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Anomalies in Seismic Wave Velocity and Attenuation Associated with a Deep Earthquake Zone (II)

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Abstract

Most deep earthquakes under Japan occur in a fairly thin dipping layer. The absorptive portion between this seismic layer and the Mohorovičić discontinuity has been outlined using seismic intensity data for recent deep and shallow earthquakes in Japan. The location of the low-Q region thus obtained also explains the variations of body wave spectra from near-by earthquakes recorded at several Hokkaido stations. It is suggested from records of distant earthquakes that there exists another low-Q region below the seimic layer. The Q value in the deep seismic layer seems to be at least several times as high as that of the low-Q regions in the upper mantle.

8. Deep earthquake zone under Japan

Hypocenter determinations for Japanese earthquakes have much improved since 1961 when data processing by an electronic computer was introudced in the Japan Meteorological Agency. Since the conventional travel time tables by Wadati *et al.* are used as a standard and no consideration is given to regional differences in crust-mantle structure, systematic errors can not be avoided in hypocenter location. However, as a result of elimination of errors involved in the graphical method used before, relative positions of hypocenters have become more reliable than before.

By using all hypocenter coordinates published by JMA for earthquakes with focal depth 100 km and larger from 1961 through 1967, the iso-depth lines of deep earthquakes have been drawn as shown in Figure 21. Since the hypocenter location is less arcuate outside the network of observing stations, iso-depth lines are shown only in land area and its immediate vicinity.

In Figure 22 the focal depth h of an earthquake determined by JMA is plotted against the predicted depth d from its epicenter location and the iso-depth map. If all hypocenters lie on the surface defined by the iso-depth lines and no errors exist in their determinations, all the plotted points in Figure 22 must lie on a straight line $h=d$. However, the focal depths by JMA

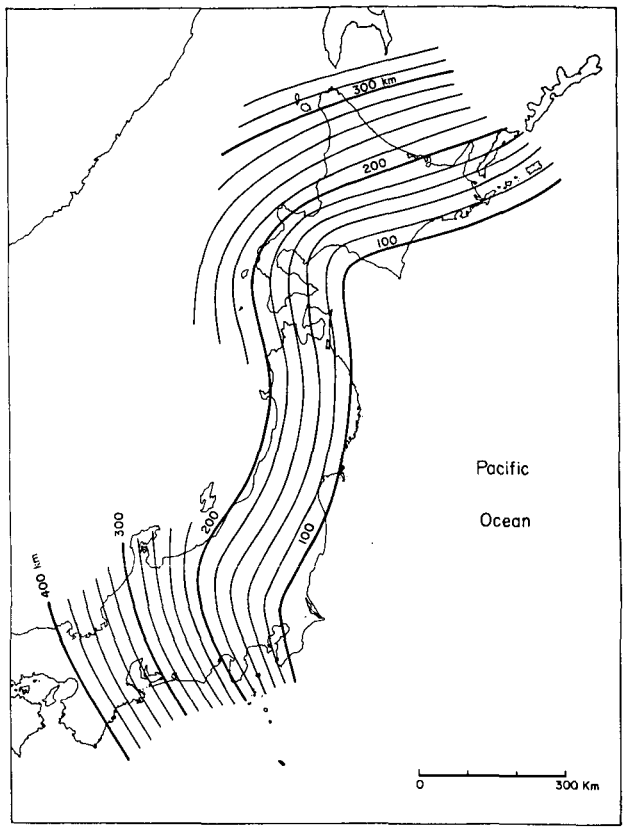


Fig. 21. Iso-depth lines of deep earthquakes.

were given at intervals of 20 km for $0<h<120$ km, of 40 km for 120 km$<h<$ 400 km, and of 50 km for $h>400$ km. (After 1967 these intervals have been reduced.) In this case the points must lie on segments of horizontal lines indicated in Figure 22. This condition is satisfied by most earthquakes with $h\geq 140$ km. This means that most deep earthquakes under Japan originate on or very close to the dipping surface defined by the iso-depth lines. In this paper we call this the "seismic sruface".

Hitherto deep earthquakes have been supposed to occur in a dipping layer with a thickness of about 100 km or more. This is a natural conclusion if one adopts the hypocenter locations published before 1960, for example, as illustrated in Figure 8. Figure 22, which is based on the recent data, indicates that most deep earthquakes occur in a thinner layer having a thickness of

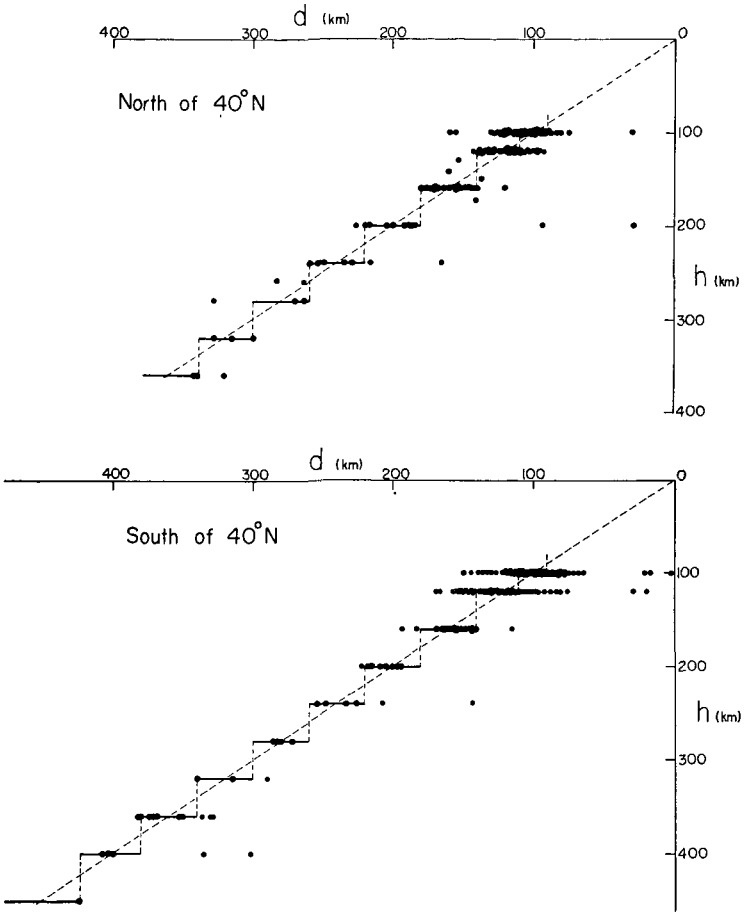


Fig. 22. Focal depth h by JMA plotted against predicted depth d from Figure 21.

a few tens of kilometers. Only several exceptional ones are found outside this layer. Sykes[41] reported that the deep earthquakes in Fiji-Tonga-Kermadec region occur in a layer not thicker than 50 to 100 km.

Earthquakes shallower than about 120 km are not concentrated in a thin layer. Many earthquakes with focal depths of 40 to 100 km occur in central Kwanto district and near the coast of Hidaka, Hokkaido where earthquakes with focal depths of 100 to 120 km also occur frequently. It is to be noted that these two regions correspond to the junctions of different island arcs.

9. Evidence from seismic intensity distributions

Previous studies[1)-3)] indicated that the deep seismic layer transmits seismic waves with smaller attenuation as compared with the adjacent part of the upper mantle on the inner (continental) side of the seismic layer. In this section an attempt is made to draw the contours of the high-Q and low-Q regions in the upper mantle under northern Japan using seismic intensity data.

As stated in a previous paper[1)], shallow earthquakes with magnitude less than about 6.5 exhibit normal seismic intensity distributions in contrast to some large shallow earthquakes and all felt deep-earthquakes. As an example of the normal seismic intensity distributions, the Kutcharo earthquake of November 4, 1967 (M=6.5, h=20 km) is illsutrated in Figure 23A. Since the earth's crust transmits high-frequency seismic waves fairly efficiently, the shock was felt at Wakkanai (northern end of Hokkaido, epicentral distance

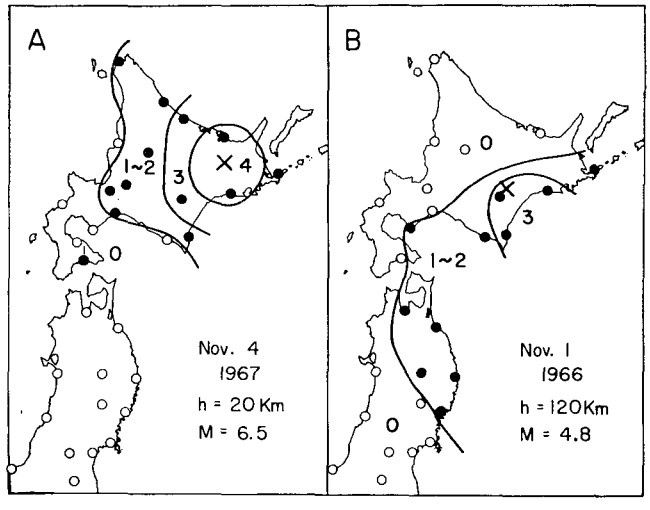


Fig. 23. Comparison of two isoseismal maps, shallow and intermidiate earthquakes.

about 280 km), where felt earthquakes are seldom observed. On the other hand, almost all near-by deep earthquakes were not felt there due to the effect of an absorptive region in the upper mantle. Figure 23B represents a typical intensity distribution of deeper earthquakes. In this example the epicenter does not differ by more than 1 degree from the Kutcharo earthquake, but the shock was not felt at Wakkanai as it is located in the shadow zone of the absorptive region.

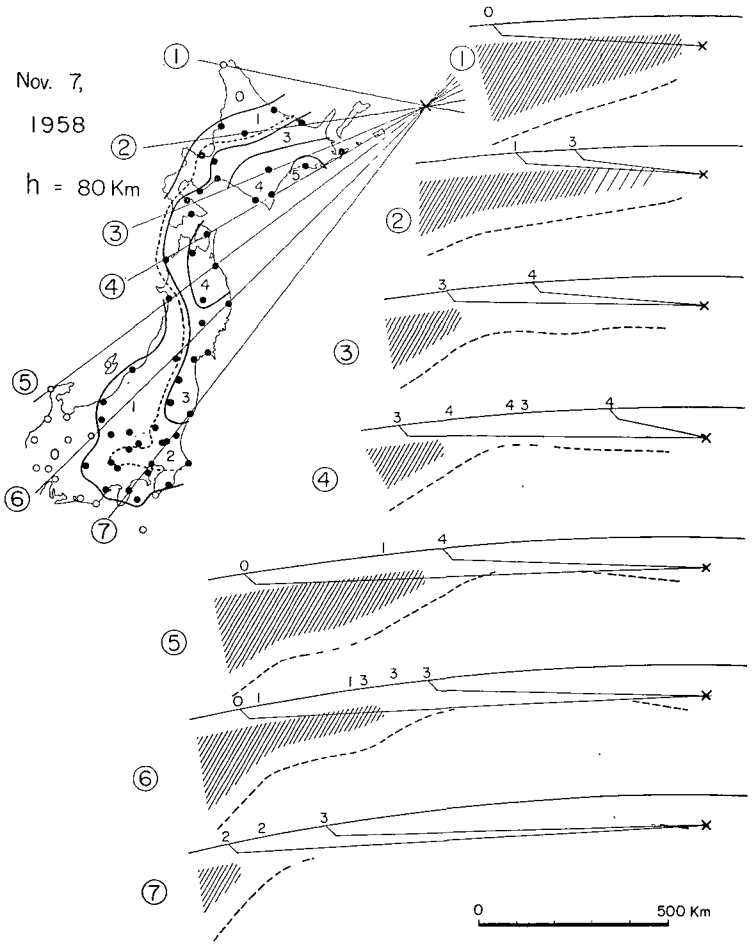


Fig. 24.

In Figures 24–29 seismic intensity maps for several earthquakes are shown together with vertical cross-sections through the respective hypocenters and some representative observing stations. Since the study is not in the stage of requiring a very high accuracy, the seismic wave velocity is assumed to be constant throughout the concerned part of the upper mantle. The broken curve in the cross-sections represents the seismic surface which is drawn using Figure 22. The hatched part is the estimated low-Q region above the seismic layer. Its shape and position are chosen to explain the variations

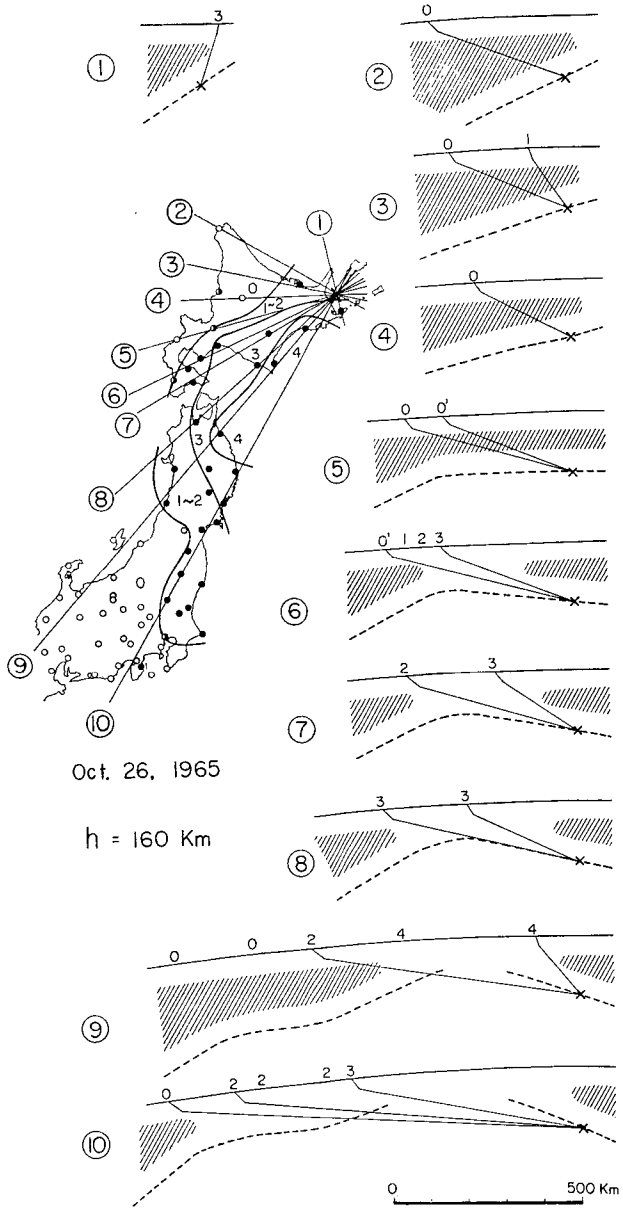


Fig. 25.

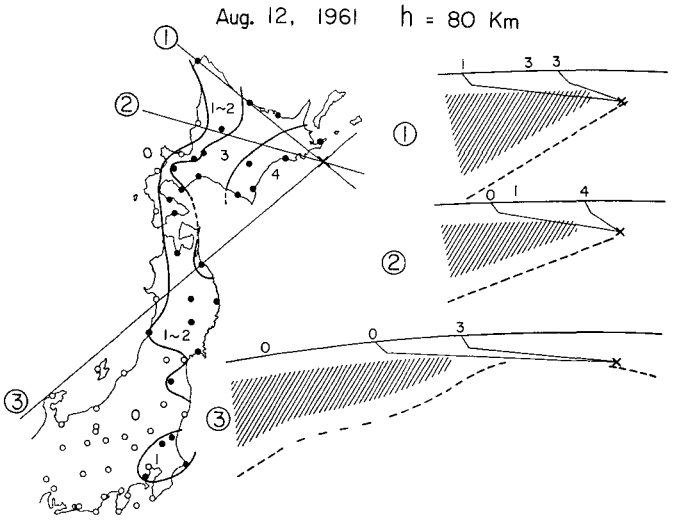


Fig. 26.

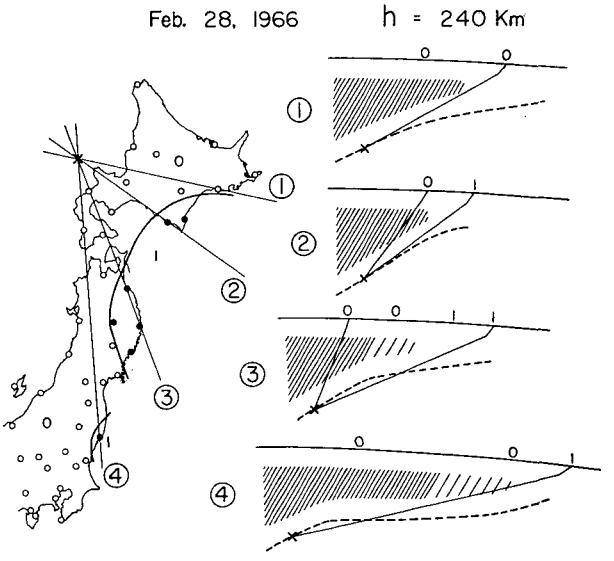


Fig. 27.

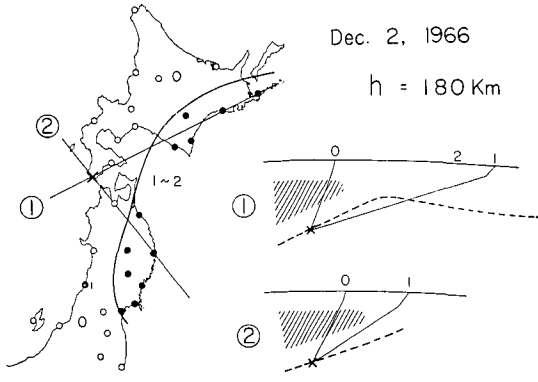


Fig. 28.

of seismic intensity from station to station. The upper boundary of this region is about 50 km below the earth's surface, and the lower boundary is parallel to the seismic surface keeping a distance of about 60 km. Of course this is a too simple model to explain all features of intensity distributions in detail. Actually the position of these boundaries may vary regionally, or the Q-value may change gradually without forming sharp boundaries. Anyway, considering the variations of ground conditions and many other factors affecting the assigned intensity to a certain station, the intensity distributions in Figures 24–29 may be regarded as adequately explained by assuming the hatched (low-Q) region shown in the figures. Another low-Q region associated with the low velocity region under the seismic layer (cf. Figure 11A') is suspected to exist, but this is not detectable by seismic intensity studies.

10. Variations in waveforms and spectra of body waves recorded at seismic stations in Hokkaido

Seismograms of fourteen near-by deep earthquakes recorded at six stations in Hokkaido were examined for differences in waveforms between the stations. The earthquakes are those listed in Table 4 (excluding No. 5) and two additional ones in Table 5. The stations are Urakawa, Nemuro, Hakodate, Sapporo, Asahikawa, and Wakkanai. The seismograms are those written by JMA Type-59 electromagnetic seismographs on smaked paper. These seismographs have a flat frequency-response with magnification of 100 between 0.2 and 10 cps. Figure 30 indicates the locations of the stations and the epicenters

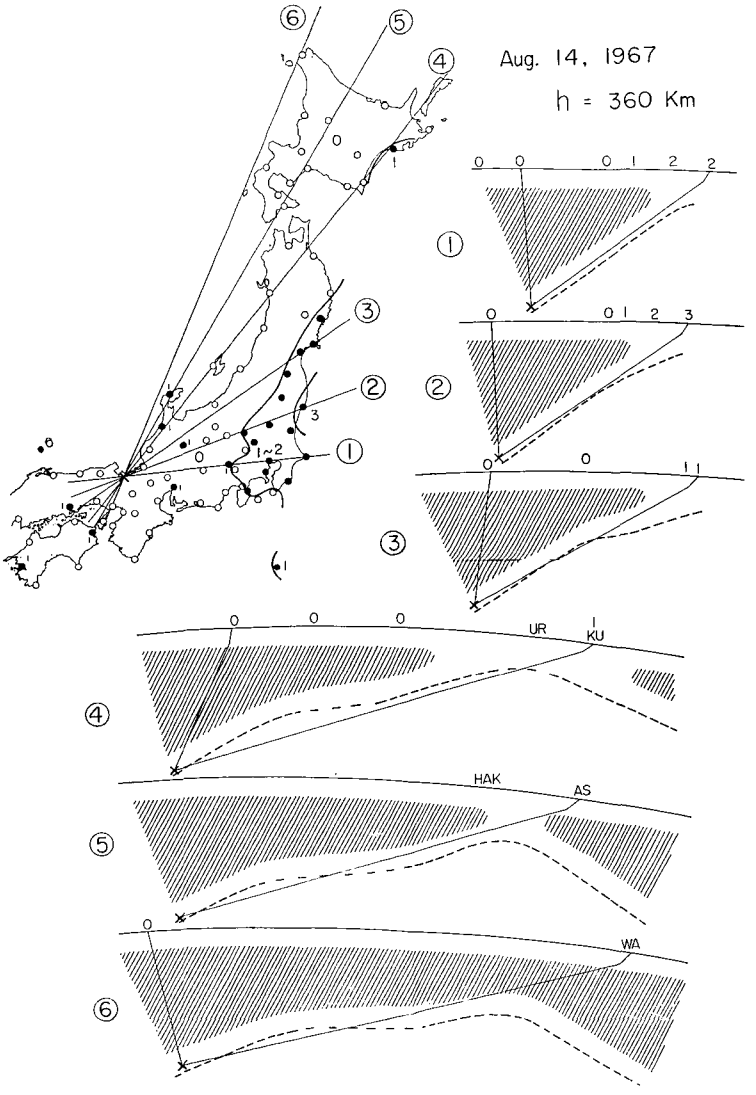


Fig. 29.

Table 5.

No.	Date and Time (J.S.T.)	JMA Epicenter Depth	CGS Epicenter Depth	*m*
13	1967 Mar. 12 01:52	143°15′ 42°36′ 110km	143°.0 42°.6 33km	5.3
14	July 5 08:42	142°36′ 43°04′ 170	142°.5 43°.2 160	5.6

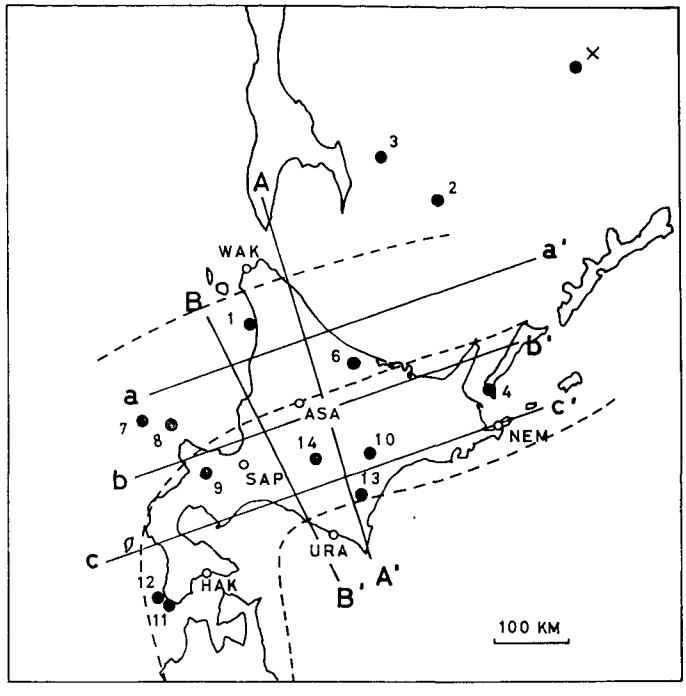


Fig. 30. Epicenters of deep earthquakes used in the waveform analysis (dots with numbers), and the positions of vertical cross-section shown in Figure 35.

by JMA.

Although only a few samples from these seismograms are reproduced here, the variations in the content of high-frequency waves from station to station are apparent for every earthquake. The seismograms of two earthquakes, July 1, 1964 (No. 2) and February 3, 1967 (No. 12), shown in Figure 31 clearly demonstrate these variations. In Table 6 all seismograms are calssified into two types, H and L. The H-type seismograms are rich in high-frequency waves of about 1 cps or more as seen from Urakawa and Nemuro seismograms in Figure 31. The L-type ones do not contain such high-frequency waves like Wakkanai and Sapporo seismograms in the same figure. Absence of an H or L mark in Table 6 means that the corresponding seismograms are too small or faulty to make a judgement.

Figures 32–34 show vertical cross-sections passing three hypocenters. Seismic rays reaching stations near the cross-sectional plane are projected on

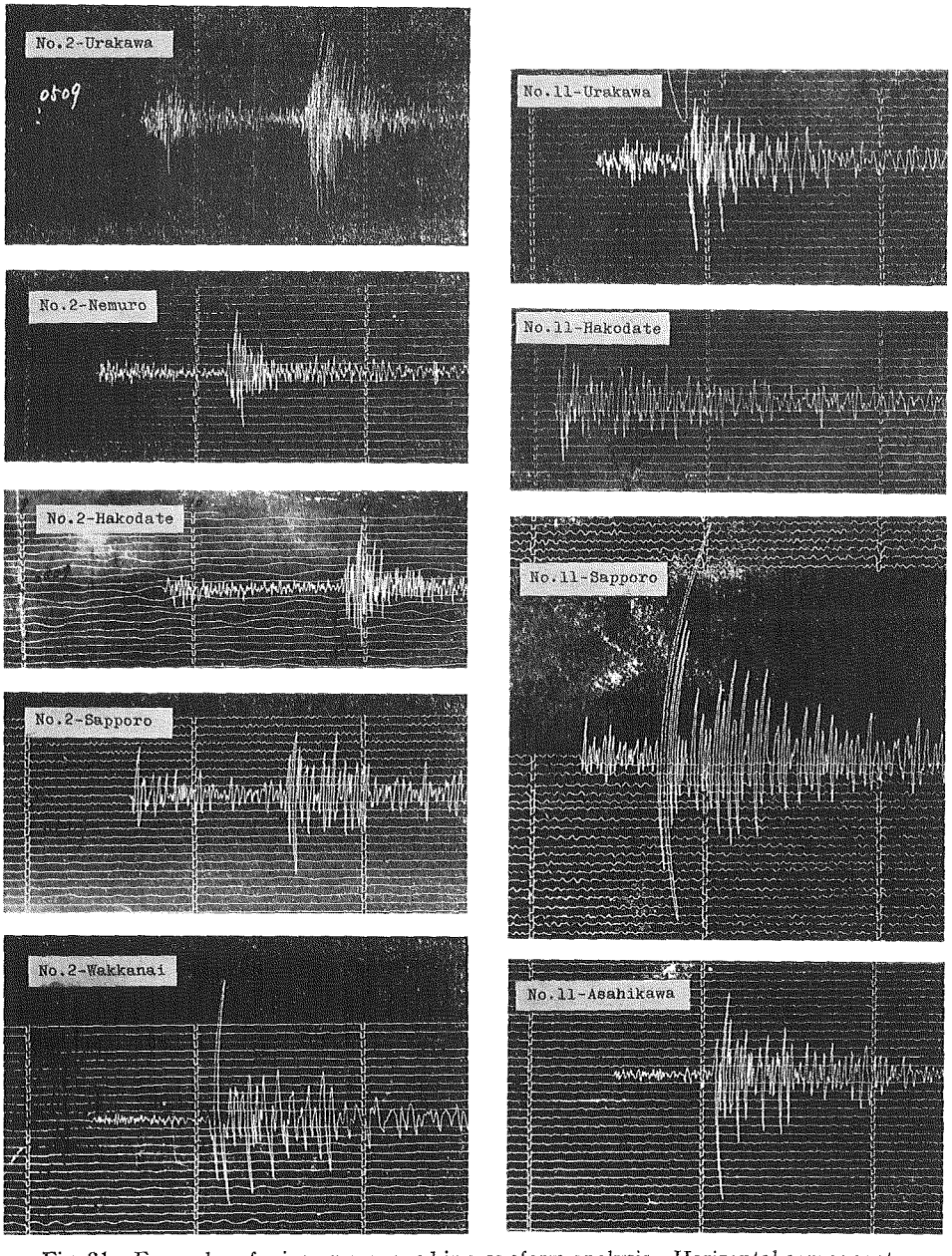
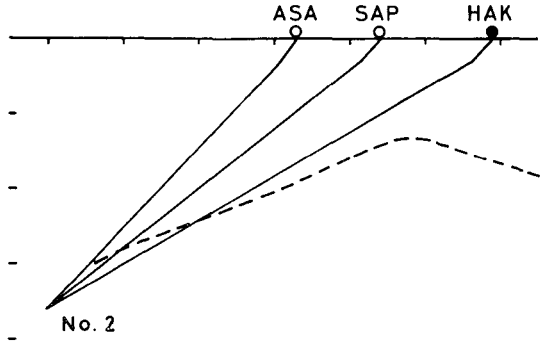


Fig. 31. Examples of seismograms used in waveform analysis. Horizontal components. For location of the earthquakes and the stations see Figure 30, and for seismic intensities see Figure 2. Time marks are placed every one minute.

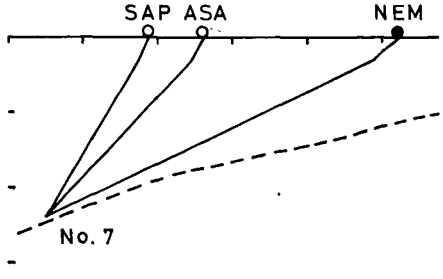
Table 6. Types of seismogram at each station for earthquakes listed in Tables 4 and 5.

No.	Urakawa	Nemuro	Hakodate	Sapporo	Asahikawa	Wakkanai
1	H		L	L	L	L
2	H	H	H	L	L	
3	H	H	H	L	L	L
4	H	H	H	L	L	L
6	H	H	L	L	L	L
7	H		L	L	L	L
8	H	H	L	L	L	L
9	H	H	H		L	L
X	H	H	H	L	L	L
10	H	H		L	L	L
11	H	H		L	L	L
12	H		L	L	L	L
13	H	H	H	H		L
14	H	H	H	H	H	L



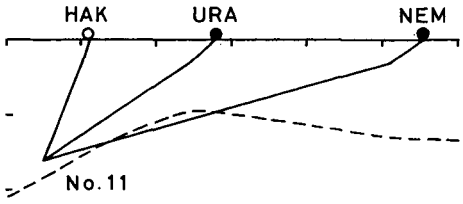
	P	S
URA	0.91	1.51
NEM	1.50	1.55
HAK	1.25	1.24
SAP	0.71	0.57
ASA	0.70	0.53
WAK		0.43

Fig. 32.



	P	S
URA	1.00	1.01
NEM		
HAK	0.70	0.53
SAP	0.65	0.52
ASA	0.80	0.55
WAK	0.47	0.36

Fig. 33.



	P	S
URA	1.31	1.02
NEM		1.12
HAK	0.82	0.53
SAP	0.77	0.49
ASA	0.75	0.51
WAK	0.54	0.35

Fig. 34.

the plane. The stations are indicated by solid or open circles according to the type of seismograms, H or L. The broken line represents the position of the seismic sruface. The average frequencies (in cps) for the main parts of P and S phases at each station are shown in the same figures. The average frequency has been determined from the frequency that the seismogram trace crosses the zero-line.

Figure 35 shows vertical cross-sections along lines AA', BB', aa', bb', and cc' indicated in Figure 30. These lines are almost parallel or perpendiculer to the iso-depth lines. A solid or oepn cricle represents the point where a ray from a certain earthquake to a certain station passes through the cross-sectional plane. Solid and open cricles denote that the ray produced H- and L-type seismograms at the station respectively. The position of the seismic surface is again represented by a broken line. It is readily seen from this figure that the solid circles distribute as far as several tens of kilometers from the seismic surface. It is safe to say that at least this region occupied by solid circles is transparent for high-frequency waves.

The above investigation of waveforms presents the results consistent with the seismic intensity studies. The stations near the Pacific coast of Hokkaido record prominent high-frequency P and S waves with average frequencies of 1 csp or more, which are easily perceptible by persons. On the other hand, the seismgorams obtained at the stations near the Seas of Japan and Okhotsk are characterized by lower frequency waves with average frequencies of about 0.5 cps or less.

A detailed examination of waveforms reveals that the content of high-frequency waves at each station varies with the location of earthquakes. For example, the Hakodate seismograms are H-type in the case of deep earthquakes

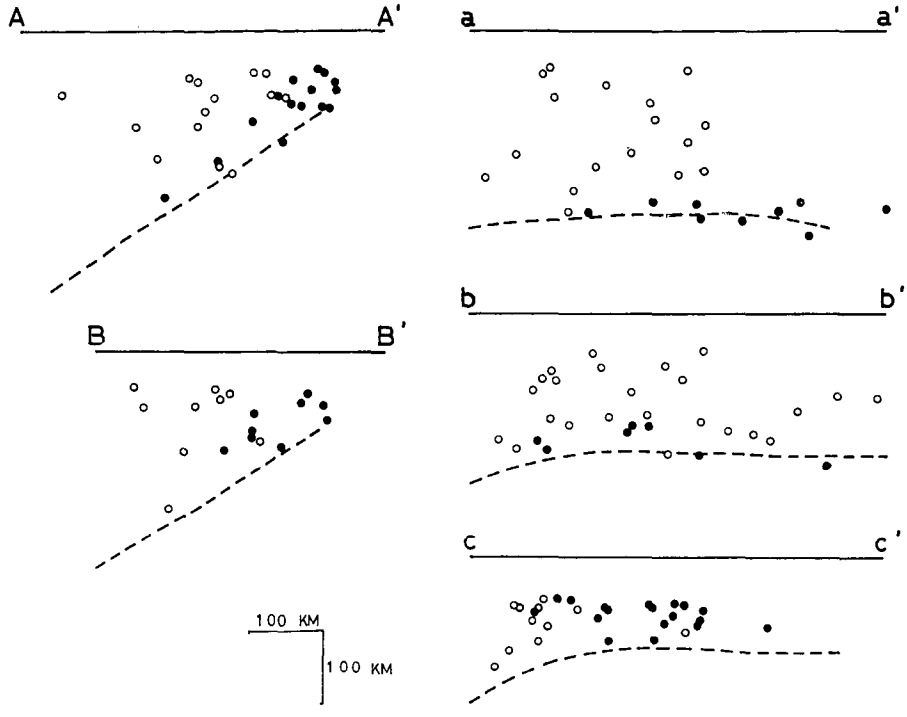


Fig. 35. Vertical cross-sections along lines AA', BB', aa', bb', cc' shown in Figure 30.

occurring in the Okhotsk Sea to eastern Hokkaido, while they are L-type for earthquakes in the Japan Sea. Such a fact can be understood by considering the relative position of the seismic (high-Q) layer to the station. The seismograms of near-by deep earthquakes obtained at Wakkanai are always L-type. However this should not be attributed to the peculiarity of the station, since crustal earthquakes in southern Sakhalin and northern Hokkaido produce high-frequency waves there.

The seismograms used in the above investigation are almost unsuitable to spectral analysis, because the recording speed is too slow to digitize the short period oscillations. However, some seismgorams of the series of earthquakes which occurred in southern Kurile Island region (149°~150°E, 43.°5~44.°5N) during October and November, 1963 can be analyzed owing to the long-period nature of P and S phases. Nine earthquakes were chosen from this series which produced seismograms of P or S phases with appropriate

amplitudes at Urakawa and Wakkanai. The first 30 seconds from the beginning of the vertical component of P phases of eight earthquakes and of the north-south component of S phases of three earthquakes were digitized at a rate of five points per second. The spectra were calculated from the autocorrelation functions, applying a lag window of the type $1+\cos(\pi l/m)$. The number of lags m was 26, thus fairly smoothed spectra were obtained.

The spectral values were averaged for eight P phases and for three S phases, since the individual P and S spectral curves do not differ appreciably among the earthquakes. In Figure 36 the logarithms of the velocity spectra are plotted. The two curves are normalized at 0.2 cps. It is evident from this figure that the attenuation in the high-frequency range is very large at Wakkanai for both P and S waves.

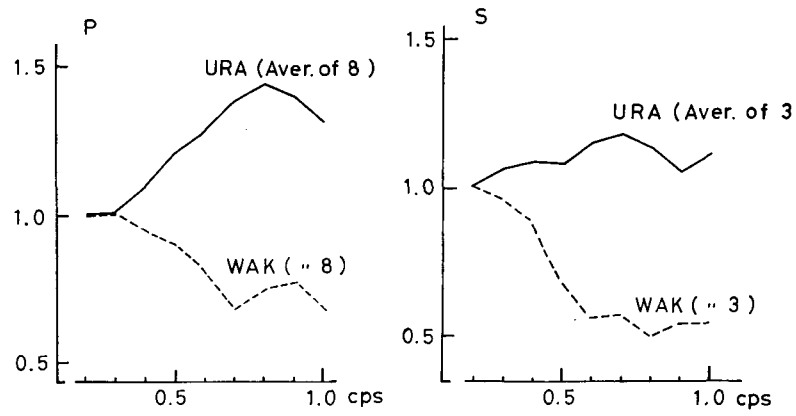


Fig. 36. Velocity spectra of P and S waves from southern Kurile Island earthquakes recorded at Urakawa and Wakkanai plotted on semi-logarithmic graph paper.

Epicentral distances to Urakawa and Wakkanai from these earthquakes are approximately equal (the average distance to Urakawa: 570 km, to Wakkanai: 630 km), and the difference in azimuth is about 30° between the two stations. Therefore, the main cause of the difference in spectra may be attributed to the difference in path. If the focal depths of about 40 km assigned by CGS are adopted, the path to Wakkanai comes in almost contact with the absorptive region whose upper boundary is assumed to be 50 km below the earth's surface (see Figure 37). The path to Urakawa is entirely free from the absorptive region.

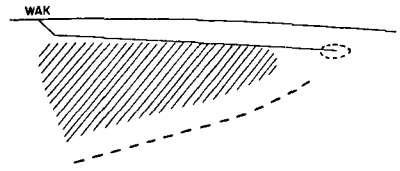


Fig. 37. Ray path from the southern Kurile Is. earthquakes to Wakkanai.

If the observed difference in spectra is due to the difference in Q-value between the two paths, the difference in the longarithms of spectral values at frequency f is a linear function of f in the form

$$\log \frac{a_1(f)}{a_2(f)} = \gamma f + \text{const.},$$

and

$$\gamma = 0.4343\,\pi\left(\frac{\tau_2}{Q_2^*} - \frac{\tau_1}{Q_1^*}\right),$$

where τ_1 and τ_2 are the travel times to the two stations, and Q^*_1, and Q^*_2 are the average Q-values along each path defined by $\tau/Q^* = \int(1/vQ)ds$ (v :seismic wave velocity). In the present case we can assume $\tau_1 = \tau_2 = \tau$. In such a case the relation between Q_1^* and Q_2^* can be represented in a diagram shown in Figure 38 taking γ/τ as a parameter. The coefficient γ determined from Figure 36 in the range between 0.2 and 0.7 cps is about 1.3 seconds for both P and S waves. Travel times of P and S waves are about 70 seconds and about 120 seconds respectively. Therefore, γ/τ is roughly 0.02 for P and 0.01 for S. If we assume a Q^*-value of 200 or more to the Urakawa path, the Q^*-value for the Wakkanai path falls in the range between 50 and 120. It is conceivable that the attenuation of high-frequency waves to Wakkanai does not occur uniformly along the path, then the variations in the local Q-value may be larger than the above-mentioned figures. In fact, the eye-exmainations of seismograms of deep earthquakes indicate that the difference between Urakawa and Wakkanai is much larger than that in the shallow-focus southern Kurile Island earthquakes.

The fact that the parameter γ/τ for S is smaller than that for P may be partially explained by the contamination of the later part of P wave trains. It is also suspected that the digitizing noise has slightly increased the spectral values at Wakkanai at frequencies higher than about 0.7 cps.

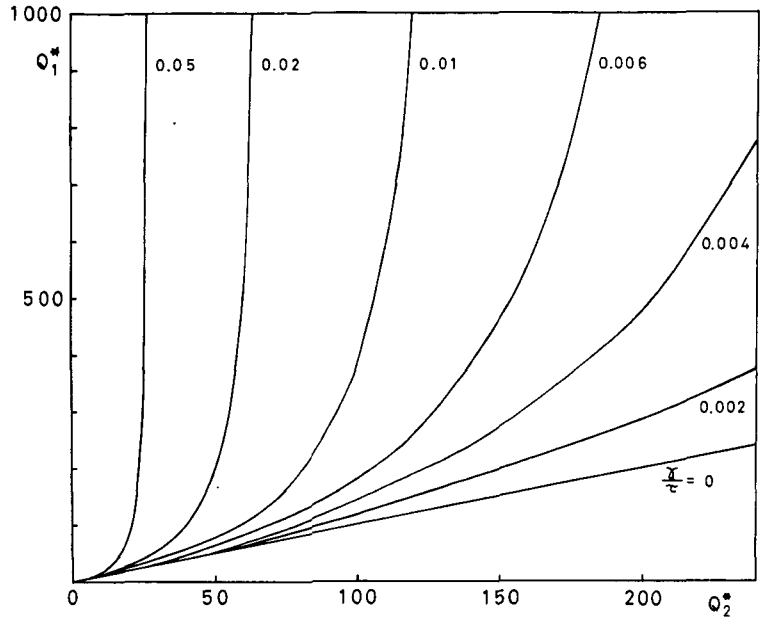


Fig. 38. Relation of Q_1^* and Q_2^* using γ/τ as a parameter.

11. Some additional remarks

The information about the low-Q region below the deep seismic layer cannot be obtained from studies of near-by earthquakes around Hokkaido. Data on distant earthquakes are required to study this problem. Although a systematic investigation of distant earthquakes has not yet been made, a few examples are illustrated here. Figure 39 shows the waveforms of P phases from two distant deep earthquakes recorded by JMA Type-59 electromagnetic shrot-period seismographs on photofilms at several stations in Hokkaido. Waveforms are not much different among the stations. This suggests the existence of a low-Q region below the seismic layer which probably corresponds to the low-velocity zone described in Section 3.

After the submission of the manuscript of Part I of this paper, two large deep earthquakes occurred in central Japan on August 14, 1967 and near the Fiji Islands on October 10, 1967. The travel time plots for these earthquakes including data recorded at the Urakawa Seismological Observatory, Hokkaido University's new station, are in good agreement with the previous results. This observatory is located at Kamikineusu about fifteen kilometers from

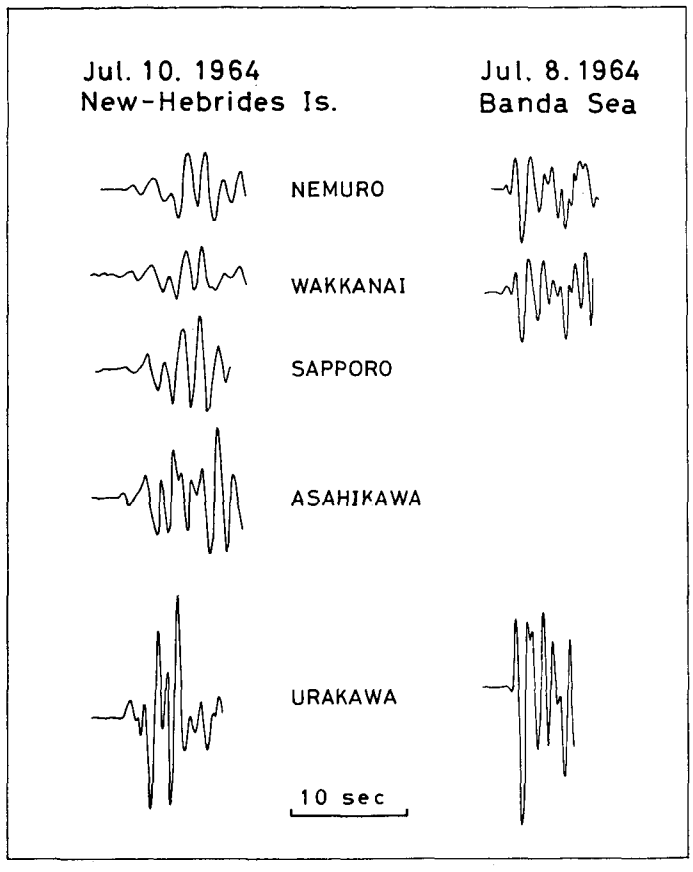


Fig. 39. Waveforms of two distant deep earthquakes. Z components.
Left: depth 120km, $\Delta=61°\sim65°$, Right: depth 165 km, $\Delta=48°\sim51°$.

the Urakawa Weather station, JMA where travel time residuals were exceptionally positive (see Section 3). This large residuals might be due to a small friction in the short-period vertical seismometer caused by a very small dust particle in the magnetic gap, which remained for about three years. (One of the authors visited the station and removed it.)

One of the interesting features of the earthquakes is the appearance of fairly strong phases probably converted from S to P somewhere in the upper mantle. A research of these phases is underway.

A travel time analysis of the Kutcharo earthquake of November 4, 1967 (*cf.* Figure 23A) was made by Nagamune[42]. This earthquake is the largest

inland crustal earthquake in Hokkaido during the past forty years and accurate data were obtained at stations in Hokkaido. Travel time residuals of P waves based on a travel time curve best fitting to the data are less than 0.7 seconds, which are fairly small as compared with those of a few seconds found for deeper earthquakes or more distant ones. This means that the travel time anomalies described in Sections 3 and 5 and also some of those described by Ichikawa[43] for many stations in Japan are mainly due to the regional differences in the upper mantle structure rather than the effects of local crustal layering.

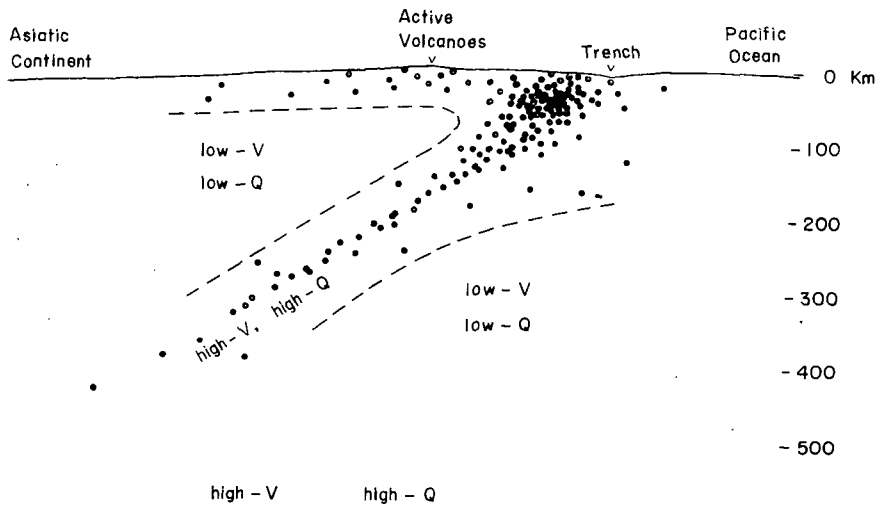


Fig. 40. A schematic representation of the upper mantle structure under northern Japan.

12. Conclusion

The results of the present investigation indicate that the inclined seismic layer which extends in the upper mantle under northern Japan transmits seismic P and S waves with higher velocity and lower attenuation as compared with the adjacent portions of the upper mantle at comparable depths. Figure 40 shows schematically a vertical cross-section normal to the island arc. In the seismic layer the velocity is higher by about 6% and the Q factor is at least several times as high as that of the low velocity regions.

Since the similar effects have been found in other island arcs,[44)-47)] the peculiar structure of the upper mantle associated with a deep earthquake

zone may be a universal phenomenon. It is a remarkable fact that earthquakes originate only in high-Q regions probably consisting of cooler and more rigid rock, in contrast to low-Q and low velocity regions having higher temperatures.

Acknowledgements: The authors wish to express their thanks to the Sapporo District Central Meteorological Observatory and its sub-stations for providing many useful seismograms.

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Note added in proof: One of the authors (UTSU, Zisin, Vol. 22, in press) has found that the velocity ratio of P to S waves (or Poisson's ratio) is approximately the same for the deep seismic layer and the overlying low-Q portion of the upper mantle, while the ratio seems to be appreciably larger in the low-Q region under the deep seismic layer. Kanamori, and Kanamori and Abe (Bull. Earthq. Res. Inst., Vol. 46, in press) also studied the anomalous upper mantle structure under the Japan arc from body and surface wave data.