NORMAL FAULT TYPE EVENTS IN THE UPPER PLANE OF THE DOUBLE-PLANED DEEP SEISMIC ZONE BENEATH THE NORTHEASTERN JAPAN ARC

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(Received May 4, 1985; Revised February 13, 1986)

1. Introduction

In the Tohoku District, the northeastern part of Honshu, Japan, the deep seismic zone is separated into two planes which are almost parallel to each other. The focal mechanism for the events in the upper seismic plane is characterized by both a low-angle thrust fault type above a depth of 60 km and a down-dip compression type below it. The lower seismic plane appears below a depth of 60 km and the characteristic focal mechanism for the events in this plane is the down-dip extension type (UMINO and HASEGAWA, 1975, 1982; HASEGAWA et al., 1978 a).

It is difficult to determine individual focal mechanisms for events below a depth of 60 km in the Tohoku District by using only P-wave initial motions, because large intermediate-depth earthquakes with magnitudes greater than 5 seldom occur there. Consequently, previous studies about the characteristic focal mechanism in this region were made mainly by using composite focal mechanisms for a number of microearthquakes. Moreover, there has been no precise investigation of the spatial distribution of the focal mechanism for the events on the western side of the volcanic front because of relatively low seismic activity. However, it is possible to determine the focal solutions for small intermediate-depth earthquakes if we use both P- and S-wave initial motions. Due to an accumulation
of the data and an increase in network stations, we can now investigate the precise spatial distribution of the focal mechanism in the whole Tohoku District.

In this paper, the focal mechanisms of the intermediate-depth earthquakes are determined by using the first motions of P- and S-waves. Spatial distribution of composite focal mechanisms has also been obtained for events occurring in each small region of the whole Tohoku District. The spatial change in the focal mechanism is discussed in detail by using these results.

2. Individual Focal Mechanisms

The double-planed structure of the deep seismic zone is most clearly seen in the central part of the Tohoku District (39°N < Lat. < 40°N). Individual focal mechanisms of the intermediate-depth earthquakes in this region are determined by using the polarity of the first motion of P-waves and the polarization angle of the first motion of S-waves. The data used are the P- and S-wave first motions

![Fig. 1. Distribution of the focal mechanisms for the events in the upper (a) and lower (b) seismic planes of the deep seismic zone beneath the central part of the Tohoku District, the northeastern part of Honshu, Japan. The mechanism solutions are determined by using initial motions of P-waves and polarization angles of S-waves, and are projected onto the lower focal hemisphere. Shaded quadrants indicate compressional P-arrivals.](image-url)
Fig. 2. Distribution of the focal mechanisms for the events in the deep seismic zone projected onto vertical sections which are perpendicular to the trench axis. Only P- and T-axes are projected. The volcanic front and land area are denoted by triangles and thick lines, respectively. The distance from the trench axis is also shown. The regions A-L correspond to the regions A-L in Fig. 4, respectively.

These mechanisms were read from the analog records of the seismic stations of Tohoku University and the P-wave data listed in the Seismological Bulletin of the Japan Meteorological Agency during the period of April, 1977 to July, 1981. In the case of events with a shallow focus and large magnitude, focal mechanisms are determined by using only P-wave first motion, because the records of these events are saturated and the incident angles of S-waves on the ground surface are greater than the critical angle at most of the stations.

The distributions of the focal mechanisms for the upper and lower seismic planes obtained by using these data are shown in Fig. 1. P- and T-axes of these focal mechanisms projected onto the vertical planes are shown in Fig. 2. In these figures, we show only the solutions that are determined using at least ten P- and S-wave first motions (at least fifteen P-wave initial motions if S-wave initial motions are not available). Magnitudes of these events are greater than 2.0. These figures show that the events in the upper seismic plane are generally characterized by the low-angle thrust fault type above a depth of 60 km and the down-dip
Fig. 3. Examples of the normal fault type events in the upper seismic plane of the deep seismic zone. The fault-plane solutions are shown by equal area projection on the lower focal hemisphere. Solid and open circles denote compressional and dilatational P-arrivals at stations, respectively. Arrows represent the directions of the polarization of the first motions of S-waves. Bars also denote the first motions of S-waves but are less reliable.

If examined in detail, however, we can see that the focal mechanisms in the upper seismic plane around 140.9°E are rather complicated, and that normal fault type mechanisms appear there. N-S extensional normal fault type mechanisms also appear in the same region of the lower plane. Some examples of the normal fault type mechanism solutions in the upper seismic plane are shown in Fig. 3. Although P- and T-axes may move about 10°, these solutions in Fig. 3 cannot be regarded as the down-dip compression type.

3. Composite Focal Mechanisms

Figure 4 shows the composite focal mechanism solutions for intermediate-
depth earthquakes in the central part of the Tohoku District. The seismic region is divided into twelve subregions from A to L as shown in Fig. 4. The size of a subregion except for region L is 100 km × 20 km and the longer side of each subregion is parallel to the trench axis. Since very few events are located beneath the Sea of Japan, the size of region L is taken to be as large as 100 km × 215 km. Earthquakes in each subregion from A to J are divided into two groups: one is for the upper seismic plane and the other for the lower seismic plane. The data used are P-wave first motion records obtained from the seismic stations of Tohoku University during the period of April, 1975 to October, 1981. P-wave first motions of the events in the same group are superimposed on the same focal sphere. The mechanism solution thus obtained for each group is shown in Fig. 4. In

![Composite fault-plane solutions of earthquakes in the upper and lower seismic planes of the double-planed deep seismic zone. The solution for each region in the inserted map is represented by an equal area projection on the lower focal hemisphere. Shaded quadrants indicate compressional P-arrivals. For each mechanism solution, the numeral in the upper part represents the total number of readings of P-arrivals, and that in the lower part represents the error ratio (the ratio of the number of the inconsistent P-arrivals with the solution to the total number of the readings of P-arrivals). Reliability of pressure and tension axes of the solutions for region G is shown on the right-hand side of the figure. Solid contours around the axes denote the ranges where the axes would move on the focal sphere if an increase of 10% in the number of inconsistent P-wave readings incorporated in the best fit solutions is allowed. (a) Upper plane, (b) lower plane.](image)
regions K and L, the hypocenters are scattered and it is difficult to separate them into two planes. Consequently, the composite mechanism solutions of the events in these two regions are determined without separation into the two groups.

Figure 4 represents remarkably different focal mechanisms for the events occurring near 140.9°E (region G) than from those in the other regions. In region G, the composite focal mechanism is a E-W extensional normal fault type in the upper seismic plane and a N-S extensional normal fault type in the lower plane. The error contours of the axes of the composite focal mechanisms for region G are shown on the right-hand side of Fig. 4. Even if the error is allowed to be 10% more than the best fit solution, the pattern is not changed. The features in Fig. 4 are the same as those obtained from individual focal mechanism solutions. Therefore the method of the composite focal mechanisms clearly represents the spatial distribution of the dominant focal mechanism when the grouping of the earthquakes is done this way.

The spatial distribution of composite focal mechanisms is also obtained for events in the upper seismic plane in the whole Tohoku District. We did not investigate further in the case of the lower seismic plane, because this plane does not have continuous seismicity except in the central part of the Tohoku District (see Fig. 11 in HASEGAWA et al., 1983). The data used are from P-wave initial motion records of the Tohoku University seismic network during the period of April, 1975 to July, 1982.

P- and T-axes of the obtained composite focal mechanisms are projected onto
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the horizontal plane, and are shown in Fig. 5. The size of each region in which initial motions of P-waves are superimposed is the same as the size of the subregions from A to K in Fig. 4, and is indicated by a hatch in Fig. 5(a). The P-axes are almost vertical in the regions along the seventh column in Fig. 5(a), which shows that the normal fault type events are prominent there. It is particularly interesting to note that this column nearly coincides with the volcanic front (dashed line in Fig. 5).

4. Discussion

Although the cause of the seismogenic (earthquake generating) stress of the deep seismic zone has been investigated by many authors (e.g., Veith, 1974; Engdahl and Scholz, 1977; Yang et al., 1977; Sleep, 1979; Tsukahara, 1980; House and Jacob, 1982; Goto et al., 1985), it is still uncertain what is the real cause of the double-planed deep seismic zone. In any case, if the descending oceanic plate is bent locally, it is expected that the focal mechanism is affected by this bending of the plate (Stauder, 1968; Coudert et al., 1981).

Fig. 6. Vertical cross sections of the deep seismic zone and P-axes of the composite focal mechanisms shown in Fig. 5. The volcanic front, the trench axis and the land area are represented by solid triangles, open reverse triangles and thick lines, respectively.
Figure 6 shows the seismicity of the intermediate-depth earthquakes and the P-axes of the composite focal mechanisms of the events in the upper seismic plane projected on the vertical section. From this figure, we can see that the upper seismic plane is locally and slightly bent downwards at a depth of about 100 km beneath the volcanic front, and normal fault type events occur at this bending point. The local bends of the upper plane are also seen in regions C5 and C9 (Figs. 5 and 6), and normal fault type events dominate in C9. In region C5, although the P axis is not so vertical, the dominant solution is the NE-SW extensional normal fault type (see Fig. 5) as pointed out by Umino and Hasegawa (1982).

Hasegawa et al. (1978 b) revealed that the upper boundary of the descending oceanic plate coincides with the upper plane of the double-planed deep seismic zone, by using the arrival times of the ScSp-phase and also by using the travel time anomaly of intermediate-depth earthquakes observed from a small-scale seismic array. Matsuwasa et al. (1986) also located the upper boundary of the plate by using the PS-phase (converted from P to S at the boundary), and they ascertain that the boundary is just above the upper seismic plane. These works indicate that the shape of the upper plane is almost the same as the upper boundary of the oceanic plate and that the oceanic plate is actually bending at the bending point of the upper seismic plane. Normal fault type events are very likely to occur at this bending point.

The lower seismic plane may also be affected by compressional stress parallel to the dip of the descending plate at the bending point, when the neutral surface of the bending is located above the lower seismic plane. In such a case, down-dip extension type events cannot be dominant there (see region G in Fig. 4). However, orientations of the principal stress axes strongly depend on the initial and boundary conditions. Thus, quantitative stress distribution is not discussed here.

Kato (1979) investigated the cause of the subsidence in the central part of the Tohoku District by using the finite element method. He showed that this subsidence can be explained if the oceanic plate moves downward beneath the volcanic front, which is consistent with our result.

If the descending oceanic plate is really bending beneath the volcanic front, the pressure in the overlying mantle may decrease on the western side of the volcanic front. Moreover, the pressure will be suddenly reduced just above the normal fault type events. This reduction of pressure may have some relation to the generation of magma and a low-Q, low-velocity region in the overlying mantle on the western side of the volcanic front.

5. Conclusion

In order to investigate the seismogenic stress distribution within the descending oceanic plate, both individual and composite focal mechanism solutions were
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obtained for the intermediate-depth earthquakes in the Tohoku District, the northeastern part of Honshu, Japan.

The events in the upper seismic plane of the double-planed deep seismic zone are characterized generally by the low-angle thrust type above a depth of 60 km and the down-dip compression type below it. The events in the lower seismic plane are generally characterized by the down-dip extension type. These features are the same as the results of the previous studies.

Beneath the volcanic front, however, the dominant focal mechanism of the events in the upper seismic plane is not the down-dip compression type but is the normal fault type. This region is located at the point where the descending oceanic plate is slightly bent downwards. This exceptional mechanism beneath the volcanic front can be explained by the downward bending of the descending oceanic plate.

These normal fault type events and the bending of the oceanic plate may have some relation to the generation of magma and the structure of the overlying mantle.

We wish to express our sincere appreciation to Prof. T. Hirasawa for his valuable advice and to Dr. K. Goto and Dr. H. Shimizu for their useful suggestions and stimulative discussions. Thanks are also due to the members of the Observation Center for Earthquake Prediction, the Aobayama Seismological Observatory, the Akita Geophysical Observatory, the Honjo Seismological Observatory, the Kitakami Seismological Observatory and the Sanriku Geophysical Observatory of Tohoku University, for their valuable discussions.

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