On the Nature of the 20°—Discontinuity in the Earth's Mantle

By EIICHI NISHIMURA, YOSHIMICHI KISHIMOTO, and AKIRA KAMITSUKI

Geophysical Institute, Kyoto University, Kyoto

(Manuscript received March 18, 1957)

Abstract

The structure of the earth's mantle, mainly its upper part, having been investigated by the analysis of seismic waves of five Kamchatka-Kurile Islands earthquakes of shallow focus and some others, the problems on the existence and property of the 20°-discontinuity and the low-velocity layer in the mantle are discussed in some detail. The time-distance graphs obtained in Japan are in fair agreement with JEFFREYS-BULLEN's Table (1939), and also the 20°-discontinuity is considered to exist certainly at nearly the same depth as given by Jeffreys. The amplitude relation observed at the epicentral distance near 20° between the direct wave propagating through the medium entirely above the 20°-discontinuity and the refracted wave penetrating down into that discontinuity is just the reverse of that commonly expected, that is, the former being small and the latter large, both for the P- and S-waves. Concerning this phenomenon some arguments are given. Moreover, the existence of a new discontinuity was ascertained at some depth below the 20°-discontinuity, as deduced from the appearance of a prominent later phase. As to the existence of a low-velocity layer in the mantle, it is somewhat questionable at least in the form after Gutenberg from the analysis of seismic waves observed at the stations in Japan of the earthquakes of Kamchatka-Kurile Islands. But its existence is still probable in some forms, which is uncertain at present, at some depths below the Mohorovičić discontinuity. This problem will be postponed to a succeeding paper.

1. Introduction

Concerning the nature and structure of the earth's mantle there exist two essentially different opinions. One is that the seismic wave velocities in the earth's mantle increase with depth and at the so-called 20°-discontinuity the rate of velocity increase begins to rise abruptly (JEFFREYS, 1939). The other is GUTENBERG's maintenance (1953) that a low-velocity layer exists at the ranges between 60 km and 150 km for P-wave and between 60 km and 250 km for S-wave, and the 20°-discontinuity does not exist at any depth.

Which structure is more applicable to the earth should not simply and hastily be judged only by the analysis of arrival time of P- and S-waves of earthquakes observed at any limited area in the world, because the local character to a certain degree of the mantle's structure is possibly supposed from the various standpoints of seismometric and geodetic investigation. From these reasons the investigation of the earth's mantle should desirably be made by the seismometric and other methods at as widely divergent areas as possible in the world to advance our knowledge on the nature of the earth's interior. And moreover, in this case, not only the analysis of P- and S-waves, but also those of other phases observed should necessarily be investigated, with regard to their travel-times, amplitudes, periods and others. In the present article a synthetic investigation was made of some large earthquakes which occurred at an area near Japan, especially taking into consideration the change of wave-mode with distance observed at many stations with the successively increasing distance as seen from their epicenters.

Namely, several earthquakes, whose observations extended over a territory of from about 6° to 26° of epicentral distance, were analysed by means of the preceding principle for the purpose of examining two different opinions, and of the further investigation of the local character, if existing, of the mantle's structure.

2. Data and Treatments

The earthquakes examined were five Kamchatka-Kurile Islands earthquakes in the main and two Formosa ones for reference. The data of these earthquakes are given in Table 1. These earthquakes were recorded at 23 observatories attached to the Japan Meteorological Agency, and with Wiechert seismographs. Instrumental constants of the Wiechert seismograph are as follows:

Component	Mass kg	Magnification	Period sec	Damping ratio
H	200	70—100	about 5	5—10
V	80	50— 80	»	»

i) Time-distance graph

A typical example is the earthquake of Jan. 5, 1953 (No. 3 in Table 1), its seismograms being shown in Fig. 1. Its time-distance graphs of both P and S are shown in Fig. 2, in which the time-distance graphs of the earthquake of March 18, 1955 (No. 5 in Table 1) are together plotted. In Fig. 2, it is to be noted that both P- and S-graphs are divided into two branches, which are represented by dots and crosses, intersecting at about 18°, and that the later branches are extended back down to 13° in both the P- and S-graphs. As the focal depth of the former earthquake is approximately estimated as 0.01 R according to Jeffreys' notation after pP – P duration at each observatory, the epicentral distance of 18° above-mentioned will correspond to the so-called 20°-discontinuity referring to the Jeffreys-Bullen Table (JEFFREYS, 1939), and moreover, two branches represented by dots and crosses in Fig. 2, may be expected to correspond to the waves annexed by the letters d and r after Jeffreys' notation respectively. Accordingly, the fitness of respective branches to the J.-B. curves will next be examined. The earlier P-branch (represented by dots) fits best to Pd curve of the J.-B. 0.01 curve, as shown in Fig. 2. The later P-branch (represented by crosses beyond 18°) fits approximately to the Pr curve of the above-mentioned curve referring to its gradient, although there are systematically positive residuals of a few seconds. As to two S-branches, the same results as P-branches are deduced as seen in Fig. 2. The time-distance graphs of other earthquakes in Table 1 are approximately the same as that of the present earthquake. In the present case, since the positions of observatories are all nearly on a straight line seen from the epicenter of each earthquake, a small shift of epicenter will change their epicentral dis-

Table I.
List of the earthquakes used in the present investigation. Latitude and longitude of epicenter, magnitude, focal depth and some origin times (*) are after the U.S.C.G.S. The Greenwich Mean Time is adopted for the origin time.

No.	Date	Origin time	Epicentral region	Epicenter	Focal depth	Magnitude (Pasa.)	Observational range
		h m s		N E	km		
1	1952 June 22	21 43 02	SE off Shinshiru Is., Kurile Is.	46°, 153½°,	—	7	6°—17°
2	1952 Nov. 4	16 58 33	Near east coast of Kamchatka	59½, 159	—	8¼	13°—25°
3	1953 Jan. 5	10 06 30	N part of Kurile Is.	4'6 156	—	6¾	9°—22°
4	1953 Oct. 11	13 08 34*	»	50, 155½	60	6¾	10°—23°
5	1955 Mar. 18	00 06 46	Near east coast of Kamchatka	54½, 161	—	—	19°—26°
6	1936 Aug. 22	06 51 37	Near SE coast of Formosa	22.1, 121.2	—	—	17°—24°
7	1955 Apr. 4	11 11 21*	»	22, 121	—	6	17°—24°

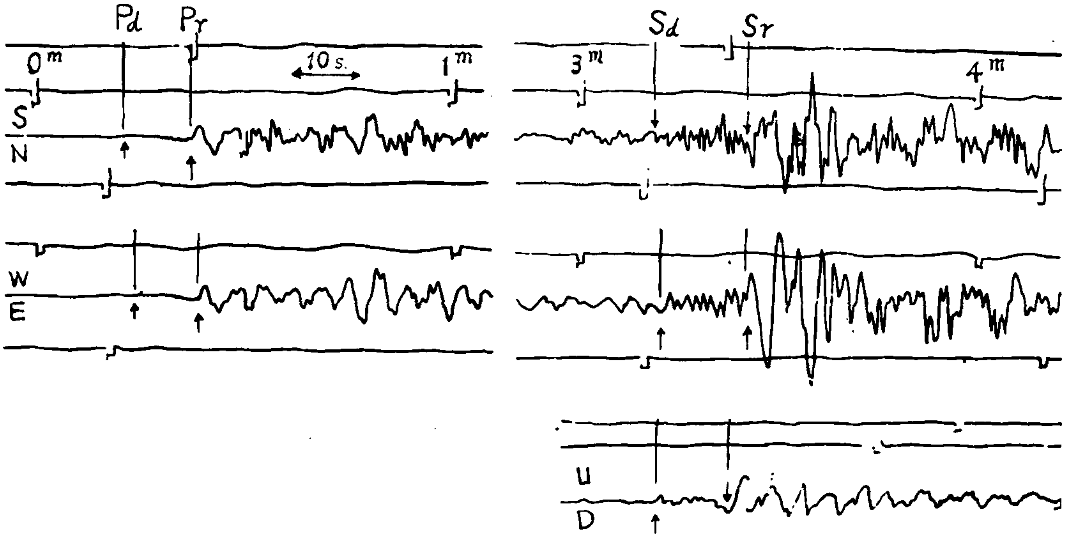


Fig. 1. Wiechert-seismograms, Jan. 5th 10h 06m, 1953, N Part of Kurile Islands, observed at Fukushima ($\Delta = 16°.03$).

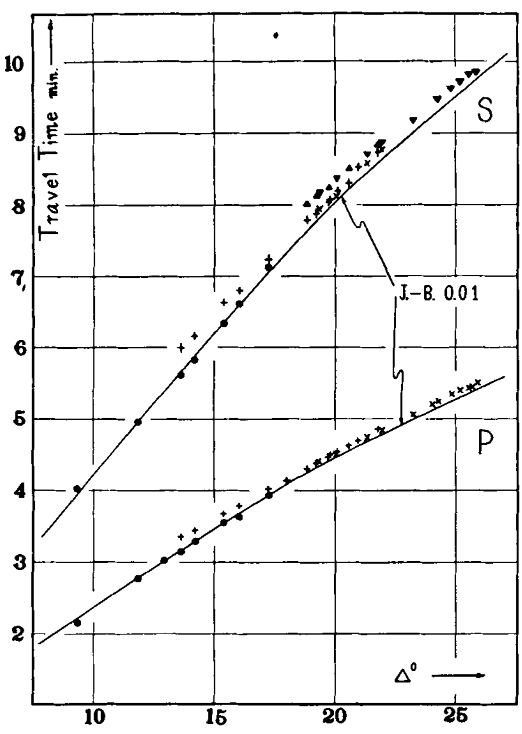


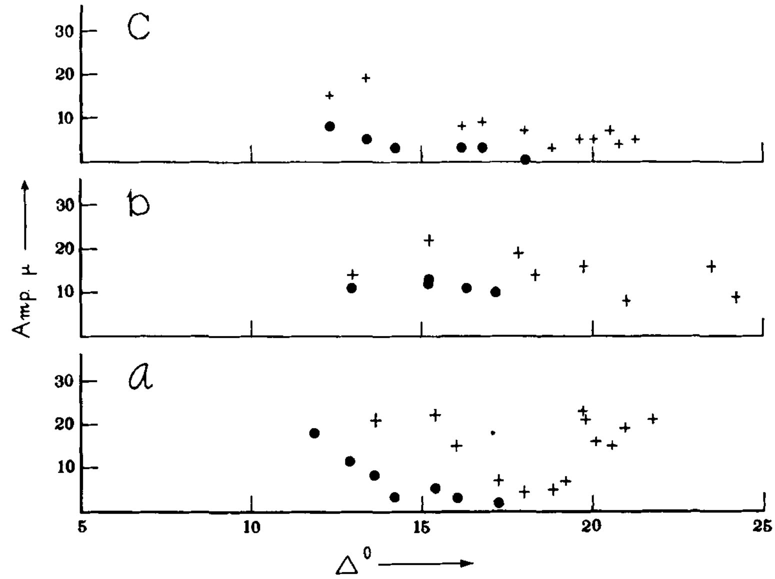
Fig. 2. Travel-time graphs superposed of two earthquakes of Jan. 5, 1953 and March 18, 1955. ●, + and ▲ belong to the former and × and ▼ to the latter. ● representing the Pd and Sd, + and × the Pr and Sr, and ▲ and ▲ represent the Sr_2.

tances and azimuths slightly. Consequently, the gradient of the time-distance graph may be considered to be nearly unchangeable; the fitness of the time-distance graph to the J.-B. 0.01 curve is kept also unchangeable by the small shift of epicenter.

It may, consequently, be concluded that two branches represented by dots and crosses in Fig. 2, correspond to two branches annexed with d and r in the J.-B. Table respectively, and, therefore, that the existence of the 20°-discontinuity was ascertained, at least, by the present analysis of the time-distance graph of earthquake which occurred in the northern area near Japan. Moreover, the extensions backward down to about 13° of both Pr- and Sr-branches coincide with what was given as an extreme case by Jeffreys in his paper of 1939 (1939). But, in the present step, the problem is not immediately solved as to whether the 20°-discontinuity is of the first order or the second order.

ii) Amplitude and period of each phase

Amplitude-distance relations of respective phases are given in Fig. 3, in the instances of some earthquakes in Table 1. In Fig. 3, a clearly discernible and remarkable fact is that the amplitudes of Pd and Sd become smaller and smaller with increasing distance and are much



F g. 3 (a). Amplitude-distance graphs for P-wave. Notations have the same meanings as in Fig. 2.
a) The earthquake of Jan. 5, 1953
b) The earthquake of Nov. 4, 1952
c) The earthquake of Oct. 11, 1953

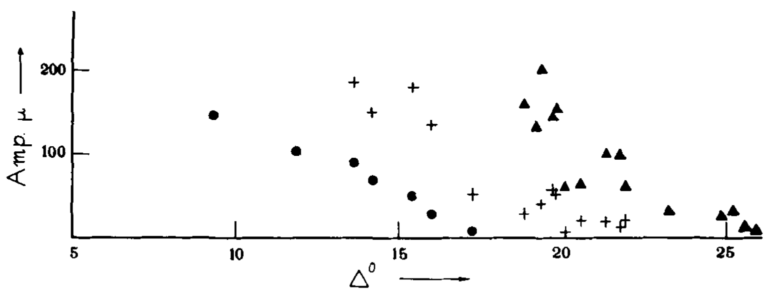


Fig. 3 (b). Amplitude-distance graph for S-wave superposed of two earthquakes of Jan. 5, 1953 and March 18, 1955, in which the corrections are made for some observatories allowing for the local structural character. Notations have the same meanings as in Fig. 2.

smaller than those of Pr and Sr near 18°. Beyond 18°, Pr and Sr of large amplitude first arrive, and the concomitant small Pd and Sd cannot usually be identified, because they may be disturbed by the wave train of the large Pr and Sr.

This behaviour with regard to the amplitude can clearly be recognized in Fig. 3, but the schematical representation of this relation, as shown in Fig. 4, will afford a reliable guide for discussing the nature of this sort of phenomena.

The periods of four phases, Pd, Pr, Sd and Sr of the five Kamchatka earthquakes in Table 1, are plotted together in Fig. 5, with the period and epicentral distance as ordinate and abscissa respectively. The periods of both Pr and Sr are concentrated in a range of about 4 sec. to 6 sec., independent of epicentral distance, ob-

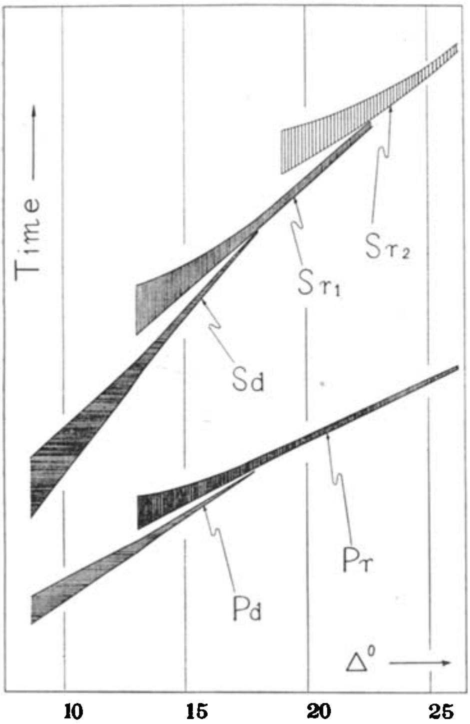


Fig. 4. Schematical representation of the amplitude-distance relation. The breadth of each branch corresponds to the amplitude at the respective distances.

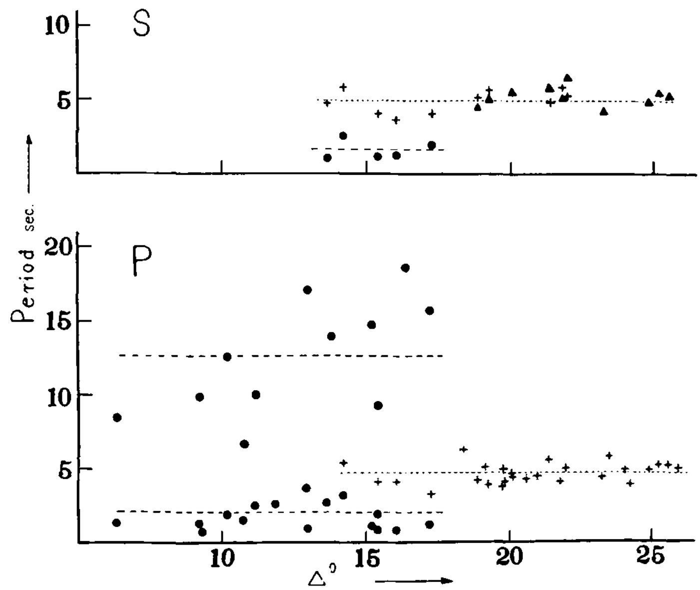
servatory, and earthquake. On the other hand, the periods of Pd and Sd differ considerably. They consist, roughly speaking, of periods shorter than 2 sec. and of ones longer than 8 sec.

Therefore it can safely be said that two phases whose branches intersect at about 18° are clearly distinguished from each other by the difference in their amplitudes and periods, and so that the danger of confusing both phases does not occur. From these, it is supposed that both phases have considerably different characters in their generation and transmission.

iii) Sr_2-wave

As shown in Fig. 2, a phase of large amplitude (represented by the triangle) is observed after Sr beyond about 19°, and the duration between Sr and this phase becoming shorter and shorter with increasing distance, and two branches intersect at about 24°. And, this new phase in S-wave beyond 24° fits well to the J.-B. curve as shown in Fig. 2. An example of this phase is presented in Fig. 6, and the amplitude-distance relation is given in the previous Figs. 3 and 4.

From these data, it may be concluded that there is a discontinuous surface at some depth below the 20°-discontinuity, namely, that



Fip. 5. Period-distance relation of each phase. Notations have the same meanings as in Fig. 2.

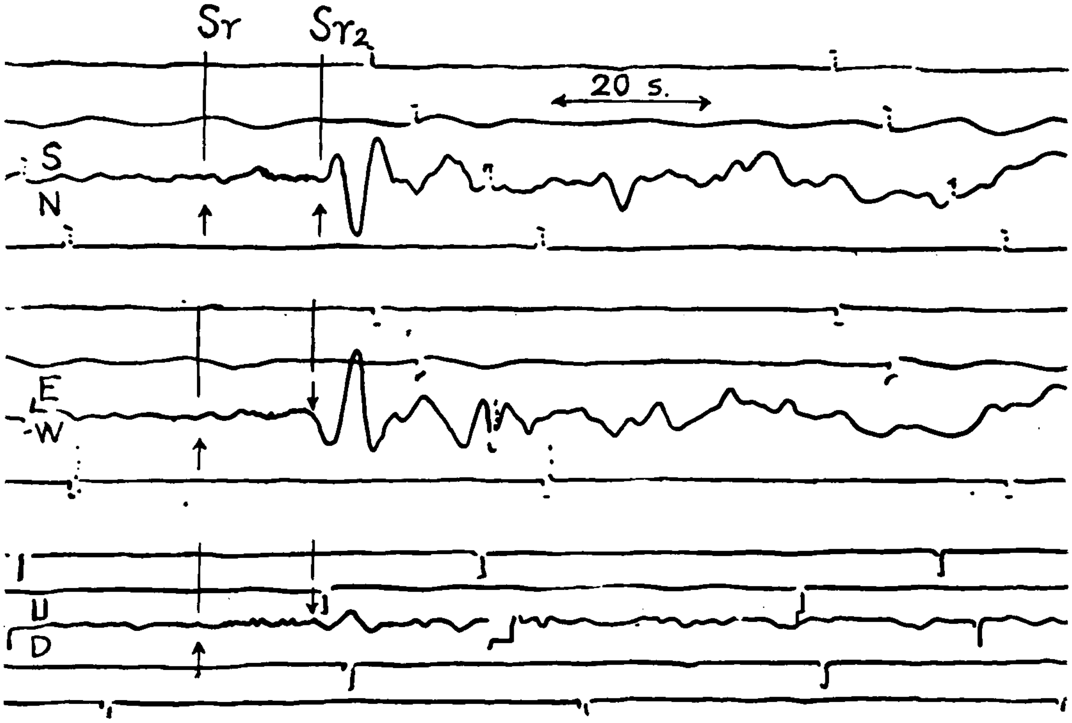


Fig. 6. Wiechert-seismograms, March 18th 00h 06m, 1955. Near east coast of Kamchatka, observed at Morioka ($\Delta = 20°.05$).

this new phase which will tentatively be called Sr_2 is the refracted wave at that discontinuity. It is, however, to be noted that this result was deduced only from the analysis of the S-wave, and regarding P-wave, the reliable identification of the later phase corresponding to the Sr_2 at distances concerned was not obtained. Consequently, it is said that the new discontinuity, if existing, is effective especially for S-wave and not for P-wave.

This new discontinuity probably relates to the behaviour of k/μ in the so-called "C-layer" calculated from the Jeffreys-Bullen's velocity distribution, as worked out by NISHITAKE (1956).

3. Discussion

Gutenberg's opinion concerning the low-velocity layer is referred to the following three phenomena, namely; 1) the abrupt diminution of amplitude of the first arrival at about 5° and its continuation up to about 15° both for P- and S-waves; 2) its gradual increasing from about 15° up to beyond 20° especially for P-wave; and, 3) the considerable difference of the time-distance curve from the J.-B. curve, especially in the range of from 5° to 20° both for P- and S-waves (GUTENBERG, 1948, 1954).

With regard to 2) and 3), as described in the preceding section number 2, the time-distance curves of the Kamchatka earthquakes fit fairly well to the J.-B. curve without the gap at any distance, and an intersection of two branches at 18°, which corresponds to 20° in normal earthquakes, are certainly observed for both P- and S-graphs. Moreover, as shown in Figs. 3 and 4, the increase of amplitude between 15° and 20° is not observed.

Next, in order to examine the phenomenon 1) mentioned above, three near earthquakes were treated, that is, May 1, 1939 (shallower than 10 km), July 28, 1951 (about 10 km deep) and July 17, 1952 (about 70 km deep). In Fig. 7, the natural logarithm of amplitude of the first P-motion is plotted against epicentral distance as abscissa for each earthquake. In any case, the sudden diminution and its continuation of the amplitude as stated by Gutenberg was not observed.

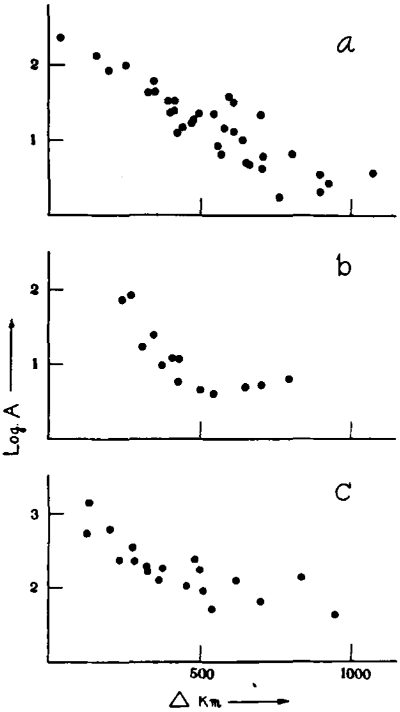


Fig. 7. Amplitude-distance graphs for the first P-motion at short distances.

a) The Oga Eartquake of May 1, 1939
b) The earthquake of July 28, 1951
c) The Yoshino Earthquake of July 18, 1952

Considering these results, it is reasonably concluded that the existence of the 20°-discontinuity is ascertained mainly by the analysis of time-distance graphs, and that the existence of a low-velocity layer, in the arrangement as mentioned not only by Gutenberg but also by Lehmann (1953), is considered questionable, at least in the case of the Japanese earthquakes. With reference to these criteria the local character of the earth's mantle is reasonably presumed referring to the areas in Europe, America and Japan.

At any rate the phenomena concerning the amplitude of two phases annexed by d and r will be interpreted as being caused by an abnormally strong attenuation of Pd and Sd observed near 18° or an abnormal enlargement of Pr and Sr. In order to examine this reverse relation between the amplitudes of Pd (or Sd) and Pr (or Sr) near 18° a deep earthquake was investigated for reference. The focus of this earthquake was seated at 350 km-depth, which is considered to be shallower than the 20°-discontinuity but deeper than the supposed low-velocity layer. In Fig. 8, the amplitude-distance graph of the first P-motion is given. This figure visibilizes the amplitudes as small in some ranges before 12°, and shows abrupt increase at 12° which corresponds to 20° in the normal earthquake. Thus, in spite of the deeper orientation of the focus than the supposed low-velocity layer, the same anomalous diminution of amplitude is observable at the distance corresponding to 20°.

But to return to the main subject, the reasonable interpretation of the anomalous amplitude relation between the direct and refracted waves is, at present, fairly difficult. One probable interpretation is the diminution of Pd and Sd due to the existence of a transient layer just above the 20°-discontinuity. On the other hand, the enlargement of the Pr and Sr by the channel-effect between the 20°-discontinuity, and the supposed new discontinuity just below the 20°-discontinuity, may possibly be assumed, when considering the constancy of the period of Pr and Sr, and allowing for the existence of the supposed new discontinuity. The detailed argument will conveniently be referred to KISHIMOTO's paper (1956, a).

Hence, several interesting behaviours of seismic waves were favourably interpreted by the effect of the 20°-discontinuity and its neighbouring region. But a problem still remains unsolved. Namely, in our previous article (1956, b), 8.1 km/sec. was obtained as the P-wave velocity at the top of the mantle, while the travel-times of seismic waves at the considerably larges distances fit fairly well to the Jeffreys-Bullen's Table, as mentioned above. This result needs inevitably the existence of a low-velocity layer at some depths below the Mohorovičić discontinuity. But this low-velocity layer is not in the form after Gutenberg but some different form will be expected. This problem will be postponed in a succeeding article.

4. Summary

Seismograms observed at observatories in Japan of five prominent earthquakes of the Kamchatka-Kurile Islands were analysed to investigate the existence and nature of the 20°-discontinuity and the low-velocity layer in the

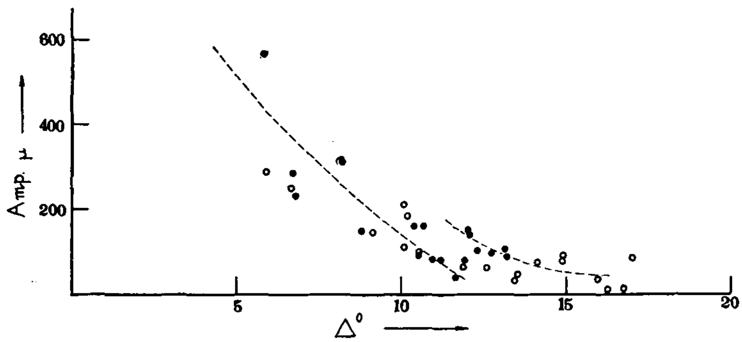


Fig. 8. Amplitude-distance graph for the first P-motion of the deep earthquake (h = 350 km) of Feb. 28, 1950. Dots and circles represent the readings by the authors and by the Japan Meteorological Agency respectively.

earth's mantle. Some results obtained in the present treatment are as follows:

i) The existence of the 20°-discontinuity was ascertained in Japan.

ii) The existence of the low-velocity layer was somewhat questionable in the form as characterized by Gutenberg at least in Japan, but it is probable in some different forms.

iii) The abnormal diminution of amplitude of the direct seismic wave, and, reversely, the large and clear appearance of the refracted wave through the 20°-discontinuity were definitely observed for both P- and S-phases near the epicentral distance of 20°. For these remarkable facts two explanations of the large attenuation of direct wave at the transition layer close above the 20°-discontinuity, or any enlargement-effect for the refracted wave by the layer-channel between the 20°-discontinuity, and the 25°-discontinuity newly found, were tentatively postulated.

iv) From the present treatment, it is reasonable to conclude that the nature and structure of the earth's mantle may have a somewhat regional character when it is compared with the regions in Europe, America, Japan and others.

REFERENCES

GUTENBERG, B., 1948: On the layer of relatively low wave velocity at a depth of about 80 kilometers. *Bull. Seism. Soc. Amer.*, **38**, pp. 121 – 148.

–, 1953: Wave velocities at depths between 50 and 600 kilometers. *Ditto*, **43**, pp. 223 – 232.

–, 1954: Low-velocity layers in the earth's mantle. *Bull. Geol. Soc. Amer.*, **65**, pp. 337 – 348.

JEFFREYS, H., 1939: The times of P, S and SKS, and the velocities of P and S. *Mon. Not. Roy. Astr. Soc., Geophys. Suppl.*, **4**, pp. 498 – 533.

KISHIMOTO, Y., 1956, a: Seismometric investigation of the earth's interior, Part III. On the structure of the earth's mantle. *Mem. Coll. Science, Kyoto Univ.*, Ser. A, **28**, pp. 117 – 142.

LEHMANN, I., 1953: P and S at distances smaller than 25°. *Trans. Amer. Geophys. Union*, **34**, pp. 477 – 483.

NISHIMURA, E. and KISHIMOTO, Y., 1956, b: On the Local Structural Character of the Earth's Crust, *Tellus*, **8**, pp. 329 – 334.

NISHITAKE, T., 1956: Elastic properties of rocks with relation to the earth's interior. *Mem. Coll. Science, Kyoto Univ.*, Ser. A, **28**, pp. 73 – 98.