On the Local Structural Character of the Earth's Crust

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Abstract.

Regional differences in the crustal structure in Japan were investigated, in detail especially around Kyoto, by a duration analysis of the refracted seismic waves of natural earthquakes propagated along the discontinuous surfaces in the crust. Generally speaking the thickness of the earth's crust or, in other words, the depth of the Mohorovičić discontinuity was estimated in our country to be greatly diverse from place to place, its range being nearly 25 ~ 50 km. It was also found that the depth of seismic focus of most frequent occurrence in any region is intimately related to the thickness of the crust in the region concerned.

1. Introduction

For the purpose of investigating the crustal structure in any region, an analysis of the travel time-distance curve obtained from the seismometric observation of natural earthquakes or artificial explosions having occurred in that region, is usually applied in calculating the seismic velocity and thickness of the crustal layer from the apparent velocity and critical distance in the travel time-distance curve. The method is certainly simple and effective for determining the crustal structure in such a case, as the crustal structure to be determined is uniform or monotonously changing in the area concerned, the positions of epicenter and the focal depth of earthquake can be precisely determined, the arrival time of each phase of seismic waves is accurately observed, the effect of locality of the observatories and the instrumental errors of seismographs are negligibly small along with other good observational conditions. But the above conditions are never satisfied in practical cases, especially in relation with natural earthquakes. Consequently the method of analysing the travel time-distance curve for a precise determination of the crustal structure, especially of the heterogeneous distribution, should efficiently be supplemented by other seismometric methods of analysis, for example, the reflected wave, the transformed wave (Wechselwelle), and the refracted wave at and along the discontinuous surfaces in the crust.

2. Method of Analysis

In the present seismometric investigation of the crustal structure, the method of analysing the duration of the seismic refracted wave, which is observed in advance of the direct wave and conveniently designated as "forerunner", was applied to a great many

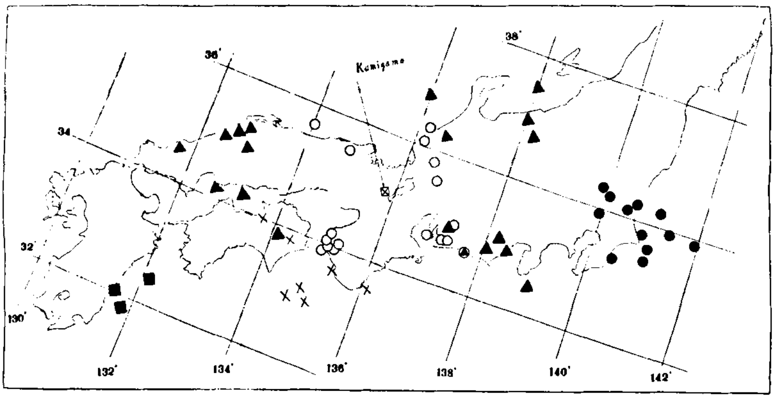

Fig. 1. Positions of the epicenters of earthquakes used in the present investigation and the Kamigamo Geophysical Observatory.

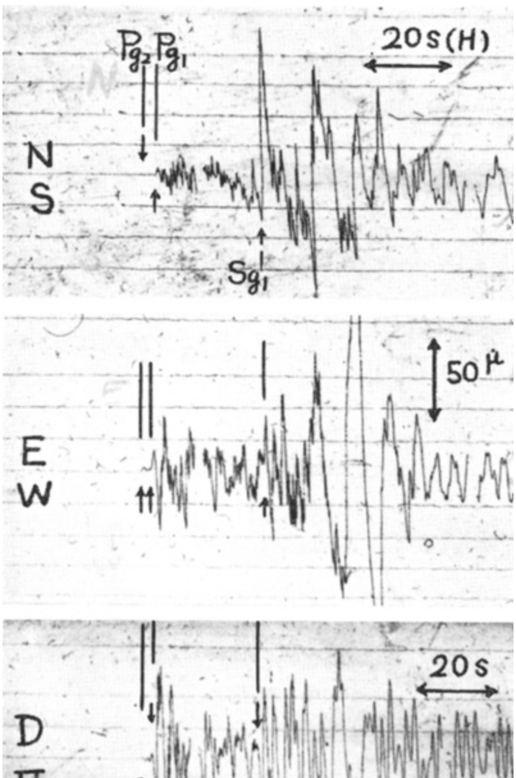

Fig. 2 (a). Wiechert-Seismograms, Jan. 3rd 21h 13m, 1945, Outfall of the Tenryu River (34.7° N, 137.9° E) $Pg_1 \sim Sg_1 = 24.4$ sec, $Pg_2 \sim Pg_1 = 2.0$ sec, focal depth < 10 km (a-group).

Pg_1 and Pg_2 denote the direct wave through the granitic layer and the refracted wave at the interface between the granitic and granodioritic layers.

seismograms obtained at one station of the Kamigamo Geophysical Observatory in Kyoto with the large Wiechert Seismographs for more than forty years. The large Wiechert Seismographs consist of the inertia mass of 1 ton in the horizontal component of inverted pendulum type and 1.3 tons in the vertical component of suspension type with spiral springs, the period of proper oscillation being 12 sec in the horizontal component, and 4 sec in the vertical component, the static magnification of both components being estimated as nearly 200, and both are critically damped with air dampers and mechanically recorded on smoked paper. This method of analysing the duration (the time difference between

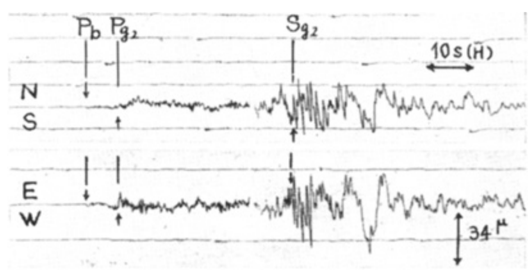

Fig. 2 (b). Wiechert-Seismograms, July 30th 17h 25m, 1953, Western Setoumi (34.1° N, 132.8° E) $Pg_2 \sim Sg_2 = 37.3$ sec, $Pb \sim Pg_2 = 6.9$ sec, focal depth = 20 km (b-group).

Pg_2 and Pb denote the direct wave through the granodioritic layer, and the refracted wave at the interface between the granodioritic and basaltic layers.

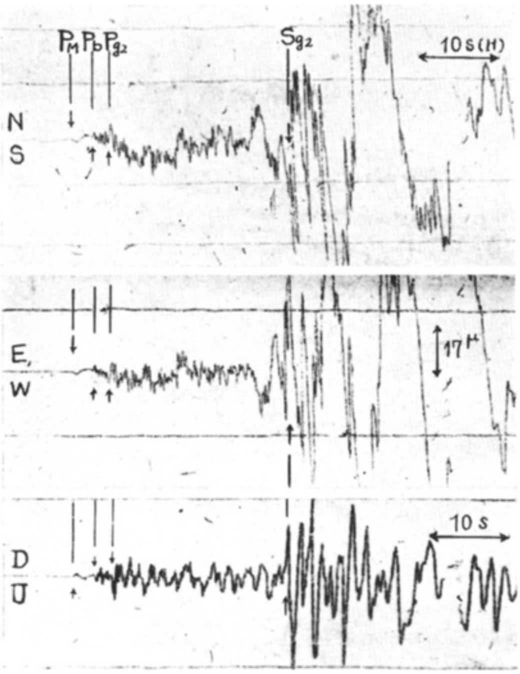

Fig. 2 (c). Wiechert-Seismograms, Jan. 17th 02h 44m, 1947, Tokushima Pref. (33.8° N, 134.2° E), $Pg_2 \sim Sg_2 = 19.7$ sec, $P_M \sim Pg_2 = 4.7$ sec, $Pb \sim Pg_2 = 2.2$ sec, focal depth $\cong 10$ km (c-group).

Pg_2, Pb and P_M denote the direct wave through the granodioritic layer, the refracted wave at the interface between the granodioritic and basaltic layers and the refracted wave at the Mohorovičić discontinuity, respectively.

Layer	Vp km/sec	Vs km/sec	Thick-ness km	Remarks
Sedimentary layer	3.8 ± 0.1	2.2 ± 0.2	1.5 ± 0.3	under Kyoto
Granitic layer	5.4 ± 0.1	3.1 ± 0.2	6 ± 2	under the area within 200 km distance from Kyoto
Granodioritic layer ..	5.8 ± 0.1	3.4 ± 0.2	14 ± 2	»
Basaltic layer	7.0 ± 0.1	4.0 ± 0.2	10 ± 2	under Kyoto
Mantle surface ...	8.1 ± 0.1	4.7 ± 0.2	—	probably under whole area in Japan

the arrival of the forerunner and that of the direct wave) of the forerunner was efficiently supplemented by an analysis of the usual travel time-distance curve, the transformed wave, and other available data. In the following the research procedure and obtained results in the present investigation will be briefly described.

The location of the epicenters of natural earthquakes and some examples of the seismograms used in the present analysis are shown in Fig. 1 and 2 respectively. In Fig. 3 the arrival time differences between forerunners and direct waves of the earthquakes observed at the Kamigamo Geophysical Observatory are plotted taking the $P \sim S$ time as abscissa and value of duration as ordinate. As seen in Fig. 3 these durations are conveniently classified into several groups named the a-, b-, c-, d- and e- group with regard to

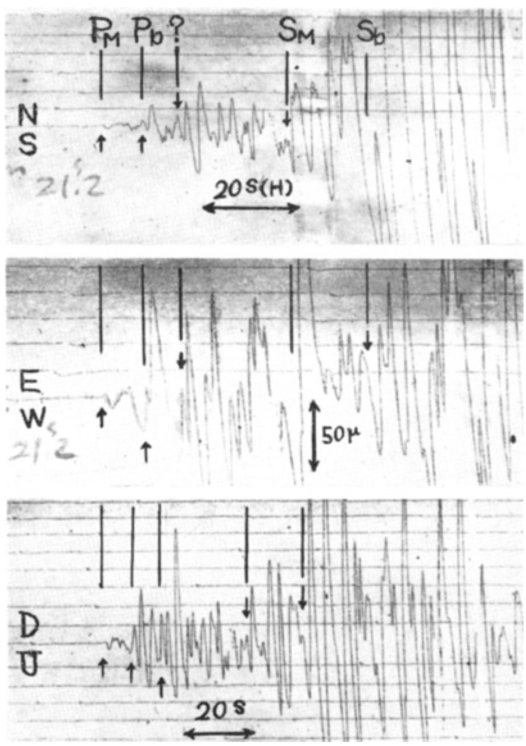

Fig. 2 (d). Wiechert-Seismograms, July 18th 07h 36m, 1954, near Choshi (35.5° N, 141.1° E), $Pb \sim Sb = 50.5$ sec, $P_M \sim Pb = 9.0$ sec, $Pb \sim ? = 8.4$ sec, focal depth $\cong 40$ km (d-group).

Pb and P_M denote the direct wave through the basaltic layer and the refracted wave at the Mohorovičić discontinuity.

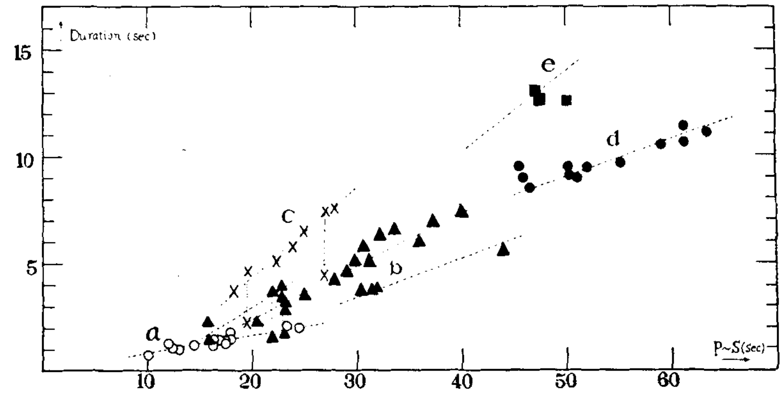

Fig. 3. Relation between the duration of forerunners and the $P \sim S$ time for each group.

the locality, distance of their epicenters seen from the Kamigamo Geophysical Observatory, and moreover duration value observed at Kamigamo. From the analytical treatment on the a-, b- and c-group and some other methods, the crustal structure around Kyoto which was most plausibly determined to fit the observed values of forerunner duration is as follows (KISHIMOTO, 1954, 1955):

However in the above table the propagation velocities of seismic dilatational wave (Vp) and shear wave (Vs) in the sedimentary and granitic layers have been determined from the travel time-distance curves of several selected earthquakes whose epicenters and focal depths were precisely known. The value of velocity for the granodioritic and the deeper layers and all values for the layer thickness except that of basaltic layer were determined from the analysis of duration of forerunner. It ought to be mentioned, particularly in this place, that any method but that of forerunner analysis might perhaps have failed to separate two layers slightly different from one another as those of the granitic and granodioritic layers, because the appearance and number of kind of forerunner (as seen in (a) and (c) of Fig. 2) in the seismograms are the most sensible and unmistakable evidence for existence of any one or two discontinuities under the focal point of earthquake concerned.

3. Results

With regard to the problem of focal depths of earthquakes concerned, all the earthquake foci in the a-group were ascertained in the granitic layer and those in the b- and c-group were estimated to be mainly in the granodioritic layer. But the c-group should clearly be distinguished from the b-group in the point of forerunner duration. The forerunners observed in the seismograms of the b-group may plausibly be explained as refracted waves propagated along the interface between the granodioritic and basaltic layers, but, on the contrary, the forerunners in the c-group could not otherwise be interpreted as the refracted waves along the interface (the Mohorovičić discontinuity) between the basaltic layer and the mantle surface in the point o forerunner duration. Really the distinct appearance of the second forerunner is clearly observed shortly after the first arrival of forerunner in some earthquakes of the c-group, as seen in (c) of Fig. 2, and it may correctly be attributed to the refracted wave along the interface between the granodioritic and basaltic layers, judging from the fact that its duration is precisely plotted on the curve of the b-group as shown in Fig. 3. Then from what causes might be derived the definite difference between the b- and c-groups? Namely, why could not the corresponding forerunner to that of the c-group be observed in the b-group? These can only be explained by the fact that the thickness of the granodioritic layer everywhere under the area within some 200 km distance from Kyoto is nearly the same, but that the thickness of the basaltic layer is considerably different under the area of the c-group earthquakes from that under other areas. Actually the forerunners along the Mohorovičić discontinuity are clearly observed of the earthquakes in the area of the b-group at the observatories over some 300 km away from the epicenter (KISHIMOTO, 1954, 1955).

4. Local Character of Crustal Thickness

In this way the regional difference in the depth of the Mohorovičić discontinuity or the thickness of the crust might easily and unmistakably be detected by the comparison of duration of earthquake forerunners in one area with that in another area. But this method is invalid for the determination of the absolute value of the crustal thickness under any area, and it should be supplemented by an analysis of the reflected waves of the shallow earthquakes and artificial explosions, or the transformed waves in deep earthquakes occurring under the area concerned. A study of the regional differences in the crustal structure by the analysis of the reflected and transformed waves under various areas in Japan is now in progress and the detailed report will soon be published.

In the present paper an analysis of the transformed waves was tentatively applied for the purpose of determining the crustal thickness under Kyoto. Namely, by the analysis of transformed waves of two similar earthquakes whose focal depths and epicentral distances from Kyoto were nearly 70 km and 100 km respectively, the crustal thickness under Kyoto was estimated as nearly 30 km. Taking the crustal thickness under Kyoto as 30 km, the values of crustal thickness for the respective Districts are schematically obtained as in Fig. 4, under an assumption of a monotonous inclination of the crustal thickness between each District and Kyoto. From this Figure, the crustal thickness may be supposed to vary greatly from place to place in our country, the range of thickness being roughly estimated as from 25 km to 50 km.

5. Focal Depth and Crustal Thickness

It is an attractive problem to examine the relation, if existing, between the focal depths of earthquakes in any area and the crustal thickness under the area concerned. In Fig. 5 the frequency curve of the occurrence of earthquakes having occurred in the last ten years in two areas of the Nankaido District (the c-group) and the Kanto District (the d-group) are plotted according to their focal depths. The difference between the focal depths of maximum occurrence in both areas (20 km and 40 km) corresponds fairly well to that between the estimated crustal thicknesses (25 km and 50 km) under both areas, as seen in the Figure. Roughly speaking, earthquakes in any area are liable to occur at positions a little above the crustal bottom under the area concerned.

6. Conclusion

In conclusion the present article is a report on an attempt to introduce into the research field a method of analysing the forerunner duration appearing in seismograms for in-

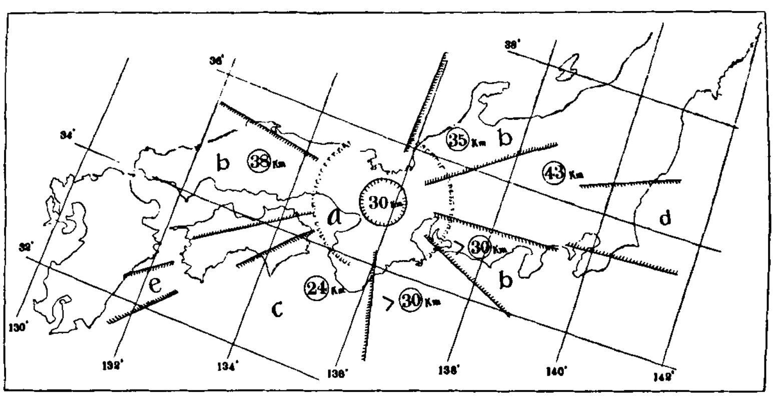

Fig. 4. Schematical representation of the crustal thickness in the various districts.

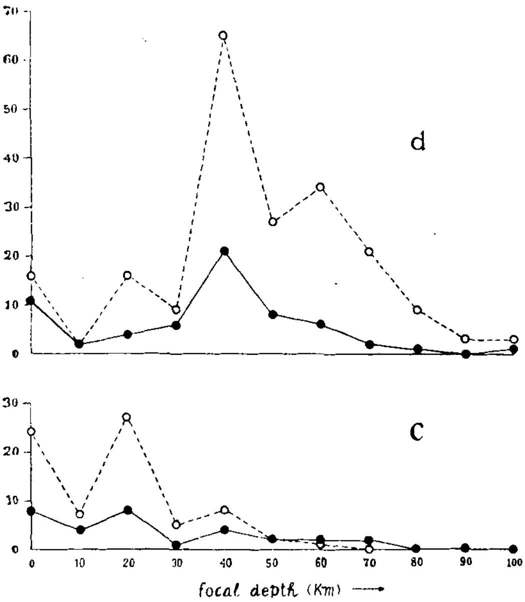

Fig. 5. Relation between frequency of earthquake occurrence and their focal depths in the *c*- and *d*-districts. *Dots and circles denote the earthquakes during the last* ten years sensible by human feeling at $\triangle > 200$ km and at 200 km $> \triangle >$ 100 km, respectively.

vestigating the structure of the earth's crust, especially in heterogeneous distribution. The remarkable regional differences of the crustal thickness roughly estimated in the present investigation are considered to be well in accordance with the heterogeneous distribution of the Mohorovičić discontinuity in U.S.A. observed with the reflected wave of artificial explosion by TUVE, TATEL and HART (1954), and on the other hand with the anomalous distribution of gravity in our country surveyed by TSUBOI (1954). The synthetic research of various methods of analysing the time-distance curve, forerunner duration, the reflected and transformed waves and other seismometric methods, combined with the gravity and magnetic survey is strongly recommended to be put in operation at many places in the world, as, in case of the Canadian Shield (1950), to classify the local character of the crustal structure. It certainly serves the development of our knowledge on the nature of earthquakes, crustal deformation and many other geophysical phenomena of great importance.

REFERENCES

KISHIMOTO, Y., 1954: Seismometric Investigation of the Earth's Interior, Part I. *Mem. Coll. Science, Univ. of Kyoto*, Ser. A, **27**, no. 2, pp. 125—143.

— 1955: Ditto, Part II, **27**, no. 3, pp. 243—288.

TSUBOI, C., 1954: Gravity survey along the lines of precise levels throughout Japan by means of a Worden Gravimeter, Part IV. Map of Bouguer anomaly distribution in Japan based on approximately 4,500 measurements. *Bull. Earthq. Res. Inst.*, Supplementary Vol. IV, Part III.

TUVE, M. A., TATEL, H. E., and HART, P. J., 1954: Crustal structure from seismic explosion, *Journ. Geophys. Res.*, **59**, pp. 415—422.

WILSON, J. T., 1950: Recent applications of geophysical methods to the study of the Canadian Shield, *Trans. Amer. Geophys. Union*, **31**, pp. 101—114.