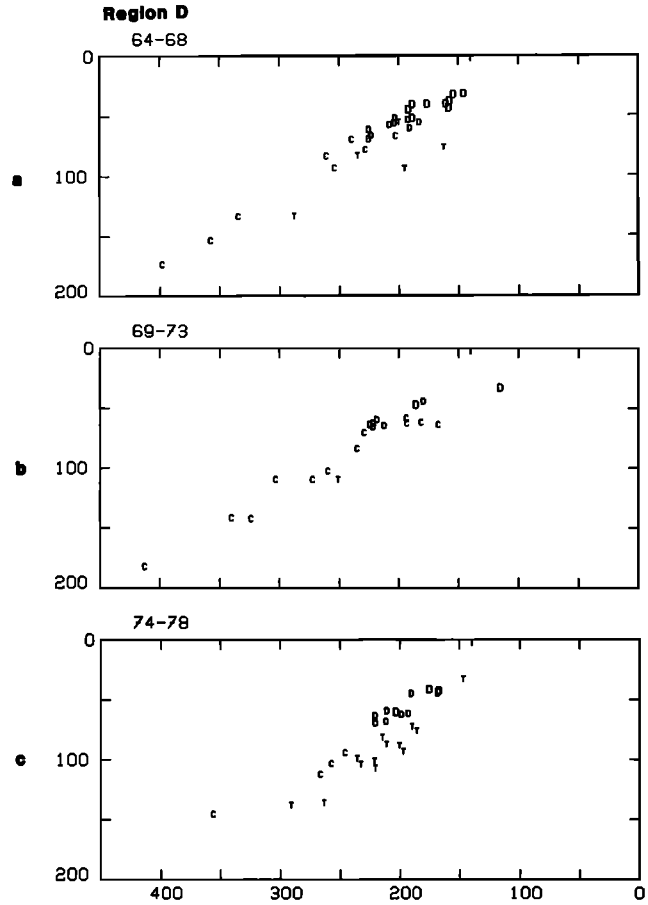

Fig. 10. Successive cross sections of seismicity in region D in 5-year intervals. (a) 1964-1968. (b) 1969-1973. (c) 1974-1978. There are fewer compressional events and more tensional events in the latest interval than the two earlier ones.

show that no large earthquakes are known near the coast in this region for at least the past 200 years [*Usami*, 1975]. This shows a distinct contrast with the regions north and south of this zone where at least two large events occurred near the coast in this century in each region (Figure 1). Thus, we propose that the deep thrust zone in region B is totally aseismic and the decoupling at the deep thrust zone, *i.e.*, no extra stress buildup, results in no extension of the double seismic zone beneath it. It is interesting to note that the shallow thrust zone in region B also shows an aseismic character. Here at the trench, a great normal fault, the 1933 $M_s=8.5$ Sanriku earthquake, occurred and a large tsunami earthquake occurred farther landward in 1896. No typical great thrust type earthquake has been known to occur at the shallow thrust zone in this region.

The Possibility of a Large Earthquake in the Near Future

If the above hypothesis that the triple seismic zone is caused by the stress concentration prior to the occurrence of a large earthquake is correct, the presence of the triple seismic zone in region D suggests the existence of a stress concentration around the deep thrust zone and a possible near-future occurrence of a large earthquake in the deep thrust zone of this region. *Abe* [1977] stated that there has been no large earthquake in this region for the last 800 years except one series of five large earthquakes in 1938 and that a large portion of the relative plate motion is taken up by aseismic slip. However, this is probably incorrect. *Utsu* [1979b] located the 1896 $M_s=7.4$ and the 1905 $M_s=7.8$ event in this zone (see Figure 1). Both events show characteristics of low-frequency earthquakes which occurred in the deep thrust zone. The magnitude determined from the intensity distribution in Japan is much smaller than that from teleseismic stations, which suggests that these events are low-frequency earthquakes [*Utsu*, 1980]. They did not cause large tsunamis, which suggests that their foci were deep. If historical large earthquakes in this region have the same character, it is likely that those events were overlooked in the ancient literature. Therefore this region, especially the deep thrust zone, should not be considered as aseismic.

The possibility of occurrence of a large earthquake near the coast in region D has already been discussed by *Mogi* [1979] on the basis of a seismicity gap seen there for the past few decades. *Mogi* [1979] pointed out that a gap in activity for earthquakes whose magnitudes were greater than 5.6 for the past 30 years could be seen near the coast in the rupture zone of the large events in 1938. He also noted that the epicenters of large earthquakes tended to migrate to the south along the northern Honshu arc and argued that there was a possibility of a migration of large events to the south from the region off Miyagi prefecture which ruptured in 1978. Recently, *Katsumata and Yamamoto* [1982] also noted seismic potential in the rupture zone of the 1938 events because the seismic activity has been very low in this zone since 1960. Thus the triple seismic zone seen in this zone would provide another line of evidence for the possibility of occurrence of a large earthquake in the near future off Fukushima prefecture (region D).

Another possible precursor to the Miyagi-Oki earthquake is the absence of down-dip compression type events in the deeper part of the double seismic zone (>100 km) in region C (Figures 4, 5c, 6c, and 7c). Strong coupling prior to the large earthquake could sustain the rest of the slab in the asthenosphere, thus creating a down-dip tensional stress field in the slab. This could counteract the preexisting down-dip compressional field in the upper plane of the double seismic zone, which would reduce the number of 'C' type events.

In region D, successive cross sections covering 5-year intervals (Figure 10) reveal a tensional stress feature in the slab during the latest interval (Figure 10c). This is consistent with the idea of current strong coupling at the deep thrust zone inferred by the existence of the triple seismic zone in region D. *Reyners and Coles* [1982] and *L.S. House and K.H. Jacob* (unpublished manuscript, 1982) made a similar argument regarding the eastern Aleutian arc; the former explained the observed down-dip tension in the upper zone of the double seismic zone as a result of the coupling at the thrust zone in the Shumagin gap, and the latter explained the predominance of the T-type events in the eastern half of the eastern Aleutian arc by the seismic coupling in the thrust zone. Thus the degree of seismic coupling at thrust zones appears to play an important role in defining the stress field in the sub-

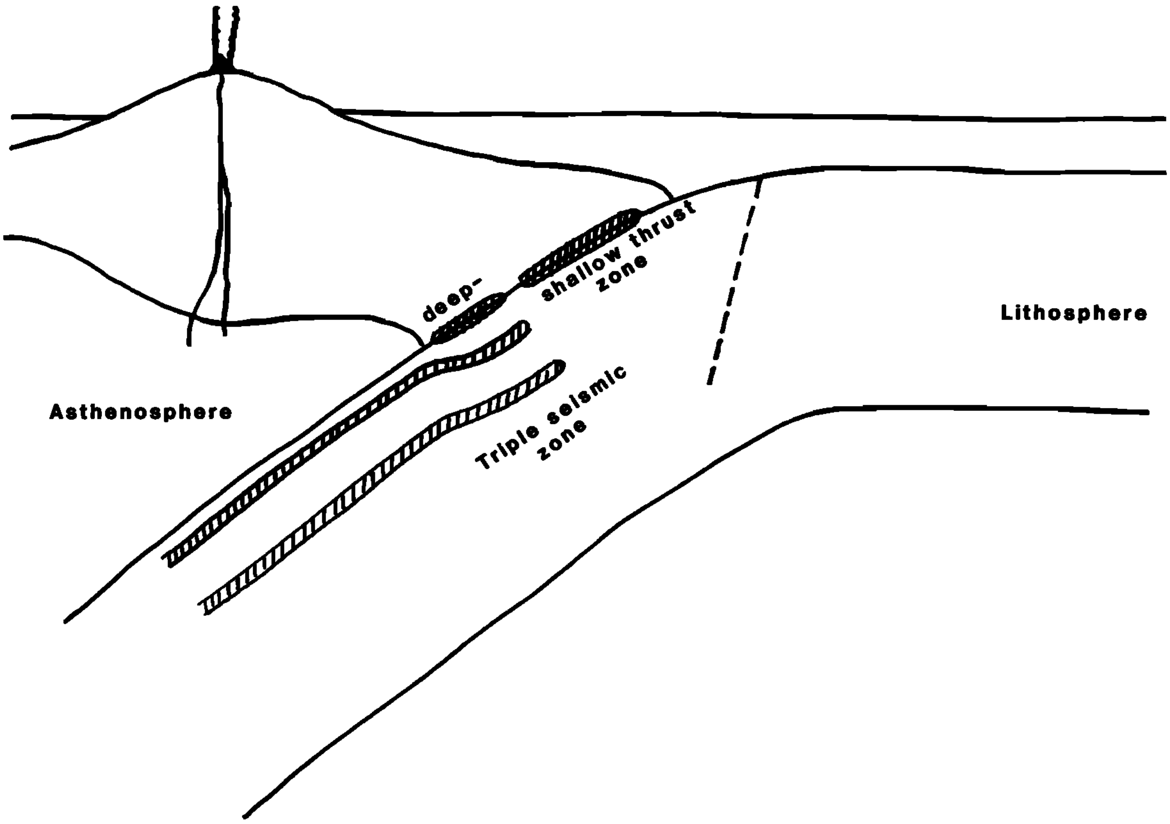

Fig. 11. A schematic figure of the subduction seismicity along the northern Honshu arc. The dashed line represents the large normal fault earthquake that occurred in region B in 1933.

ducting slab at intermediate depths (80–200 km) on a relatively short time scale in contrast to the effects of tectonic features (*e.g.*, age of the slab, convergence speed, etc.). This suggests the possibility of detecting the current degree of seismic coupling at the thrust zone by studying the stress pattern in the slab at intermediate depth. It is also important to include the possible perturbing effects of shallow coupling on deeper seismicity for studying the relative forces acting on the descending slabs. Since our knowledge about the state of stress within the slabs is obtained from the source mechanisms of earthquakes that occurred in the past two decades [*e.g.*, *Fujita and Kanamori,* 1981], any short term temporal effects could significantly affect our interpretations.

In region A, the extension of the double seismic zone seaward beyond the aseismic front cannot be seen clearly. The seismic activity immediately beneath the deep thrust zone is lower than those of regions C and D. Therefore, although there have not been large earthquakes for about the last 40 years, we do not see any evidence of phenomena precursory to a large earthquake in this region. The possibility of a near-future large earthquake in the deep thrust zone of region A would be very small.

Deep Thrust Zone

We have proposed characterizing the subduction seismicity along the northern Honshu arc in terms of the shallow and deep thrust zones and the double seismic zone. Figure 11 shows a schematic characterization of this activity. The shallow thrust zone (0–40 km) is where great thrust type earthquakes occur regularly (~100-year interval). The deep thrust zone (40–60 km) is characterized by the frequent occurrence of large thrust earthquakes.

The most recent deep thrust earthquake is the June 12, 1978, Miyagi-Oki earthquake. *Seno et al.* [1980] gave a depth of 27.8 km for the main-shock, referring to the data of a local network. We redetermined the focal depth by synthesizing long-period P waves, using a technique developed by *G.C. Kroeger and R.J. Geller* (unpublished manuscript, 1982), which allows us to include the effect of local crustal structure around the source. Since the rupture process of the main-shock is too complicated to allow the application of body wave synthetics, we determined the depth of the foreshock which occurred 8 minutes before the main-shock. The depth of the foreshock was determined as 35 km. Because the focal depth of the main-shock is a few kilometers deeper than that of the foreshock and the rupture propagated westward [*Seno et al.,* 1980], we conclude that the Miyagi-Oki earthquake ruptured the thrust zone deeper than at least 35 km, *i.e.*, the deep thrust zone. The depth obtained by *Engdahl et al.* [1979] using short-period depth phases is consistent with our result.

Although the physical difference between the shallow thrust zone and the deep thrust zone is not clear, the phase change of basalt/gabbro to eclogite in the crust of the oceanic plate may be responsible for the change of sliding characteristics at the 40 km depth of the plate interface, as proposed by *Ruff and Kanamori* [1981] and *Pennington* [1982]. Although they contend that no large

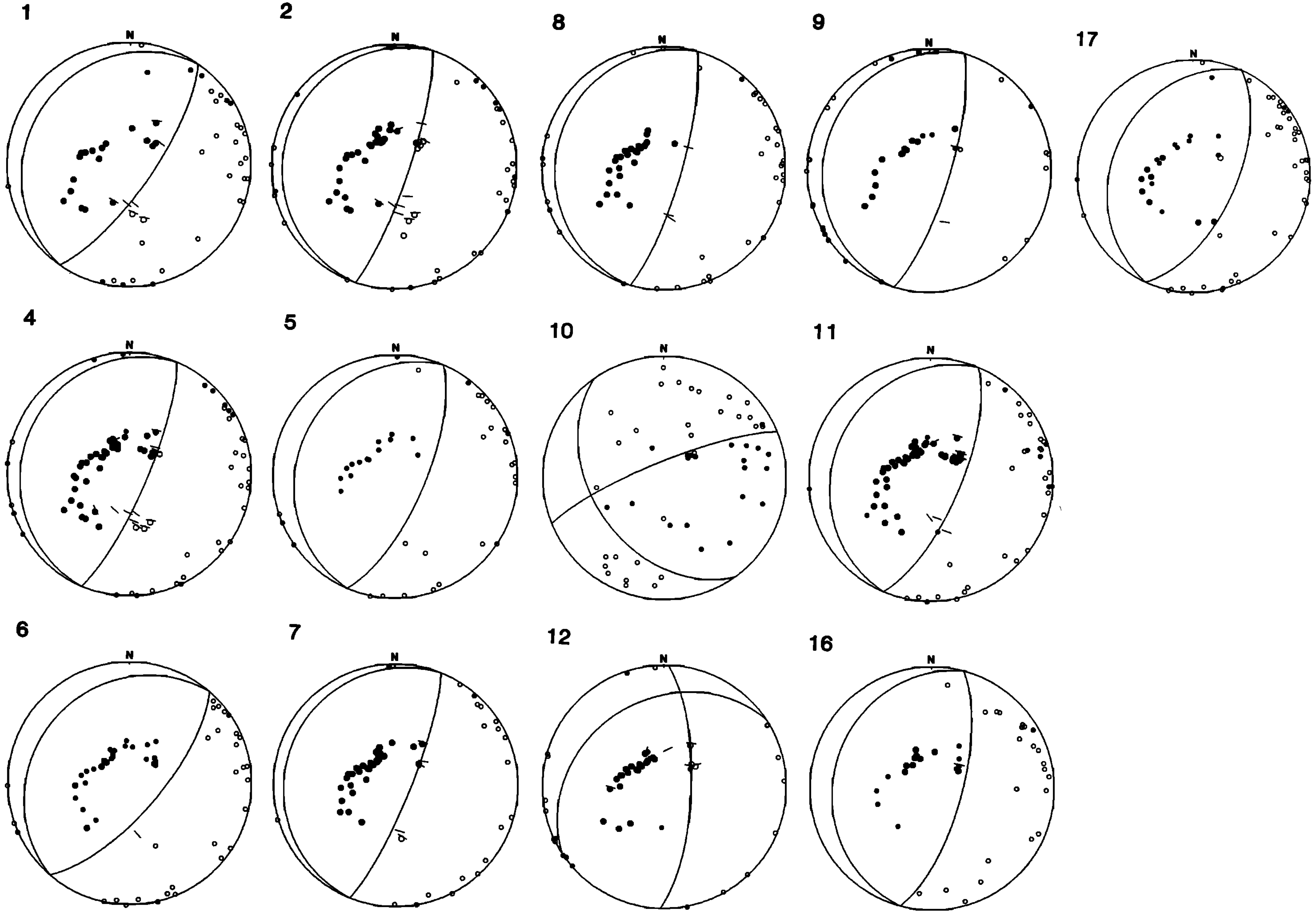

Fig. A1. Focal mechanism solutions represented as equal-area projection of the lower hemisphere of the focal sphere. Closed and open circles represent P wave first motion compression and dilatation, respectively. Dashes indicate S wave polarization direction. The numbers denote earthquake events in Table 2.

thrust type earthquake occurred beneath a depth of 40 km, this is clearly not the case for the northern Honshu arc. The sharp increase of the dip of the Wadati-Benioff zone at 25–40 km depth observed in some island arcs [*Engdahl*, 1977; *Stefani and Kawakatsu*, 1982; *L.S. House and K.H. Jacob*, unpublished manuscript, 1982] is another possible explanation for the change of seismicity between the shallow and deep thrust zones, as proposed by *Stefani and Kawakatsu* [1982].

Seismic Slip Front

The map view of 'D' type events in Figure 5a clearly shows the landward limit of the distribution of the thrust type events. This landward limit of the thrust zone is almost identical to the aseismic front proposed by *Yoshii* [1975] except in the region B. We propose to call this a 'seismic slip front', which physically defines the edge of the zone of seismic coupling at the thrust zone between the two converging plates. The aseismic front is defined as the seaward edge of the aseismic mantle wedge beneath the island arc [*Yoshii*, 1975]. The aseismic character along the plate interface deeper than the seismic slip front is likely caused by the low Q, low velocity hot mantle adjacent to the plate interface there. The seismic gap at the deep thrust zone in region B may be caused by the penetration of the aseismic mantle into the interface of two plates. However, the coincidence between the aseismic front and the seismic slip front may be an artifact, because *Yoshii* [1975, 1979b] defined the aseismic front by the landward edge of the seismicity in the depth range of 40–60 km using JMA data. As can be seen in Figure 6 (also see Figure 2 of *Yoshii* [1979a]), the activity within the mantle wedge above the thrust zone is very low for moderate to small size events. Thus there is a possibility that *Yoshii* [1975, 1979b] defined just the landward edge of the thrust zone and not the edge of aseismic mantle wedge. If this is the case, the aseismic front presented in *Yoshii* [1975, 1979b] is simply the landward edge of the 60 km depth earthquakes which does not have any physical meaning. Detailed information on other geophysical parameters, such as heat flow, gravity, seismic velocity, attenuation, and crustal deformation might help us to understand the nature of the gap and to solve the question of whether the seismic slip front is the aseismic front.

CONCLUSIONS

Regional variation of seismicity along the northern Honshu arc was studied in detail along with the types of focal mechanism. We propose to separate the interface of two converging plates into the shallow thrust zone (0–40 km) and the deep thrust zone (40–60 km). The regional variation of the seaward edge of the double seismic zone was found; in some regions, the double seismic zone constitutes a triple seismic zone with the overlapping deep thrust zone. The subduction zone was segmented into four regions A, B, C, and D from north to south, and each region was characterized by different activity in those thrust zones and the double seismic zone. Triple seismic zones were observed in regions C and D, where large historic earthquakes are recorded in the deep thrust zone. No triple seismic zone was observed in region A, although large earthquakes have occurred there historically in the deep thrust zone. In region B, there is a gap in activity for historic large and recent smaller earthquakes in the deep thrust zone. There the double seismic zone does not extend beneath the deep thrust zone. We interpret this variation of activity as spatial and temporal variation of the degree of the seismic coupling at the deep thrust zone. In regions C and D, the triple seismic zones are caused by the stress buildup prior to the occurrence of large interplate earthquakes at the deep thrust zone. In region C, the large event has already occurred in 1978, and in region D, the occurrence should be in the near future. In region A, we interpret the low activity within the slab beneath the deep thrust zone as an indication of the low level of the stress buildup in this zone. The aseismic character of the deep thrust zone in region B indicates that the seismic coupling is quite weak in this zone, and this is consistent with the lack of activity within the slab beneath the deep thrust zone in this region.

We believe that the fine structure of the seismicity at the uppermost part of the Wadati-Benioff zone provides a key to understand the seismic coupling at the plate interface, especially at the deep thrust zone. This may also give us information on the subduction process, stresses within the slab, and driving forces of plates.

APPENDIX

Focal mechanism solutions for the earthquakes in region D newly obtained in this study are presented as equal-area projections of the lower hemisphere of the focal sphere in Figure A1. Large circles indicate WWSSN long-period P wave first motion data and small circles WWSSN short-period and JMA data. Polarization angles of long-period S waves are indicated by the dashes. Nodal lines are indicated by the thin lines in this figure and their parameters are listed in Table 2. For thrust type mechanisms, it is often difficult to constrain the shallower dipping nodal planes. For such cases, we assumed that they are pure dip slip mechanisms.

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