

20. *On the Anomaly of Travel Time of P waves Observed at Japanese Stations. Part(1)*

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Abstract

The P-wave travel times to Japanese stations were investigated. Kurile Islands earthquakes gave arrivals earlier than those expected from the Jeffreys-Bullen table. Neither location errors nor reading errors are likely to be the cause of this phenomenon. The early arrivals may be due to a high velocity structure beneath the Island Arc from the Kuriles to Japan. It is found that the upper boundary of this high-velocity structure is dipping toward south west and not shallower than 60 km. Its thickness is increasing in the same direction and the lower boundary is not deeper than 400 km. This pronounced anomalous structure could not be found in any direction other than that of the Kurile Islands. The seismic waves which travel in this anomalous region are less attenuated than those travelling elsewhere, especially in higher frequency range.

1. Introduction

This paper presents observational facts relating to travel times in the Japanese region. The P-wave registered at Japanese stations equipped with high sensitivity short-period seismographs will be discussed.

As early as 1931, Wadati observed early arrivals at the eastern Japanese stations from earthquakes which occurred in the Pacific coastal region of Japan. He also observed that the intensity of the earthquakes shows an abnormal distribution around the epicenter. Katsumata (1960) found that the seismic waves propagate faster through the Island Arc toward north than toward west beneath the Japanese Islands. He attributed this difference to the difference in seismic activity in north-eastern and southwestern Arcs of Japan. Hisamoto (1965a, b) observed anomalously early arrivals of S-waves when a part of the propagation path is just below a region of high seismic activity. Utsu (1967) studied the travel time of several deep focus earthquakes and found a systematic variation of travel time residuals among various stations in

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Hokkaido. He attributed it to a lateral inhomogeneity of mantle structure, and proposed a model in which P-wave velocity is about six per cent lower on the continental side than on the ocean side of the deep seismic plane.

Kanamori (1968) analyzed the travel time from LONGSHOT to Japanese stations. He concluded that the P-wave velocity in the mantle above the deep seismic plane is smaller by about 0.2 to 0.4 km/sec than the normal value. Oliver and Isacks (1967) intensively studied the propagation of seismic waves through the Tonga-Kermadec Arc. They demonstrated an anomalous structure in the upper mantle associated with the deep seismic zone.

Bolt and Nuttli (1966) investigated the azimuthal dependence of P-wave travel time residuals. They pointed out that the seismic travel times to any station from large distances may be strongly dependent on the azimuth. Ritsema (1966) has drawn attention to early P-wave arrivals from earthquakes to the southwest of the European stations and late arrivals from earthquakes to the northwest.

2. Data

The data were collected from the Earthquake Data Report (EDR) supplied by the U.S. Coast and Geodetic Survey (USCGS), for the period from Jan. 1966 to April 1968. The readings at the individual stations as well as their distances and azimuths from the epicenter and also the travel time residuals are listed in EDR for each shock. The epicenters

used in this work are plotted in Fig. 1. Readings at the stations given in Table 1 are used.

According to the direction of approach of seismic waves to Japanese stations, we classified the earthquakes into four groups as shown in Fig. 1. Each group is defined by a quadrant of a circle centered at 139°E and 36°N . The first group is called the "Kurile Group". Events from northern Honshu, Hokkaido, Kurile, Kamchatka, Rat, Fox and Aleution Islands are included in this group. The second is the "Mariana Group". It includes events from

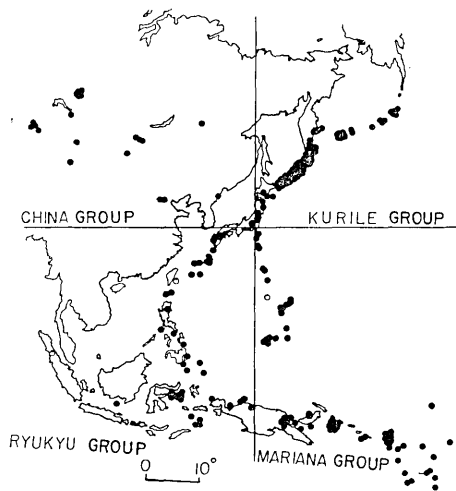


Fig. 1. The epicenters of earthquakes and the classification into four groups.

Table 1

Station	Code	Latitude	Longitude	Height	Seismograph
Tsukuba	TSK	36.210°N	140.109°E	280 m	RTS ⁺ II (400 MHz) SP
Dodaira	DDR	35.998	139.193	800	RTS (7000 MHz) SP
Matsushiro	MAT	36.541	138.208	440	Benioff SP (WWSSS)
Shiraki	SHK	34.532	132.677	285	Benioff SP (WWSSS)
Sapporo	SAP	43.050	141.332	18	S, VI, OP (JMA)
Oishiyama	OIS	34.131	135.326	800	RTS I (60 MHz) SP

+ RTS: Radio Telerecording Seismograph

the south east Honshu, Bonin, Volcano Island, Mariana, Eastern New Guinea, Solomon, Fiji, New Ireland, New Hebrides, Santa Cruz, Loyalty and Tonga Islands. The third is the "Ryukyu Group" and includes events from southwestern Honshu, Kyushu, Taiwan, the Phillipine Islands, Molucca Sea and Sumatra. The fourth is the "China Group" which includes events from China, Mongolia and U.S.S.R.

3. Analysis

1) Hypocenter accuracy and reading error

The U.S. Coast and Geodetic Survey determines the hypocenter elements using the J-B table and P arrivals at the stations all over the world except China and U.S.S.R., while Japan Meteorological Agency (JMA) determines them using the Wadati-Sagisaka-Masuda's table and the data at the Japanese stations exclusively.

Aki (1965) examined the accuracy of the JMA hypocenter location of local earthquakes, and concluded that significant corrections are necessary to the origin time and the focal depth, but not so much corrections for the epicenter. Earthquake hypocenters in the vicinity of Japan are determined by USCGS and JMA independently. Utsu (1967) showed the difference of the JMA and USCGS epicenters in and around Japan (Fig. 2). In most cases the USCGS epicenter is shifted towards the Japanese Islands. The deviation is very small for the inland and shallow earthquakes, but is large for Kurile earthquakes.

In the present work, four earthquakes from the Kurile Islands were selected arbitrarily to examine this situation. Figure 3 shows both the USCGS and JMA epicenters for each shock. The deviation of the epicenters is as large as 150 km. (earthquake No. 2) The J-B travel time residuals (observed-computed in seconds, O-C) were recalculated using the JMA hypocenter and origin time, for the world-wide stations which registered these Kurile earthquakes. The ellipticity and station height

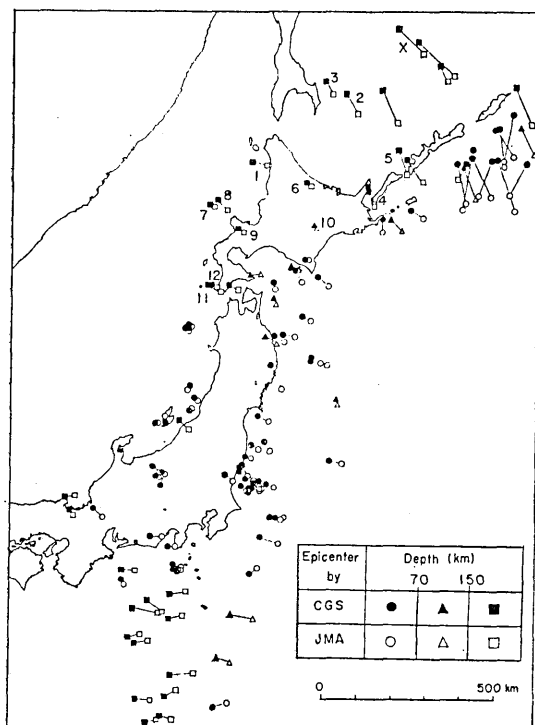


Fig. 2. Comparison of epicenters determined by JMA and USCGS (after Utsu 1967).

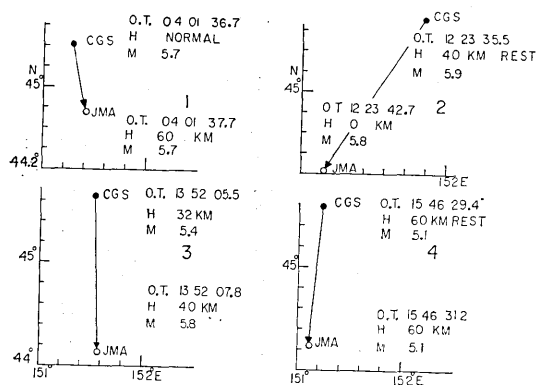


Fig. 3. The deviation of JMA epicenter from that of USCGS for four Kurile earthquakes.

short-period vertical instrument and for DDR direct filtered sum are used. Accordingly the reading of these stations are reliable.

In locating the Kurile earthquakes, JMA uses the Japanese stations exclusively which lie in nearly one azimuthal direction from the Kurile

corrections were included. Figures 4a and 4b show the residual (O-C) as a function of distance. The closed circles are for the USCGS hypocenter and origin time, while open circles are for JMA's. In all cases the residuals for JMA hypocenter and origin time are very large especially at $\Delta > 20^\circ$, while the Japanese stations ($\Delta \leq 20^\circ$) show large negative residuals for the USCGS hypocenter and origin time. On the contrary, other stations which are distributed around the epicenter at large distances show generally very small residuals (± 1.0 sec.) for the USCGS hypocenter. Almost always USCGS rejects the Japanese station readings in locating the Kurile earthquakes because of their too large residuals. The Japanese station readings, especially those at TSK and DDR, are reliable as they operate a special seismograph system. The signals at these stations are telemetered to the Earthquake Research Institute in Tokyo and are recorded on a multichannel strip chart side by side. For TSK on-line band path filtered seismograms of

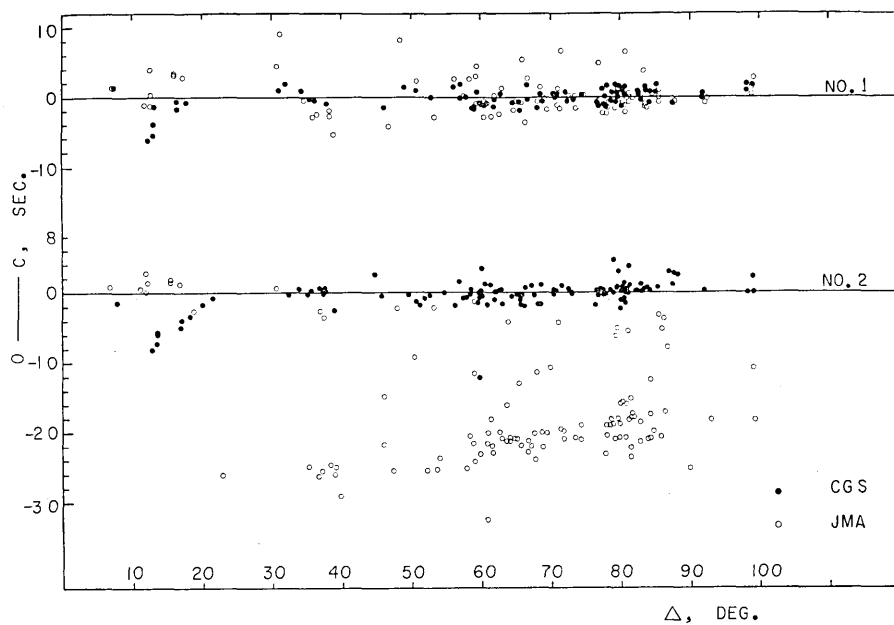


Fig. 4a. The travel time residuals calculated for USCGS and JMA epicenters as a function of distance for the Kurile earthquakes No. 1 and 2, as given in Fig. 3.

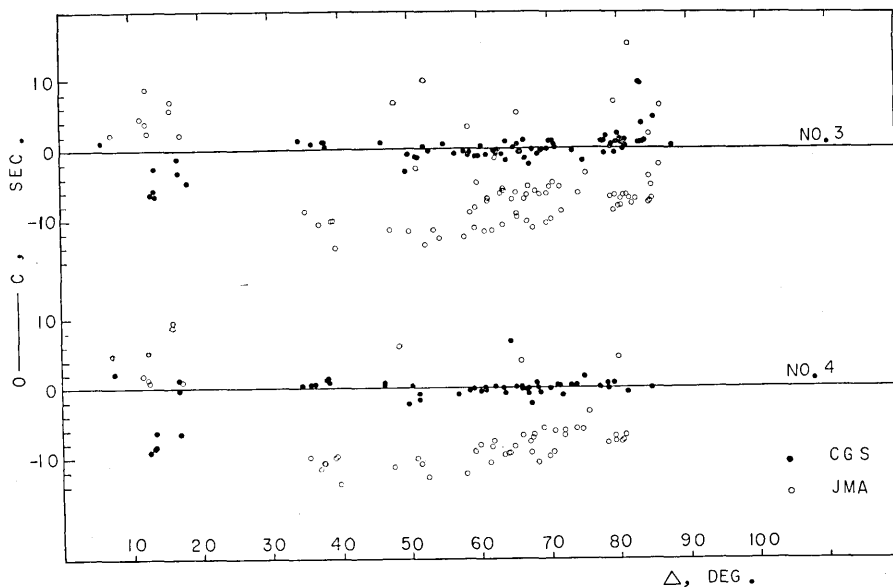


Fig. 4b. The travel time residuals calculated for the USCGS and JMA epicenters as a function of distance for the Kurile earthquakes No. 3 and 4 as given in Fig. 3.

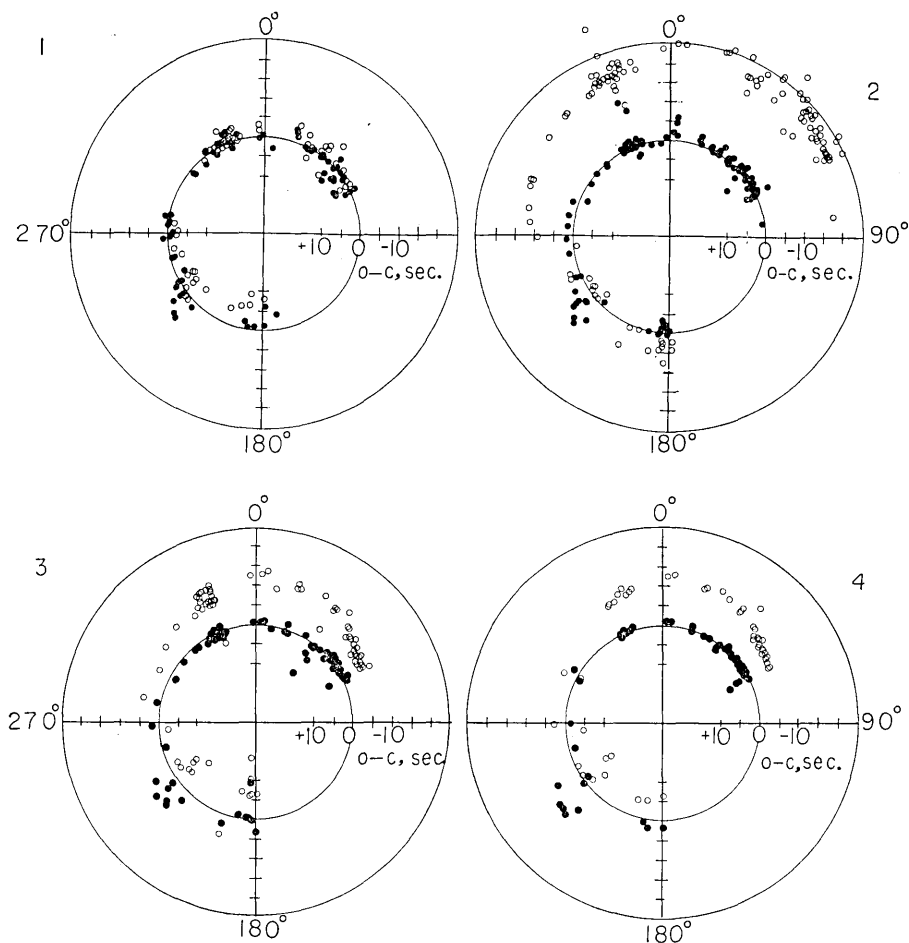


Fig. 5. The travel time residuals at the world wide stations, calculated for USCGS and JMA epicenters as a function of azimuth at the epicenter.

Islands. If an anomalous structure exists between Japan and the Kurile Islands, the JMA locations for the Kurile earthquakes become inaccurate. The incorrectness of the JMA location can be clearly demonstrated by the unbelievably large residuals which appeared at the stations outside Japan (open circles at $\Delta > 20^\circ$) by using JMA hypocenters and origin times.

The azimuthal distribution of the residuals (open circles), at the world wide stations, based on the JMA hypocenters, is shown in Fig. 5. The Eurasian (4th quadrant), and Canadian and American stations (1st quadrant) indicate large negative residuals, while the Australian stations (2nd and 3rd quadrants) and Southeast Asian stations (3rd quadrant) show positive residuals.

Utsu (1967) showed that, for the inland and shallow earthquakes

both JMA and USCGS are reliable. Utsu suggested that the failure of JMA in locating the Pacific and the Kurile earthquakes must be due to regional anomalies in structure. We will therefore use the USCGS hypocenters which are based upon the world wide data.

The travel time residuals are independent of the magnitude as shown in Fig. 6 which gives the residuals at TSK and DDR for the Kurile earthquakes in the distance range $7^\circ \leq \Delta \leq 18^\circ$. It suggests rejecting the possibility of an inaccurate determination of origin time for small shocks causing eventually those large negative residuals.

2) The Kurile Group

As discussed above, for the earthquakes of this group the USCGS hypocenters seem to be more reliable than the JMA hypocenters, (e.g. Utsu 1967, Kanamori and Ishida 1968 and Masahiro and Yamakawa 1968). Figure 7 shows the travel time residuals at SAP, TSK, DDR, MAT, OIS, SHK as given in the EDR of USCGS, as a function of epicentral distance.

The travel time residuals at SAP are positive i.e. arrive later than normal. Since SAP reports only near earthquakes, the range of the distance is small. Thus, the seismic rays from either Hokkaido or

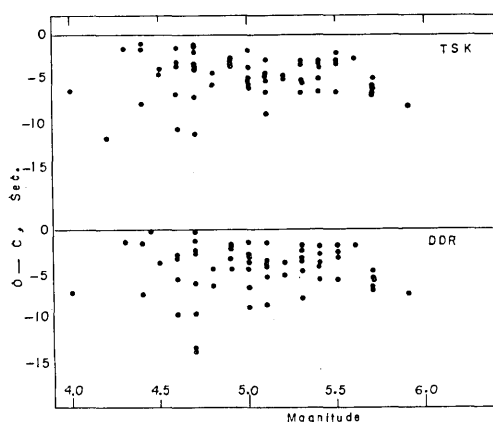


Fig. 6. The travel time residuals as a function of magnitude for Kurile earthquakes at TSK and DDR ($7^\circ \leq \Delta \leq 18^\circ$).

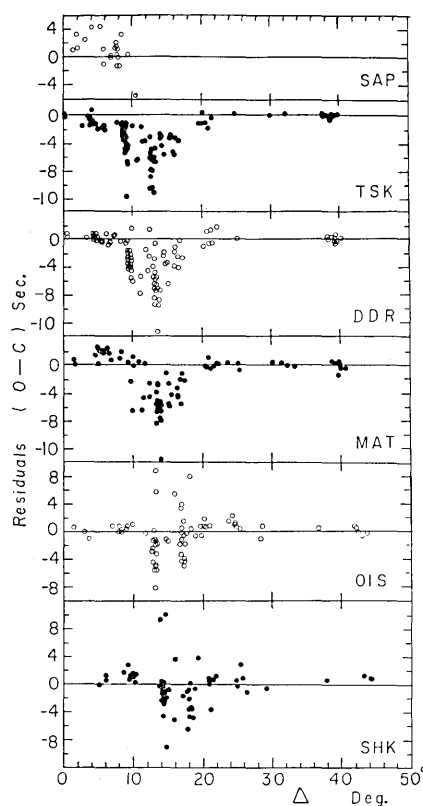


Fig. 7. The travel time residuals are shown as a function of distance, at SAP, TSK, DDR, MAT, OIS and SHK, for Kurile group.

western Kurile earthquakes to SAP do not penetrate deep into the mantle. Therefore, the shallower structures may probably be responsible for this positive residual at SAP. At a distance greater than 8° , the residuals are slightly negative indicating early arrivals from eastern Kurile earthquakes.

The residuals at TSK and DDR are nearly identical. This is natural because these stations are located close to each other, and their magnifications are high (c.f. Tsujiura 1963). Inspecting the residuals at these two stations, we can see that the earthquakes from northern Honshu ($\Delta = 5.0^\circ$ to 5.5°) showed small residuals (± 1.0 sec.). The residuals for the earthquakes from eastern Hokkaido ($\Delta \leq 7.8^\circ$) are always small and negative. As we go through the Kurile Islands toward the north-east, the negative residuals become abruptly large at $\Delta = 9^\circ$ and increase as Δ increases to 12° . The negative residuals decrease as Δ increases to 18° . Earthquakes with normal depths seems to show larger negative residuals than shallow and deeper ones. Such early arrivals become very small for the Kamchatka earthquakes ($19 \leq \Delta \leq 25^\circ$). For the Rat and Aleutian earthquakes ($32 \leq \Delta \leq 40^\circ$), the residuals are scattering around zero line in the positive and negative directions.

MAT is located at nearly the same distance as TSK and DDR from the epicenters considered, but in different azimuth. The behaviour of residuals relative to Δ is the same; although their absolute values at MAT are slightly smaller than those at TSK and DDR. This difference is probably due to an azimuthal effect.

At OIS, the general trend of the residuals is about the same but large negative residuals are found at a distance (12.7° to 20.0°) somewhat greater than that at TSK, DDR, and MAT. Moreover the residuals, on the whole, are shifted in the positive direction. The large negative residuals at SHK are found at distance i.e. 14° to 21.0° which is greater than that at TSK, DDR, MAT and OIS. The residuals also become small as compared with those at these stations.

In general the scatter of the residuals at the same Δ is probably due to difference in focal depth and may be partially due to inaccurate hypocenter location.

Figure 8 shows the detailed locations of the Kurile earthquakes. The focal depths of these earthquakes are between 25 and 80 km. The travel time residuals of the earthquakes occurred within each mesh (1° latitude $\times 1^\circ$ longitude) are averaged at TSK and DDR separately. The average residuals are shown against the average azimuth from epicenter to station. The residual becomes more negative as the azimuth increases. The largest residual (-7.0 , -8.0 sec.) was observed for the earthquakes which occurred in the mesh from 151° to 152° E and from 45° to 46° N.

The azimuthal variation of the residuals may be used to delimit the horizontal extension of the anomalous region.

These anomalous early arrivals found above can be interpreted in terms of a high-velocity zone in the mantle. The broad feature of this zone can be delimited as follows. We noted that the distance where the large negative residuals are observed, differs from one station to another. The distance where the residuals start to be negative Δ_1 and that where the residuals return to normal Δ_2 were read from Fig. 7 and are given in Table 2 for each station. The deepest points D_1 and D_2 corresponding to distances Δ_1 and Δ_2 were calculated for a ray from a normal depth earthquake based on J-B model. It is assumed that the ray which reaches either Δ_1 or Δ_2 does not penetrate the anomalous region, but just pass above or below this region. Accordingly the possible thickness of this anomalous region at the midway between each station and the epicenters was roughly estimated and is given in Table 2. The azimuthal range at which this negative residual appears at each station is also given in Table 2.

It is to be noticed that the distance interval $(\Delta_2 - \Delta_1)$ where the negative residuals appear is nearly the same at all stations. The deepest points D_1 and D_2 listed above suggest roughly the upper and lower boundary of the anomalous region. Therefore, it can be concluded that this anomalous structure is dipping in a south-west direction. Its thickness also increases in the same direction. The upper boundary is not shallower than 60 km and the lower one is not deeper than 400 km. The azimuthal interval decreases as we go from TSK to SHK. This may explain the shift of the residuals upwards at MAT, OIS and SHK. Moreover, it suggests that this anomalous structure may be laterally limited. Figure 9 shows the possible horizontal extension of this anomalous

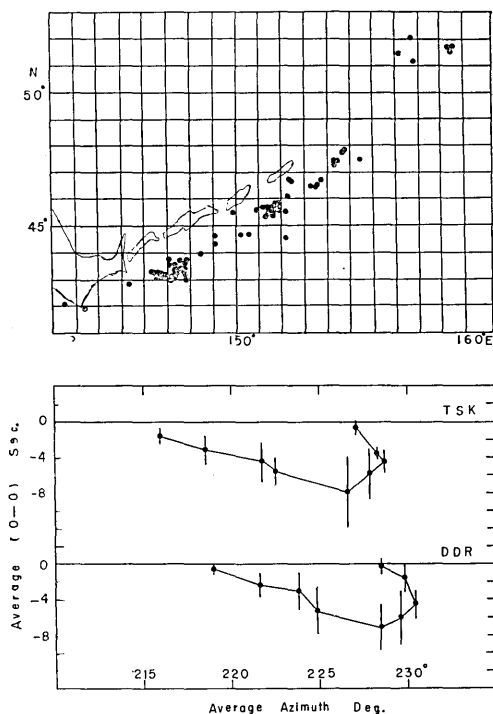


Fig. 8. The upper figure shows the detailed location of Hokkaido, Kurile and Kamchatka earthquakes. The lower figure shows the relationship between the average azimuth at the epicenter and the average travel time residuals for each mesh (1° latitude \times 1° longitude) at TSK and DDR.

Table 2

Station	Δ range		Range of deepest Point		Possible thickness km	Range of azimuth	
	Δ_1	Δ_2	D_1	D_2 km		Degree	
TSK	8.5°	16.0°	85	238	153	218—229	11
DDR	9.3	16.6	98	251	153	221—232	11
MAT	9.4	16.8	100	261	161	227—236	9
OIS	12.7	20.0	157	360	203	228—236	8
SHK	14.0	21.0	187	395	208	236—241	5

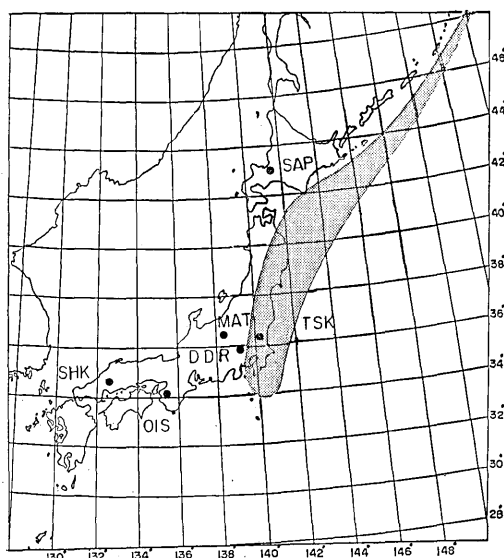


Fig. 9. The location of the used stations as well as the horizontal extension of the anomalous region.

region. The velocity contrast cannot be assigned to this region from the present data. It is rather important to use the data of the USCGS and JMA together for the better location of these Kurile earthquakes.

Most of the seismograms used for the analysis are reproduced in Fig. 10a, b, c, and Fig. 11a, b, c, at TSK and DDR respectively. They are arranged in the order of increasing azimuth, from the western Kuriles to Kamchatka. The onsets are usually very clear. The reading error must therefore be very small.

3) Mariana Group

The travel time residuals at the five stations are shown in Fig. 12. The pronounced anomaly such as observed for the Kurile group is not found for this group. But we note that the negative residuals are observed at TSK and DDR for $\Delta \leq 23^\circ$. For $\Delta \geq 40^\circ$ (for $23^\circ \leq \Delta \leq 40^\circ$ no earthquake is observed), the residuals are slightly scattered around zero line. At MAT the residuals are also slightly negative at all distances. At OIS and SHK, they are slightly positive particularly at $\Delta \leq 25^\circ$, and then the residuals are more or less scattered around zero line. The difference between the residuals at TSK and DDR on one hand and those at OIS and SHK on the other hand may be due to the difference

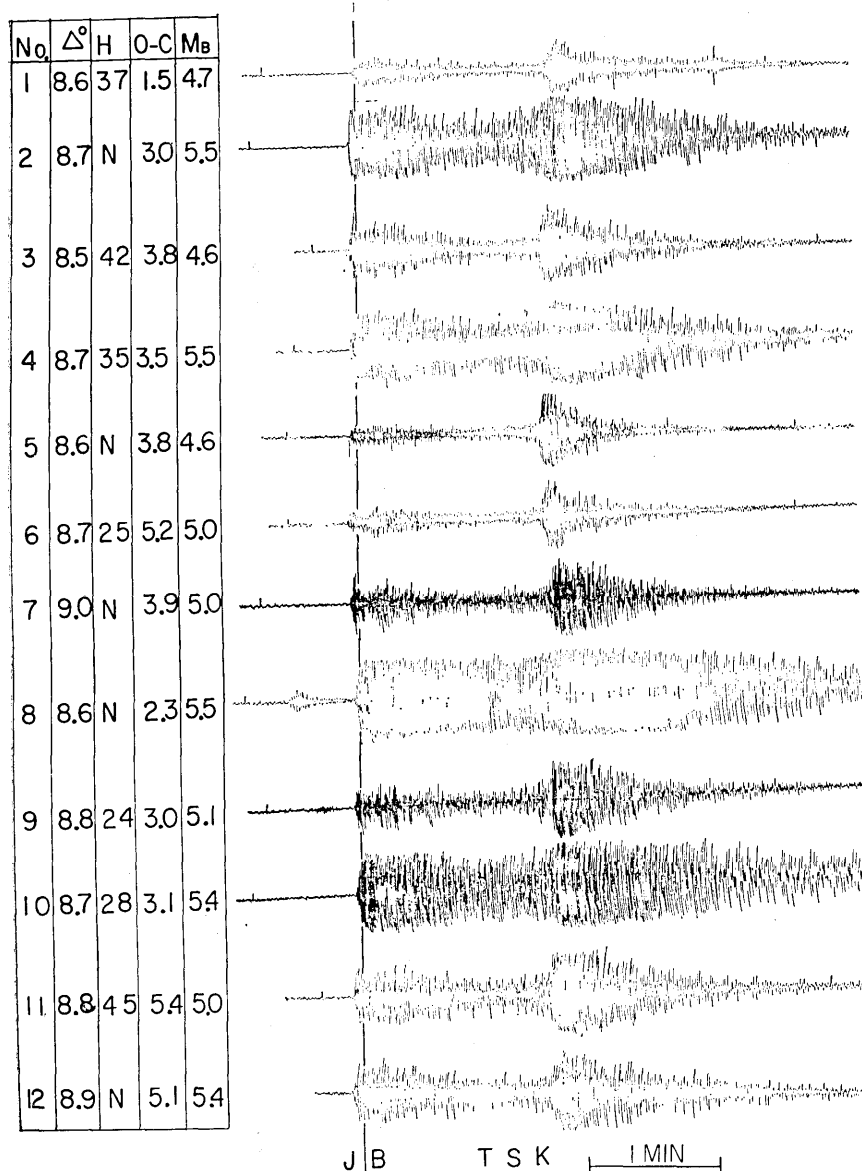


Fig. 10a.

in path. The seismic waves arriving at TSK and DDR pass through the Izu-Mariana Arc, while those arriving at OIS and SHK pass through the Philippine Sea. Moreover, the propagation of seismic waves through the northeastern and southwestern parts of Honshu Island is different (Katsumata, 1960). The Japanese Honshu Island is divided into two parts by the Fossa Magna rupture zone which was found by Neumann

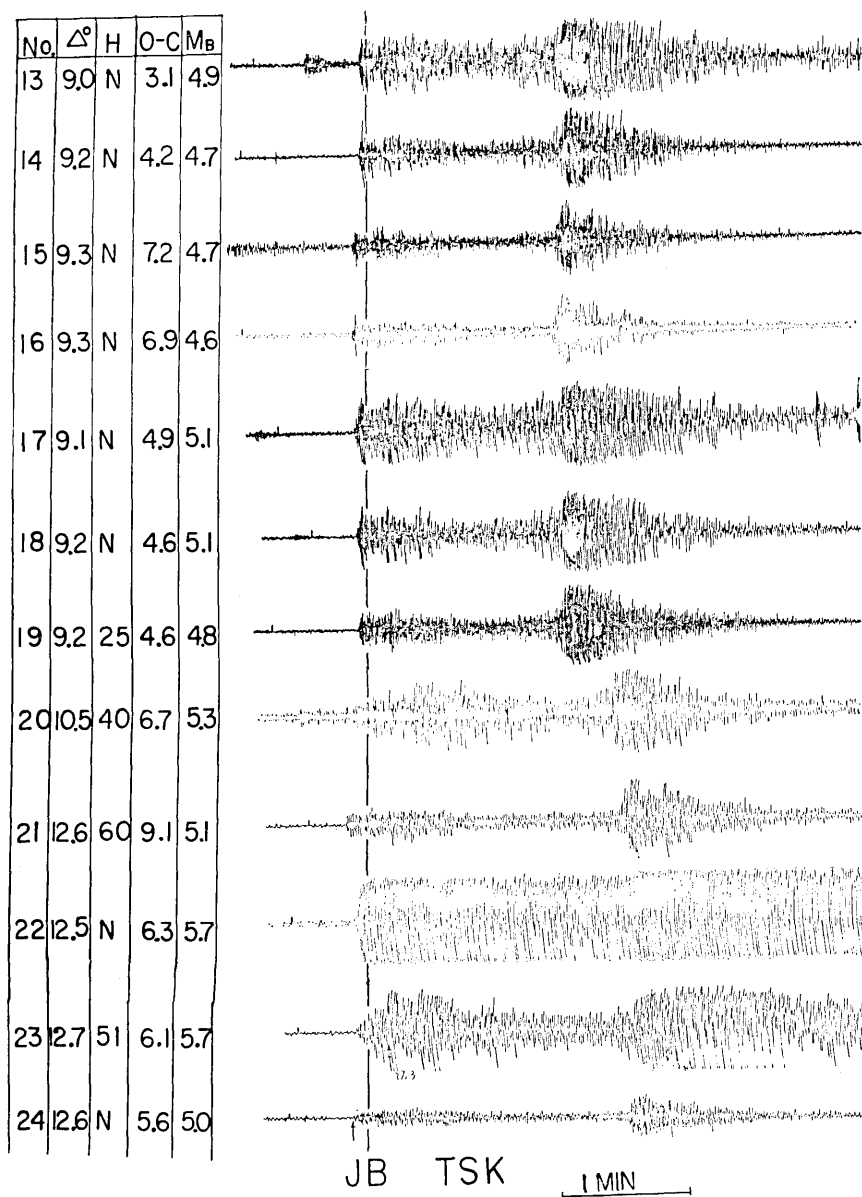


Fig. 10b.

(1885). TSK and DDR are on the eastern side of the Fossa Magna, while SHK and OIS are on the western side.

4) *Ryukyu and China Group*

Figure 13 shows the residuals at the five stations for the Ryukyu group. We found that at TSK, the residuals for the earthquakes from

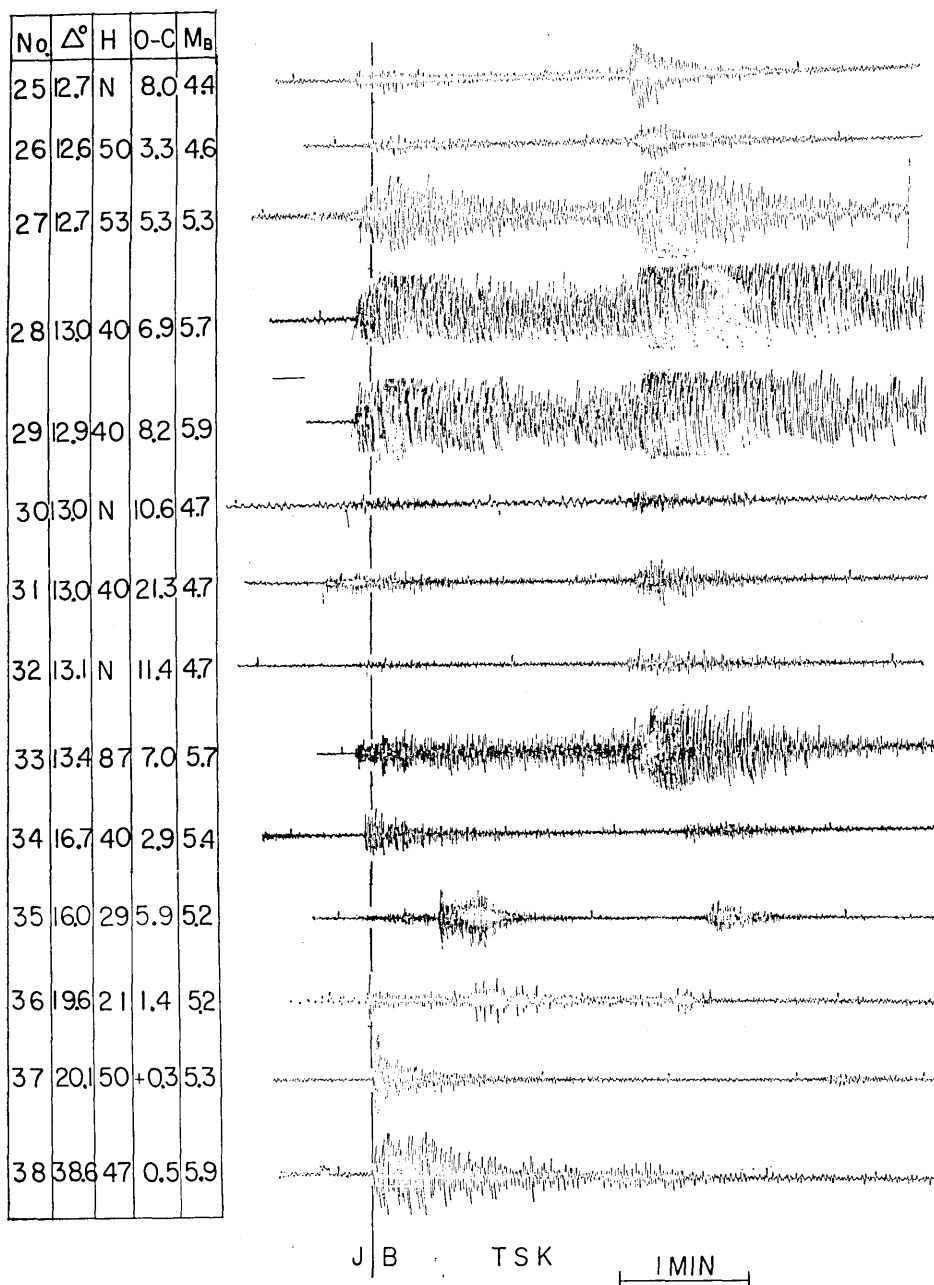


Fig. 10c.

Fig. 10. a, b, and c, show reproduced seismograms of most the Kurile and Kamchatka earthquakes at TSK. They are arranged in the order of increasing azimuth, from the western Kuriles to Kamchatka. Earthquakes are given serial numbers. Up to 36, the earthquakes are from the Kurile Islands, and the others are from Kamchatka. The epicentral distance is in degrees, focal depth, in Km., travel time residuals, in seconds (all residual values are negative unless there is a plus sign.). The J-B times are marked by the line J-B.

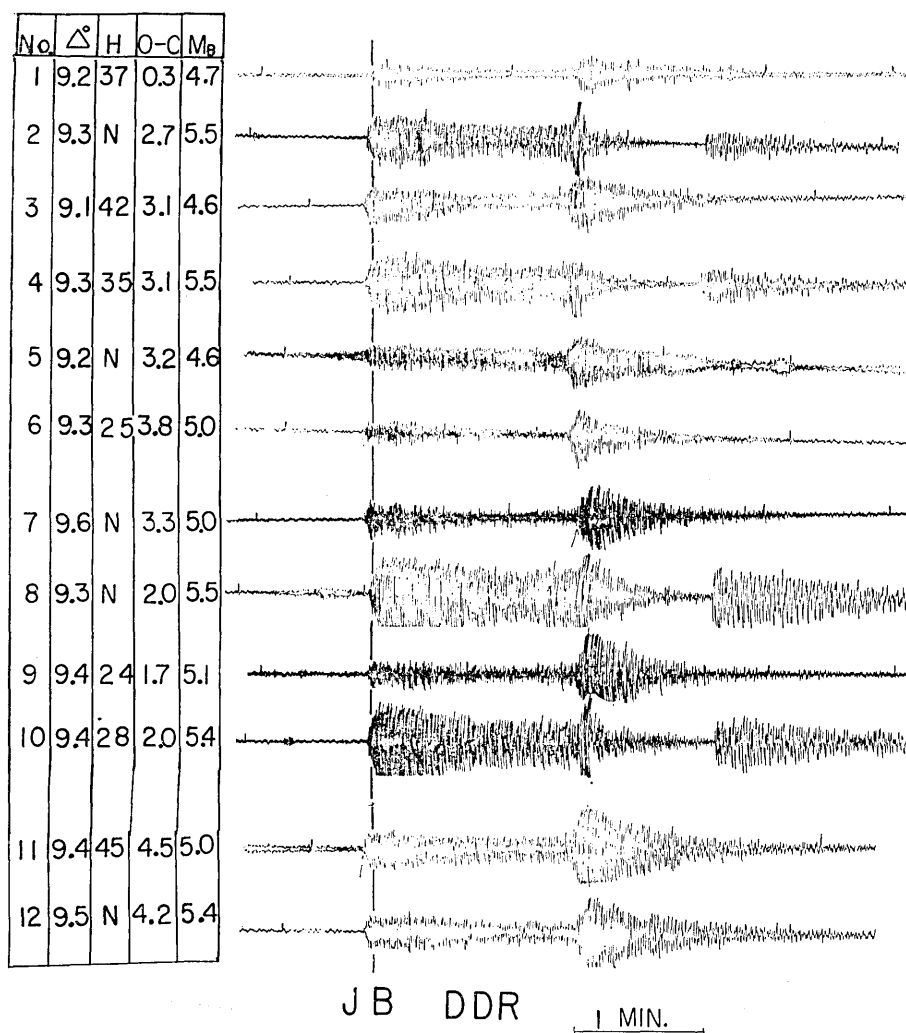


Fig. 11a.

the southwestern part of Honshu and from Kyushu Island ($8^\circ \leq \Delta \leq 13^\circ$), are scattered around zero line, while at DDR they are positive. At distance greater than 20° , the residuals are negative at both stations. But we can no longer notice such pronounced residuals as found for the Kurile group.

At MAT and SHK, the residuals do not show any trend. The residuals at OIS show early arrivals in the beginning till $\Delta = 18^\circ$. These early arrivals may be due to the local structure effect under this station.

Figure 14 shows the residuals for the China group. For this group there are rather few data available. Even though, we can say that no

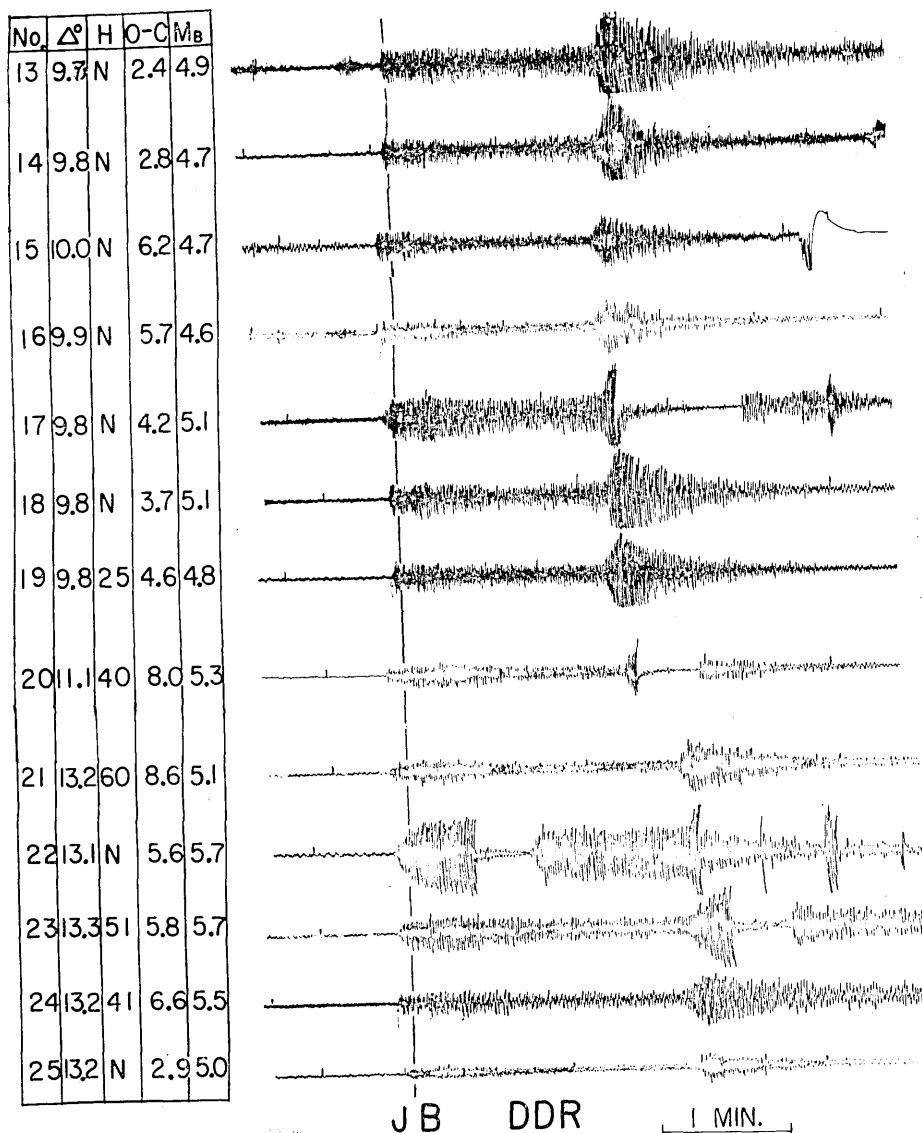


Fig. 11b.

appreciable trend or anomaly exist in the residuals.

5) Path Effect and the Appearance of Seismograms

The seismograms of earthquakes from the four groups are shown in Fig. 15 for TSK and DDR. The earthquakes are selected in such a way that they have about the same focal depth, magnitude and distance. The arrival time expected from the J-B table is indicated by a line J-B.

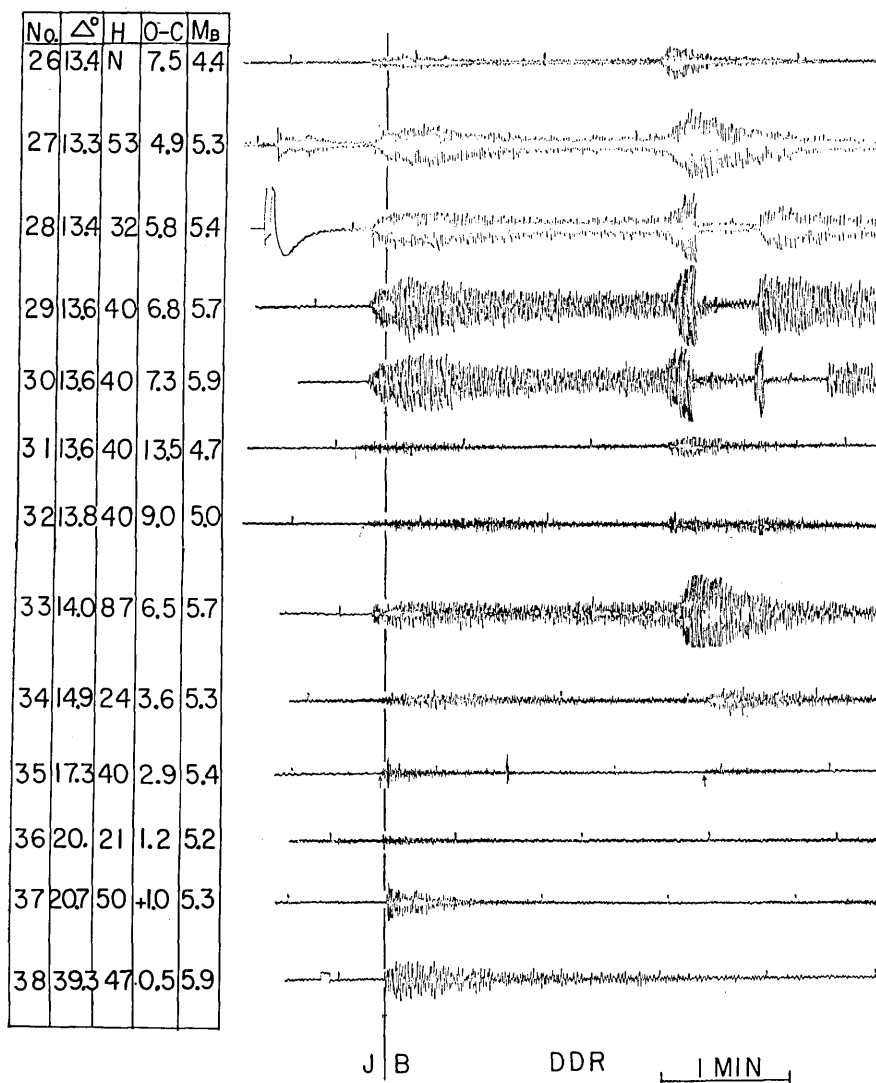


Fig. 11c.

Fig. 11. a, b, and c, are the same as those in figure 10 but at DDR.

It is seen that the Kurile earthquakes always show early arrivals. Earthquakes from the other groups do not show this phenomena, and usually the seismic waves from these groups arrive within a very small error of the expected arrival times from J-B travel time tables.

At TSK and DDR, all earthquakes from the Kurile Islands and the Mariana Islands usually show high frequency P and S waves. (Compare the seismograms in regard to magnitude.) This is observed neither

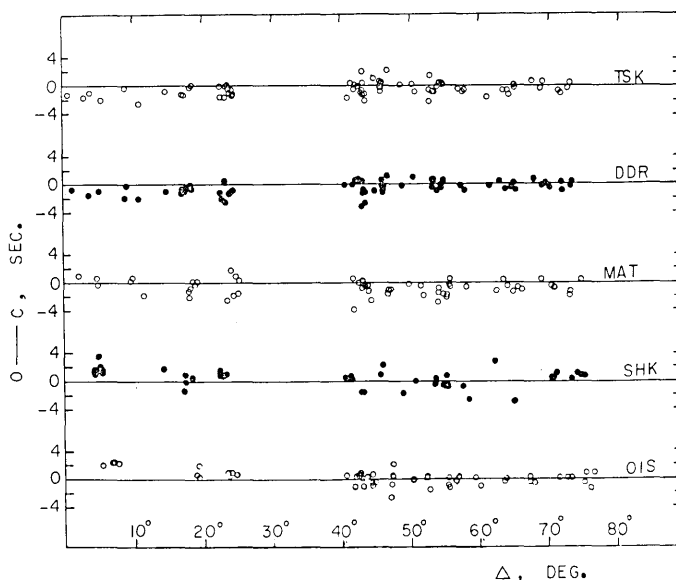


Fig. 12. The travel time residuals in seconds against epicentral distance in degrees for the Mariana group at the five stations.

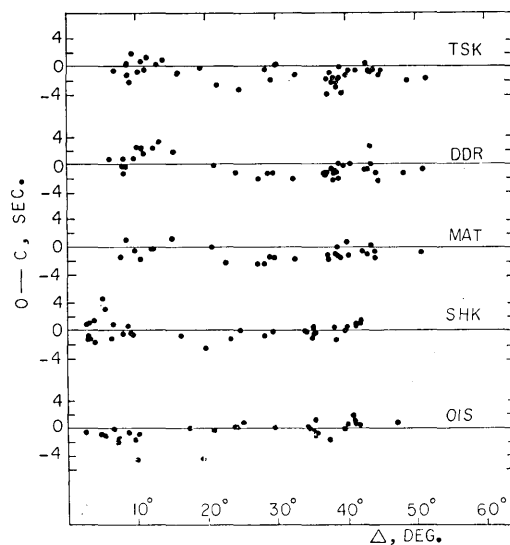


Fig. 13. The travel time residuals in seconds against epicentral distance in degrees for the Ryukyu group.

from the Ryukyu nor from the China group earthquakes. This may be due to the path effect, but might be partially due to source effect.

The fact that the Kurile earthquakes usually show very high frequ-

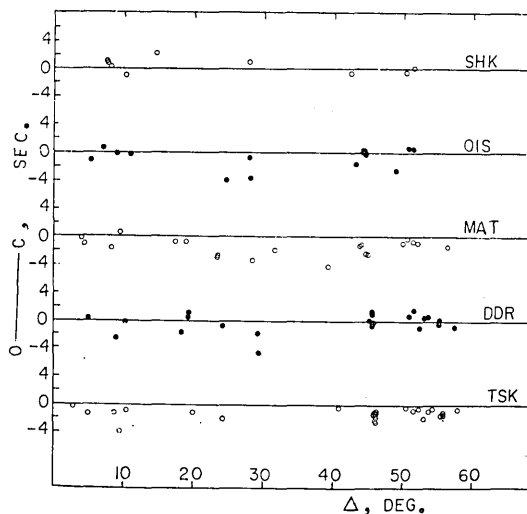


Fig. 14. The travel time residuals in seconds against epicentral distance in degrees for the China group.

ency waves, may indicate that the attenuation along the path from the Kurile Islands to Japan is very small.

Note added in proof: Recently Uyeda (personal communication) derived the amount of heat flow (Q in μ cal. $\text{cm}^{-2} \text{sec}^{-1}$) at the Moho under Japan. He found a region with a comparatively low Q stretching parallel to the Island arc and the Kurile trench. His region is quite similar to the anomalous region derived here from the travel time anomaly as shown in Fig. 10. Both approaches are consistent.

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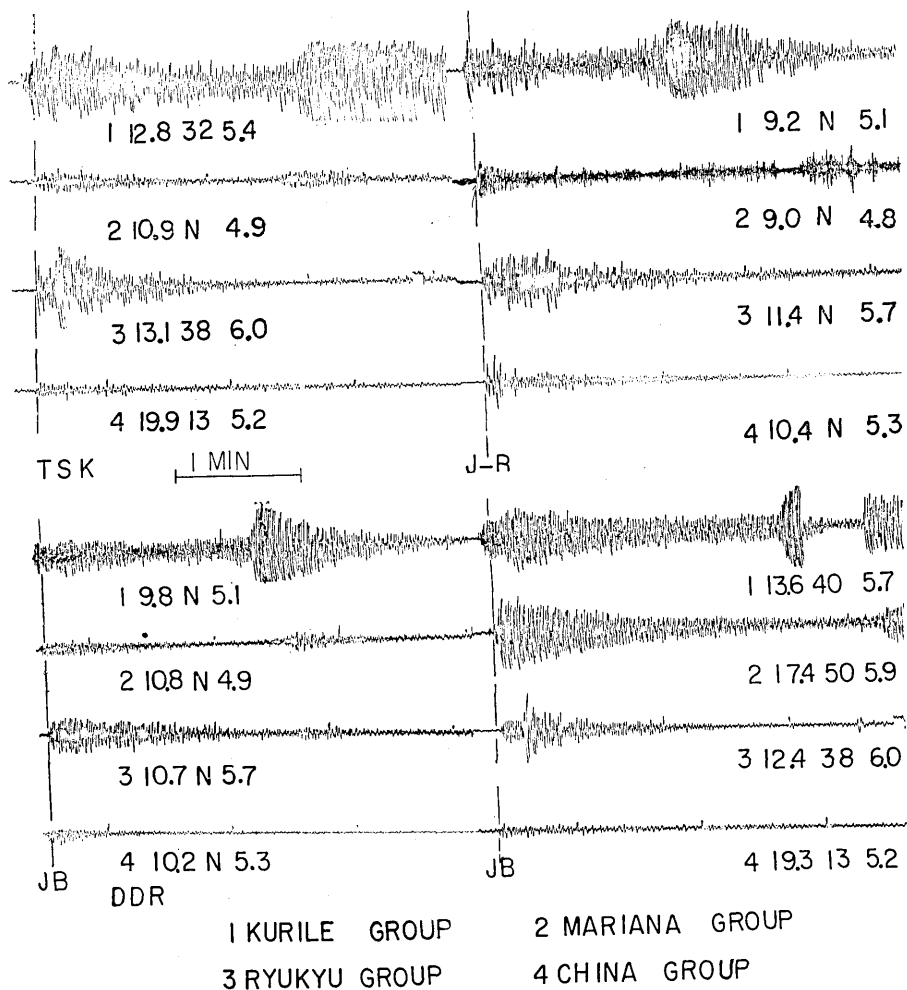


Fig. 15. Comparison of seismograms of earthquakes from the four groups at TSK and DDR. The upper part shows two examples at TSK, while the lower one shows another two examples at DDR. The parameters of each earthquake are written on its record. The first parameter from left indicates the group serial number as 1, 2, 3 and 4 from the Kurile, Mariana, Ryukyu and China groups respectively. The second is the epicentral distance in degrees, the third is the depth in km (N means normal depth), and the fourth is the magnitude. The arrival times expected from the J-B table are indicated by a line. It is seen that the Kurile earthquakes always show early arrivals and high frequency phases.

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20. Nihon no Kansoku-ten de miidasareta P-ha no Sōji no Ijyō (Dai ippō).

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Nihon no kansoku ten made no P-ha no soji o shirabeta. Chishima no jishin wa Jeffreys-Bullen hyo kara kitaisareru yorimo hayai totatsu-jikoku o ataeru. Shinō kettei aruiwa yomitori no gosa ga kono gensyo no gen'in towa kangaerarezu, Chishima kara Nihon made no kojyō-rettō no shita no kōsokudo kōzō ni yoru mono to omowareru. Kono kōsokudo kōzō no jyogen wa nan-seini shitamuki ni katamuiteori, 60 km yori mo asaku wa naranai. Kono kōzō no atsusa wa onajiku nansei-hōkō ni zōkashi, sono kagen wa 400 km yori mo fukaku wa nai. Kono ijyō-kōzō wa Chishima-rettō igai no dono hōkō kara mo miidasarenai. Kono ijyō-chiiki o tōru jishin no nami wa tokuni kōshuha-ryōiki ni oite hokano basho kara kita nami to kurabete gensui ga sukunai.