SEISMIC STUDIES OF THE UPPER MANTLE BENEATH THE ARC-JUNCTION AT HOKKAIDO: FOLDED STRUCTURE OF INTERMEDIATE-DEPTH SEISMIC ZONE AND ATTENUATION OF SEISMIC WAVES

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Distribution of intermediate and deep earthquake hypocenters beneath the Hokkaido corner, one of the notable arc-junctions in Japan, is investigated. A specially designed projection of the hypocenters is made to demonstrate the configuration of the seismic zone beneath the arc-junction. The configuration is characterized by a peculiar folding in the depth range between 80 and 150 km, which seems to be caused by plastic deformation of the descending lithosphere.

Attenuation of seismic waves of local earthquakes is also studied. Q values for S waves fall in the range between 50 and 200 in the upper mantle beneath Hokkaido. The distribution of Q values shows that the high attenuation zones correspond to the areas of high heat flow.

1. Introduction

The spatial distribution of intermediate and deep earthquakes is useful for confirming the deformation of the descending lithosphere and provides an important clue to the response of materials to the subduction process. Beneath an arc-junction like the Hokkaido corner, the descending lithosphere must be deformed and overlapped due to conservation of the surface area. There are three notable arc-junctions in Japan. These are the Hokkaido corner at the junction of Kurile arc and northeast Honshu, the central part of Honshu near the triple junction of the Pacific plate, Philippin-Sea plate and Honshu, and the Kyushu corner at the junction of Ryukyu arc and southwest Honshu.

The spatial distribution of earthquake hypocenters in and around Japan has been investigated by many authors (e.g., WADATI et al., 1969; KATSUMATA and SYKES, 1969; KATSUMATA, 1970; UTSU, 1971). The more accurate observations have revealed the more detailed structure of deep seismic zone. Beneath the Hokkaido corner, UTSU (1968) showed curved contour lines for deep seismic zone, but UTSU (1974) later modified them to discontinuous contour lines (Fig. 1). To obtain more distinctive structure of the deep seismic zone, highly accurate distribution of hypocenters must be required. The Hokkaido island is a place suitable to observe intermediate and deep earthquakes and to resolve the problem of deformation of the lithosphere beneath the arc-junction because of relatively high seismicity comparing with the other two junctions.

In this paper, the distribution of intermediate and deep earthquakes which occurred in and around Hokkaido is investigated. In addition to the distribution of hypocenters, attenuation of seismic waves of local earthquakes is studied to reveal the regionality of low Q zone in the upper mantle beneath Hokkaido.
2. **Seismic Network and Method of Hypocenter Determination**

   The location of observation stations in the routine as well as temporary seismic network used in this study is shown in Fig. 2. The digitized data of the routine stations are telemetered to the observation center of Hokkaido University. At each temporary station, a system of slow speed magnetic tape recording with AC bias is used. The system can observe for two months by a tape of 1,100 m long continuously with very low power consumption of about 1 W. To keep high time resolution, the system has a crystal coded clock and a radio to compensate the clock. Time accuracy is kept better than 0.02 sec at any time.
Seismic Studies of the Upper Mantle Beneath the Arc-Junction at Hokkaido

The temporary network in the southwestern part of Hokkaido was in operation for four months in 1973, and the central and northern parts of Hokkaido have been operated from 1974. The routine observation by telemetered network was begun in July, 1976.

The hypocenters are determined by the following method. First, the origin time \( t_{oi} \) is calculated at the \( i \)-th station by

\[
 t_{oi} = t_{pi} - (V_p/V_s - 1)^{-1} t_{(s-p)i}
\]

where \( t_{pi} \) and \( t_{(s-p)i} \) are P-wave arrival and S-P times, respectively and \( V_p/V_s = 1.73 \) is assumed. The average value of \( t_{oi} \) at each station provides the origin time. Then coordinates of hypocenter are calculated by the least squares method to fit \( t_{pi} \) to ICHIKAWA-Mochizuki’s table (1971). The computer program was designed by SHIBUYA et al. (1973).

3. Hypocenter Distribution of Intermediate and Deep Earthquakes

About 200 hypocenters are determined using the routine and temporary observation data during the period, July 1976–November 1977, and about 200 hypocenters which are relocated using JMA (Japan Meteorological Agency) and some of the routine and temporary observation data during the period January 1961–June 1976, are added. Figure 3 shows the epicenter distribution of the earthquakes. Beneath the Hokkaido corner, the deeper seismicity is generally lower and less uniform. A northeast trend of seismicity from west off Hokkaido seems to constitute an edge of the deep seismic zone. Some aseismic regions appear in southwestern and central Hokkaido, and along the coast line of Okhotsk Sea. A clear northwest trending seismic zone appears in northeastern Hokkaido. The nonuniform seismicity suggests that the stress distributes inhomogeneously in the descending lithosphere which is deformed beneath the arc-junction.

Because the seismic zone beneath Hokkaido changes its dip angle and dip direction, and has a relatively low seismicity, vertical and horizontal projection of the hypocenters are not adequate for establishing the configuration of the seismic zone, and another device is required. In this study, specially designed projection is made. In making this projec-
Fig. 4. Distribution of hypocenters of earthquakes on the azimuth-dip plane in a depth range between 80 and 150 km.

Fig. 5. Distribution of hypocenters of earthquakes projected on the vertical plane in the N-S direction. These occurred in an area northeast of the line directing N60°W from the origin, × in Fig. 3.

tion, a point is placed on the Earth’s surface near the junction of the Kurile and Japan trenches. From this point, the hypocenters are projected on the azimuth-dip plane. Then the seismic zone becomes a thin plane. The position of the point is selected (× in Fig. 3) so that the thickness of the seismic zone on the azimuth-dip plane becomes thinnest. Figure 4 shows the distribution of the hypocenters in the depth range between 80 and 150 km by the projection. A fairly thin continuous seismic zone which has a small scale Z-shaped peculiar folding appears just beneath the junction. If the distribution of hypocenters is nonuniform, the folded seismic zone may be an only apparent feature made by the projection. But the existence of the folding is reliable because hypocenters are located rather uniformly even in the folded seismic zone which corresponds to an area between the lines of N30°W and N60°W from × in Fig. 3. It has been predicted that the seismic zone may be deformed notably at the transitional zone between Kurile and
northeast Honshu (Isacks and Molnar, 1971; Utsu, 1971; Aoki, 1974), and existence of the folded seismic zone is significant.

Beneath the Tohoku and Kanto districts, northern and central Honshu, a double planed seismic zone was discovered (Tsumura, 1973; Umino and Hasegawa, 1975). But beneath Hokkaido, double planed seismic zone is not obvious in the present analysis (Fig. 5). It may be suspected that absence of a double planed seismic zone was caused by the low accuracy of hypocenter determination. But Umino and Hasegawa (1975) showed that the seismic zone can be separated into two planes even using JMA data of low magnification seismographs. We believe that the time accuracy of the data of Hokkaido University is high enough to distinguish the hypocenters into two planes if they exist. Therefore the absence of double planed seismic zone beneath Hokkaido may be one of the essential characteristics of the arc-junction.

The thickness of the seismic zone in Fig. 5 is about 40 km and almost the same as that of Tohoku District (Umino and Hasegawa, 1975). If the thickness of the lithosphere including the seismic zone is about 40 km, it can be understood easily how the folding can be produced by conservation of area at the junction. But the lithosphere has thickness of about 100 km near the Japan trench (Yoshii, 1973). It is quite reasonable that the descending lithosphere keeps its thickness to the depth of 150 km at least. If the whole lithosphere with thickness of 100 km is rigid body and is folding in such a narrow region as shown in Figs. 3 and 4, earthquakes may occur in the whole lithosphere and thickness of seismic zone must become 100 km. Figure 4 shows that there is no difference in thickness of the seismic zone even in the folded zone and that just only the seismic zone with thickness of about 40 km is folding. These suggest that the thickness of rigid part in the lithosphere is about 40 km and that outer parts of the seismic zone in the lithosphere behave as a plastic body. Turcotte et al. (1978) suggested the existence of plastic behaviour of the lithosphere at the trench.

The focal mechanisms of intermediate earthquakes in the folded seismic zone may be influenced by the development of the folding. Maximum compressional and tensile stresses of these earthquakes are expected to have directions nearly perpendicular to the folding axis. Focal mechanism solutions for earthquakes that occurred in and around Hokkaido, have been obtained by many authors (Ichiyama, 1971; Isacks and Molnar, 1971; Koyama et al., 1973; Sasatani, 1976). Figure 6 shows distribution of the focal mechanism solutions after Sasatani (1976). In and around the folded seismic zone, the distribution of maximum stress direction appears to be not systematic. Nos. 29 (h=114 km), 38 (h=133 km) and 51 (h=147 km) earthquakes in Fig. 6 having E-W directions of compressional axis, are probably affected by the folding. But Nos. 2 (h=300 km) and 47 (h=169 km) direct their compressional axes almost parallel to the folding axis. These suggest that development of the folding affect the mechanisms of the earthquakes shallower than 150 km.

Figure 7 shows the distribution of hypocenters deeper than 150 km on the azimuth-dip plane. In this depth range the folded structure disappears. This suggests the existence of lateral tensile stress to smooth the folding. In Fig. 6, Nos. 4 (h=240 km), 8 (h=280 km), 18 (h=309 km), 20 (h=221 km), 22 (h=224 km) and 36 (h=238 km) direct the axes of tension almost perpendicular to the folding axis. To establish the configuration of deep seismic zone and to understand how the folded seismic zone is smoothed, more data of deep earthquake are required.

There are three notable arc-junctions in Japan. Aoki (1974) investigated P-wave
Fig. 6. Focal mechanism solutions of earthquakes that occurred near the Hokkaido corner. In the solution a filled small circle represents the axis of tension and an unfilled small circle the axis of compression (after SASATANI, 1976).

Fig. 7. Distribution of hypocenters of earthquakes on the azimuth-dip plane deeper than 150 km.

travel time anomaly of Cannikin event and concluded that the descending lithosphere separates into two segments and overlapped beneath central Honshu. However, folded seismic zone is not found beneath central Honshu or any other arc-junctions except for the Hokkaido corner.
4. **Attenuation of Seismic Waves in the Upper Mantle**

A large scale anomalous structure of the upper mantle beneath the island arcs of Japan has been confirmed by Utsu (1966) and Utsu and Okada (1968) from the evidence of anomalous seismic wave propagation. According to these studies, ratio of $Q$ for high $Q$ to low $Q$ zones in the upper mantle is estimated to be 10. In this section, distribution of $Q$ values for S wave in the low $Q$ wedge beneath the Hokkaido corner using local earthquakes, is described. $Q$ values are determined by using S/P method (Sacks and Okada, 1974). In this method, the spectra of P and S waves originated from the same source are compared and two assumptions are required to obtain $Q$ values. One is that ratio of $Q$ for P wave to S wave is assumed to be constant. Anderson et al. (1965) suggested the value of 2.25 for the ratio. The other, the source spectra of P wave and S wave are assumed to be identical.

There are many methods for determination of $Q$ (Okada, 1977), for example, direct slope method (Asada and Takano, 1963; Takano, 1966; Oliver and Isacks, 1967), spectral ratio method, comparative path method (Utsu and Okada, 1968), differential path method, and S/P method. S/P method, though containing some ambiguities, has an advantage for evaluating the regional variation of $Q$ values beneath the island arcs.

Forty earthquakes including several shallow earthquakes are used for the determination of $Q$ values. For spectral analysis, multichannel band-pass filters are used. The electric $Q$ values of the filters are adjusted to be 20. Average amplitudes of P and S waves are measured from filtered records. Time intervals for the averaging are selected to be 0.5 and 1.0 sec for P and S waves respectively. Distribution of the apparent $Q$ values along the paths from hypocenters to stations is shown in Fig. 8. Beneath the central and northern parts of Hokkaido, apparent $Q$ values appear to be 150, while southwestern part,
it is about 70 for intermediate and deep earthquakes. For shallow earthquakes, $Q$ values of about 400 are obtained beneath the southwestern part. To obtain the average $Q$ values in the upper mantle, the effect of $Q$ in the crust must be excluded. Apparent $Q$ and travel time $T$ are expressed simply by

$$\frac{T}{Q} = \frac{T_c}{Q_c} + \frac{T_m}{Q_m}, \quad T = T_c + T_m$$

where $T_c$, $T_m$ and $Q_c$, $Q_m$ are travel times and $Q$ values in the crust and upper mantle respectively. Beneath the central and northern part of Hokkaido, $Q_m$ is estimated to be 120 and southwestern part, to be 50. The latter is extremely low and smaller than that of central Honshu obtained by using the same method (SACKS and OKADA, 1974). But this value is almost the same as those beneath the Lau basin, west off the Tonga arc (BARAZANGI and ISACKS, 1971) and northern part of New Zealand (MOONEY, 1970), though different methods were used to estimate $Q$ values.

In the southwestern part of Hokkaido, high heat flow values (2–4HFU) are observed and high temperature in the upper mantle is estimated, while in the central and northern parts, heat flow values are not so high (1.0–1.5HFU) (EHARA, 1974). BARAZANGI et al. (1975) pointed out that the high attenuation zones correspond to the areas of high heat flow and low seismic wave velocities by using spectral ratios for $P$ and $pP$ phases. And they indicated that the upper mantle beneath the whole Hokkaido is a low attenuation zone, and they could not distinguish such a regional difference in Hokkaido.

Distribution of $Q$ values beneath Hokkaido obtained in this study suggests that high temperature and partial melting in the upper mantle is probably the main cause of the seismic wave attenuation.

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