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SEISMOMETRIC INVESTIGATION OF THE EARTH'S INTERIOR PART IV. ON THE STRUCTURE OF THE EARTH'S MANTLE (II)

BY
Yoshimichi KISHIMOTO

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1. Introduction

In our previous article (**1**), the earthquakes of shallow focus of Kamchatka-Kurile Islands and Formosa were investigated in order to clarify the structure and property of the upper mantle. The time-distance graphs of these earthquakes fitted fairly well to the Jeffreys-Bullen's 1939–Table in the range of from about 9° up to 26°. This result suggests that the structure of the upper mantle near Japan accords with that deduced from the J.–B. Table, except the uppermost part, probably down to about 100 km below the earth's surface.

In order to investigate the structure of this uppermost part, the time-distance graph of the shallow earthquake up to about 10° should necessarily be treated. And this problem, namely the time-distance graph of the shallow earthquake at short distances, has been investigated by many authors.

According to Gutenberg, *Pn*–branch extends up to about 5° with the velocity of 8.1∼8.2 km/sec, and breaks off at that point, being followed by the diffracted wave of low apparent velocity (**2**). Jeffreys stated that *Pn* at short distances had the velocity of 8.0 km/sec in the case of the Burton-on-Trent Explosion in 1944 (**3**). On the other hand, Lehmann (**4**) investigated some North American earthquakes of shallow focus and obtained the result that *Pn*–branch extended up to about 14° with the velocity of 8.2 km/sec and thence ran parallel to the J.–B. surface focus curve, which probably suggests the constant velocity of *Pn*–wave down to some considerable depth. And the writer obtained previously 8.1 km/sec as the *Pn*–velocity at short distances in Japan (**5**).

Thus, recent investigations have almost consistently given 8 km/sec or more as the velocity of *Pn* at short distances. This suggests that the *P*–velocity at the mantle's surface is 8 km/sec or more. But we have not yet reached a coincident opinion as to the velocity-distribution thereafter, namely, there remain the problems whether or not the low-velocity layer exists, or how far that layer extends if existing, and etc. On this problem, Nishitake (**6**) has recently suggested a possibility of the existence of the low-velocity layer by means of combining the rock experiments with the theoretical treatments.

In the present article, the time-distance graphs up to about 10° in the case of Japanese earthquakes of shallow focus were treated in some detail for the purpose of investigating the structure of the uppermost part of the mantle, and accordingly finding a connection between two data by us mentioned above, namely, the *Pn*-velocity of 8.1 km/sec at short distance and the good fit of the structure to the Jeffreys-Bullen's one in the considerable depths.

2. Data

The data used in the present analysis are seven normal earthquakes which are tabulated in Table 1. These earthquakes are favourable due to the followlng reasons; namely, they have considerably large observable distances and each of their foci is nearly in the same direction seen from the observatories in Japan, which minimize the variation of the gradient of time-distance graph by the small shift of epicenter. The epicenters and the time-readings of these earthquakes are after the Seismological Bulletin published by the Japan Meteorological Agency.

Table 1. List of the normal earthquakes used in the present investigation. All data are after the Japan Meteorological Agency, except the origin times and some of focal depths. * shows the earthquakes used in our previous article, Part II.

No.	Date	Origin time (G.M.T.) h m s	Epicenter N	E	Focal depth km	Magnitude
1	1929 May 21*	16 35 32	31.°8	131.°8	<30	—
2	1939 March 20	03 22 26	32.°4	131.°8	<30	6.8
3	1948 June 28*	07 13 29	36°08′	136°17′	<20	7¼
4	1951 Oct. 15*	21 02 01	32.°8	134.°3	40~50	—
5	1951 Oct. 18	08 26 28	41.°4	142.°1	40	—
6	1955 July 27	01 20 50	33.°75	134.°3	<20	—
7	1957 June 12	08 28 37	41.°1	142.°9	40	6.1

3. Treatment and results

We shall consider the deviations of the travel-times of *P*-wave from the corresponding J.-B. Table, in order to determine the shape of the time-distance graph. As regards *S*-wave, the observations showed so large scattering of time-reading that the deduction of the reliable result was impossible. Consequently, the present analysis was obliged to analyse the *P*-wave only.

The earthquake of June 12, 1957 (No. 7 in Table 1), whose focal depth was about 40 km, gave us fairly good observations. As this focal depth corresponds to just below the Mohorovičić discontinuity, the J.-B. 0.00 Table was preferably applied. In Fig. 1, the deviations (O–C) of the observed travel-times of P–wave (O) from the J.–B. 0.00 Table (C) are plotted, taking 08h28m37s as the origin time.

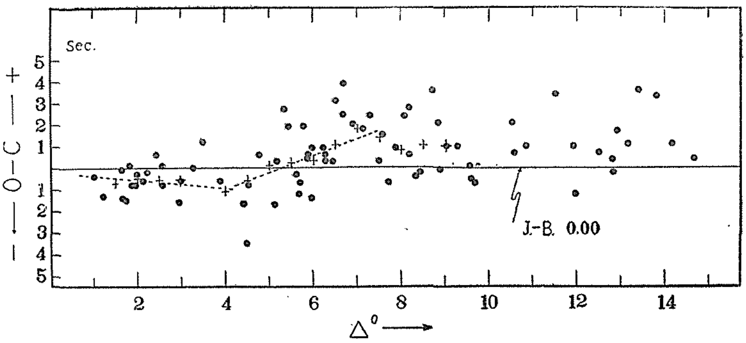

Fig. 1. The deviation graph of the earthquake of June 12, 1957.

The plotted points thus obtained are considerably scattered, because of uncertainty of time determination for small amplitude of refracted Pn–phase. But the large part of them, excepting anomalous ones, shows a tendency to cluster in a band of about 3 sec-breadth. Consequently, in the present treatment, the anomalous points which deviate more than 2 sec from the running mean in every 1°–distance were reasonably excluded. As seen in Fig. 1, which is thus corrected as above-remarked and in which the cross is the running mean in every 1°–distance after this correction, O–C decreases gradually up to epicentral distance of about 3.5° and reaching the minimum at this distance (this distance will tentatively be called the minimum-distance in the followings). O–C increases up to about 7.5° (this will be called the recovery-distance in like manner) and thence runs nearly parallel to the J.–B. curve with the same value as at the recovery-distance or even slightly less.

The earthquake of October 18, 1951 (No. 5 in Table 1) occurred in the same epicentral region as one mentioned above and its focal depth was also estimated as

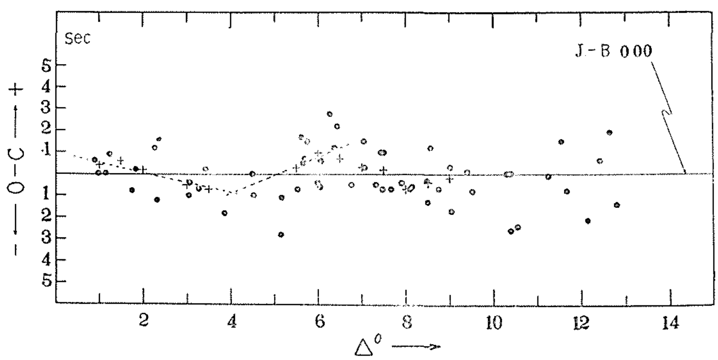

Fig. 2. The deviation graph of the earthquake of October 18, 1951.

about 40 km. Its deviation graph, which is samely corrected as in Fig. 1, is shown in Fig. 2, and moreover that correction will be made also in Figs. 3. 4 and 5. Fig. 2 shows nearly the same behaviours of deviation as in the case of the earthquake of June 12, 1957. In this case, the minimum- and recovery-distances were estimated as about 4° and 6.5° respectively.

The earthquake of July 27, 1955 (No. 6 in Table 1) was investigated by A. Kamitsuki (7). Its focus is considered to lie in the granodioritic layer (5). In Fig. 3, the deviation graph is shown, taking the J.-B. surface focus Table. The *Pn*-branch is observed from about 2.5° as the first arrival, which seems reasonable referring to such a shallow focal depth as in this case. In the range of from 2.5° up to 5.5°, the deviation decreases gradually followed by the slight increase from 5.5°.

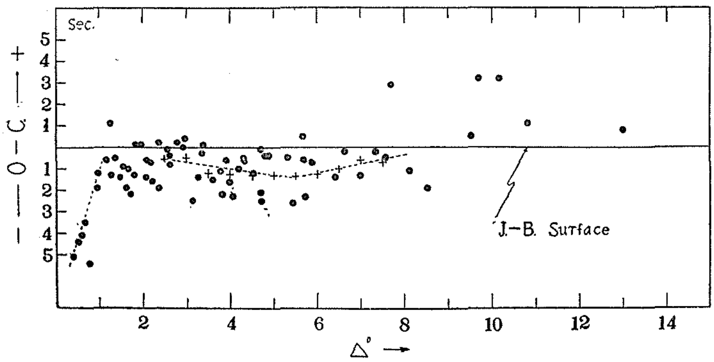

Fig. 3. The deviation graph of the earthquake of July 27, 1955.

Lastly, Figs. 4 and 5 show the corrected deviation graphs of two earthquakes of May 21, 1929 and March 20, 1939, the former of which was analysed in our previous article (5), in which the focus of the former was estimated to lie in the crust. As seen in both figures, the tendencies of deviation with distance show nearly the

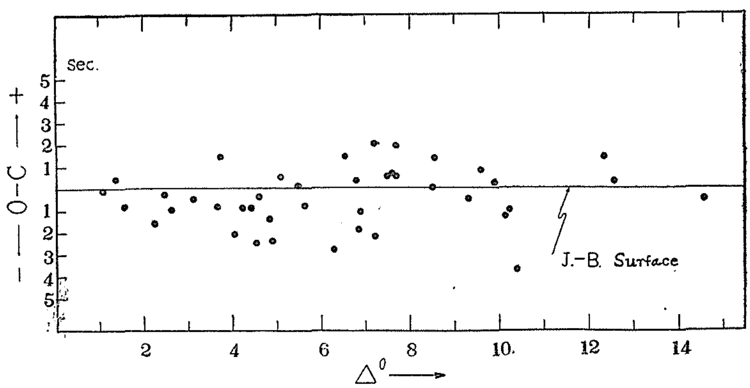

Fig. 4. The deviation graph of the earthquake of May 21, 1929.

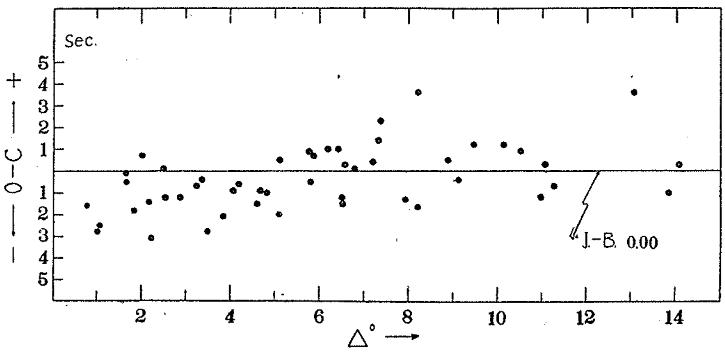

Fig. 5. The deviation graph of the earthquake of March 20, 1939.

same behaviours in both cases. The minimum- and recovery-distances are 4° and 7.5° for the former, and 3.5° and 7.5° for the latter respectively.

Thus, it was clarified that, if the focus lies in the crust or at not so great depth below the Mohorovičić discontinuity, the deviation of the travel-time of *Pn*-wave from the corresponding J.-B. Table shows a systematic distribution, namely, the slopes of the gradual decrease up to the minimum-distance and of the gradual increase from the minimum-distance up to the recovery-distance, and the interval between both distances, are nearly the same. Consequently, since this tendency is not likely to be the errors of observation, the time-distance graph at short distances (0°–10°) for the Japanese normal earthquake should be corrected for the J.-B. Table by the above-stated deviation graph.

Unfortunately, however, as each graph shows some fluctuations of observation and has not sufficient number of observation, we are obliged to use any statistical treatment. For this reason, the 'grouping method' was applied in like manner as used in our pervious article (8). Fig. 6 is the superposed deviation graph thus obtained of earthquakes in Table 1 except one of October 18, 1951, allowing for the differences in

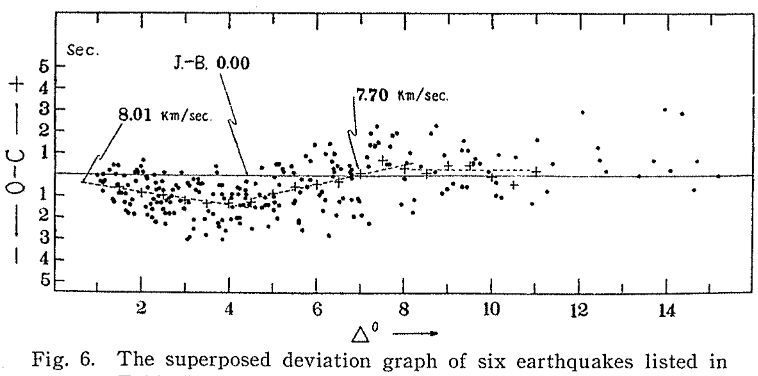

Fig. 6. The superposed deviation graph of six earthquakes listed in Table 1, except one of October 18, 1951.

the beginning distance of the *Pn*-branch due to the differences of focal depths of these earthquakes. In this process the earthquake of October 18, 1951 was omitted owing to its too fast arrival times beyond about 8°. In this figure, the crosses show the running means in every 1°-distance. The method of least squares was applied to two branches represented by the running means, namely, one is up to 4° and the other from 4.5° up to 7.5°. The results are as follows:

8.01 km/sec up to 4°,
7.70 km/sec from 4.5° up to 7.5°.

Consequently, the followings will be concluded as for the time-distance curve at short distances (0°–10°) of the Japanese normal earthquakes. The *Pn*-branch has the velocity of 8.0 km/sec up to about 4° with breaking off at that distance. The apparent velocity is very small, namely about 7.7 km/sec, at range between about 4° and 7.5°, and thenceforth the time-distance curve runs nearly parallel to the J.–B. 0.00 curve with no gap at 7.5°. Needless to say, the minimum- and recovery-distances will differ slightly from the values obtained just above, owing to the variations of the focal depth and the crustal structure. But the difference is within about 1°, and the slopes of the respective branches and the interval between both the minimum- and recovery-distances are kept unchangeable, as mentioned earlier.

4. Discussion

The writer examined previously (**1**) the Gutenberg's low-velocity layer in the mantle. And it was ascertained that at the epicentral distance from about 9° up to beyond 20° the time-distance graph of shallow earthquake fitted fairly well to the J.–B. Table for both *P*- and *S*-waves and the effect of the low-velocity layer was not observed. But at shorter distances the reliable conclusion was impossible owing to the lack of data.

As mentioned in §3, 8.0 km/sec was obtained as the *Pn*-velocity at shorter distances, and this value coincides fairly well with our previous results (**5**) and with the values having been obtained by many authors. The *Pn*-branch breaks off at about 4°, and up to about 7.5° the apparent velocity is very small. At larger distances than about 7.5°, the time-distanc graph seems to run nearly parallel to the J.–B. curve, and this result coincides well with that in our previous article (**1**), namely, the fitness to the J.–B. curve beyond about 9°, as mentioned above.

The break of the *Pn*-branch at about 4° and the decrease of the apparent velocity thereafter seem to accord with Gutenberg's result (**2**) that the *Pn*-branch breaks off at about 5° and thence the diffracted wave-branch of low apparent velocity begins. But both cases differ in the point that our branch of low apparent velocity breaks at about 7.5°, although Gutenberg's diffracted wave extends up to about 12°. And the apparent velocity of the so-called diffracted wave-branch was 7.7 km/sec in the present case, compared with 7.74 km/sec in Gutenberg's result.

These facts may suggest that the low-velocity layer exists also near Japan, but, if existing, it is of small scale as to the range of depths of existence compared with that in North America. In order to examine this problem, we treated time-distance graphs of some slightly deeper earthquakes, which are shown in Table 2. In Figs. 7 and 8, the deviation graphs of two earthquakes of July 17, 1952 and September 29, 1955

Table 2.

No.	Date	Origin time (G.M.T.)	Epicenter N	Epicenter E	Focal depth	Magnitude
		h m s			km	
1	1952 July 17	16 09 51	34°27′	135°49′	70	7 (Pasa.)
2	1953 Feb. 6	13 13 03	42.°0	144.°2	80	—
3	1955 Sept. 29	19 58 27	40.°1	141.°3	90-100	—

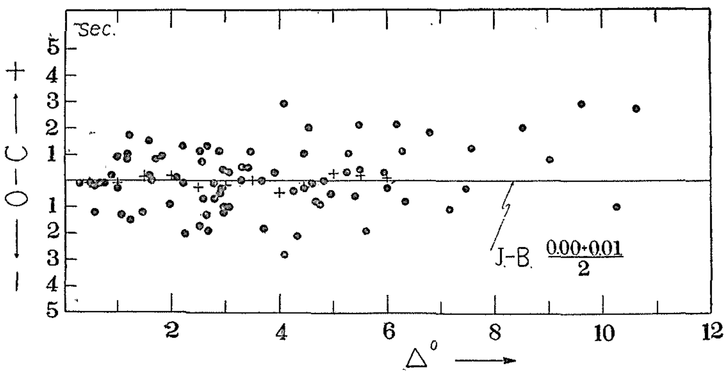

Fig. 7. The deviation graph of the earthquake of July 17, 1952.

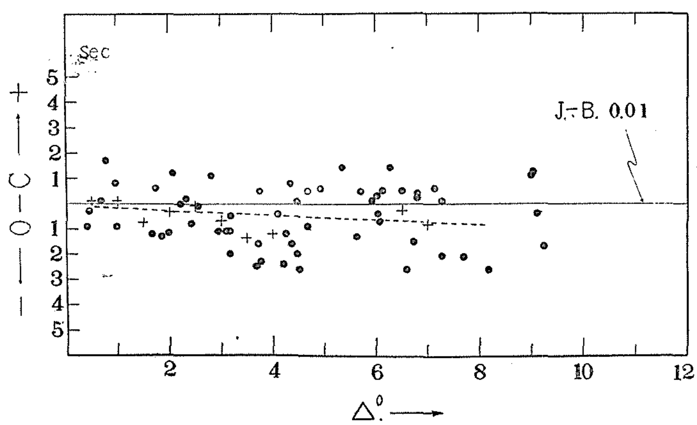

Fig. 8. The deviation graph of the earthquake of September 29, 1955.

are shown. The focal depths of these earthquakes are estimated as 70 km for the former and 90–100 km for the latter. As seen in these figures, their deviation graphs show the parallel running to the corresponding J.–B. curve or the monotonous but slight variation. Namely, the systematic variations of deviation with distance seen in the normal earthquakes are not observed in the case of the earthquakes of the deeper focal depth than about 70 km. If this is the case, the low-velocity layer should reach its minimum velocity at about 70 km, which is shallower compared with that in North America.

Thus, the existence of the low-velocity layer seems to be possible also in Japan, but it is noted that the state of the low-velocity layer, if existing, differs somewhat from those in North America and in Europe (**9**). Accordingly, we may safely presume the regional difference of the mantle's structure down to some considerable depth, including the low-velocity layer.

5. Summary

Seven normal earthquakes were analysed to investigate the structure of the uppermost part of the mantle, including the problem of existence of low-velocity layer. The results arrived at will be summarized as follows:

i) 8.0 km/sec was obtained as the *P*–velocity at the mantle's surface in the present analysis too.

ii) The existence of the low-velocity layer seems possible also in Japan. Accordingly, some parts of Summary in our previous article (**1**) should be corrected. But the state of the low-velocity layer in Japan will, if existing, differ somewhat from that in North America and in Europe, as have been presumed in our previous article cited above.

iii) The structure at deeper part than about 100 km-depth from the surface seems to coincide with that of Jeffreys-Bullen (**10**).

iv) The regional difference in the mantle's structure will be presumed down to some considerable depth, including the low-velocity layer.

Aknowledgment

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