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16. *Regional Variation of P_n Residuals and Its Application to the Location of Earthquakes in and around the Kanto District.*

By Tadashi MAKI,

Earthquake Research Institute, University of Tokyo.

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Abstract

Regional variation of the crust and uppermost mantle structure in Japan was estimated from the analysis of P_n arrivals. Travel-time curves represented by the cubic equation were separately fitted to 83 well-observed shallow earthquakes which occurred in and around the Kanto district by taking into account the velocity gradients with depths. P_n velocities vary from 7.4 to 8.1 km/sec and velocity gradients with depths have a mean of 0.007 km/sec per km.

Residuals from the fitted travel-time curves show some systematic geographical features, i. e. early arrivals on the Pacific Ocean side of Northeast Japan and late arrivals on Southwest Japan and on the Japan Sea side of Northeast Japan. Such features are closely correlated with the regional variation of the crustal thickness derived from the Bouguer gravity anomaly and the surface dispersion.

Hypocenters of 4865 earthquakes occurring in and around the Kanto district during the 16 years from 1963 to 1978 have been relocated by correcting the mean P_n residuals at each station. Focal depths have been determined to a tenth of a kilometer instead of the 10 or 20 km step employed by JMA. Relocated epicenters show a tendency of clustering in smaller regions.

A low P_n velocity of about 7.4 km/sec was observed for the Middle Gifu Prefecture earthquake of September 9, 1969. The travel-time curve for this earthquake requires lower velocities by about 0.4 km/sec over the entire depth down to about 100 km than those for the ICHIKAWA and MOCHIZUKI (1971) model.

An exceptionally low P_n velocity of 7.1 km/sec was observed for an earthquake occurring near Sado Island, Niigata Prefecture. Its velocity profile suggests either the absence of the normal velocity jump around the Moho discontinuity or the existence of the unusually thick "intermediate layer".

I. Introduction

Travel-time anomalies have been studied extensively in Japan, as reviewed by UTSU (1971). Travel-time anomalies in the Japanese region are considered to be caused mostly by the existence of a high velocity zone of the Pacific lithospheric plate descending beneath the Asian continent. Recently, travel-time residuals for nearby-deep earthquakes were studied by UTSU (1975) and MAKI (1978). Teleseismic residuals were also studied by MAKI (1979b). Systematic regional variations in the travel-time residual were observed for both residuals. UTSU (1975) obtained less of a velocity contrast within and around the inclined seismic zone in the upper mantle by separating the effect of the crust and uppermost mantle. Significant regional variations in the crust and uppermost mantle structure have recently been derived by the refraction measurements using explosions. Further discussions on the lateral variation of the upper mantle structure must be made by separating the effects of the shallow parts or the crust and uppermost mantle.

Accurate hypocenters can be obtained by applying the station corrections to the travel times (MAKI, 1979a). However, for such a region of complicated velocity structure as the Japanese Islands, it is not easy to estimate appropriate station corrections. Especially in the case of locating local shallow earthquakes, only the regional variation in the crust and uppermost mantle structure must be corrected, since the travel times travelling only in the shallow part are free from the anomalous structure in the upper mantle. In this paper a crustal bias directly beneath the stations has been estimated from the P_n travel times and applied to the relocation of earthquakes in and around the Kanto district.

Refraction measurements of the crustal structure were extensively conducted by the Research Group for Explosion Seismology. The results summarized by ASADA and ASANO (1972) indicate that the P_n velocity varies from 7.7 to 8.0 km/sec, the crustal thickness from 20 to 40 km, and the velocity in the lower crust from 6.0 to 7.0 km/sec. Recent studies of the crustal structure from explosions at seas around Japan show more distinct lateral variations in the P_n velocities from 7.5 to 8.2 km/sec (Research Group for Explosion Seismology 1977 ; OKADA *et al.*, 1978a, 1978b).

Crustal structures were also studied by the use of the travel time data from natural earthquakes (AKI, 1965 ; Research Group for the Travel Time Curve, 1967, 1972 ; YOSHII, 1971 ; SUZUKI, 1978).

Regional variations in the crustal thickness were also studied from the Bouguer gravity anomaly (KANAMORI, 1963a, b), and from the surface wave dispersion (KAMINUMA and AKI, 1963). MIKUMO (1966) proposed a number of possible models for the crustal structure in Japan by reanalyzing the data of seismic refraction, gravity anomaly and surface wave dispersion.

Residuals of P_n arrivals were used to detect the regional variation in the P_n velocity around the San Andreas Fault (KIND, 1972). Time terms of the P_g wave were also studied in California (HAMILTON, 1970; WESSON *et al.*, 1973). Nearly identical values of the mean residuals and the time terms of the P_n arrivals were shown by BEDNAREK and MEYER (1966).

In the last part of this paper regional variation of the P wave velocity in the uppermost mantle will be estimated from the P_n arrivals of some typical shallow earthquakes in and around the Kanto district by taking into account the velocity increase with depth. Some velocity models will be constructed for the travel time curves showing a typically low P_n velocity profile.

II. Materials and method

Travel-time data were compiled from the JMA Data File. In the early stage of the present study, the travel-time data were collected from 427 shallow earthquakes in and around the Kanto district. They occurred in the region bounded by the latitudes of 31° and 39°N and by the longitudes of 137° and 145°E (shaded area in Fig. 1) during the 16 years from 1963 to 1978. The data from 83 well-observed shallow earthquakes selected from the above 427 were used in this study. These earthquakes have magnitudes of 5.5 or greater and provide more than 40 travel-time data which were read to a tenth of a second. Fig. 2 shows the epicenter distribution of these 83 earthquakes. Focal depths are indicated by the number of pairs of sticks for every 20 km, and the radii of the circles are proportional to the earthquake magnitude. Their origin times and hypocentral coordinates redetermined in this study are given in the Appendix.

In determining the hypocenter coordinates, preliminary determinations of the origin times using S wave travel times were not made because of their large scattering. The travel times for the different kinds of waves are observed, or S_g wave times are read instead of the S_n wave times, while the P_n times are read.

Composite travel time data for same depths were used by YOSHII (1971), and average travel time curves for same depths were used by the

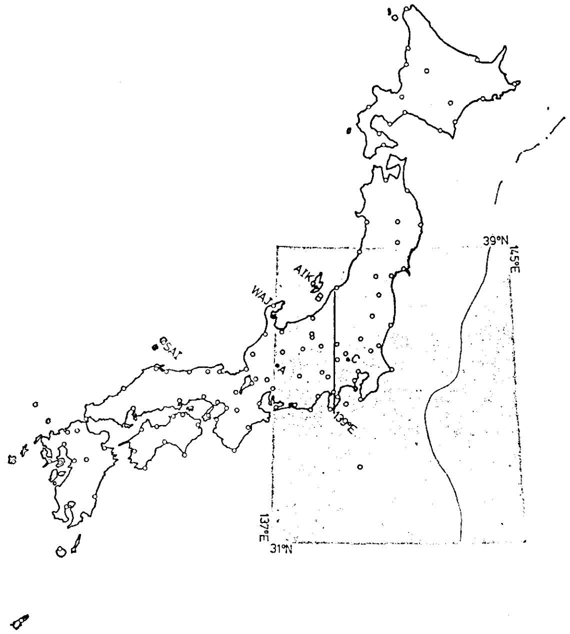


Fig. 1. Location of the JMA seismographic stations (open circles), and earthquake region used in the present study (shaded area). Asterisks A, B and C show the epicenter of the earthquakes used for the study of the velocity structure in chapter V.

Research Group for the Travel Time Curve (1967, 1972). In order to reduce the effects of the errors of hypocentral locations and origin times, and to detect regional variation of the crust and uppermost mantle structure, travel time data were analyzed separately for each earthquake.

YOSHII (1971) obtained the P_n velocities by the time term method applying the relation,

$$t=a+b\Delta\,, \tag{1}$$

for the distance range from 175 to 600 km. Here t and Δ denote the travel time and the epicentral distance, respectively. On the other hand, the Research Group for the Travel Time Curve (1967, 1972) applied the relation,

$$t=a+b\Delta+c\Delta^3\,, \tag{2}$$

for the distance range up to 1500 km.

Taking into account the results in the early stage of this study, the second relation is used over the distance range from 100 to 1000 km. For

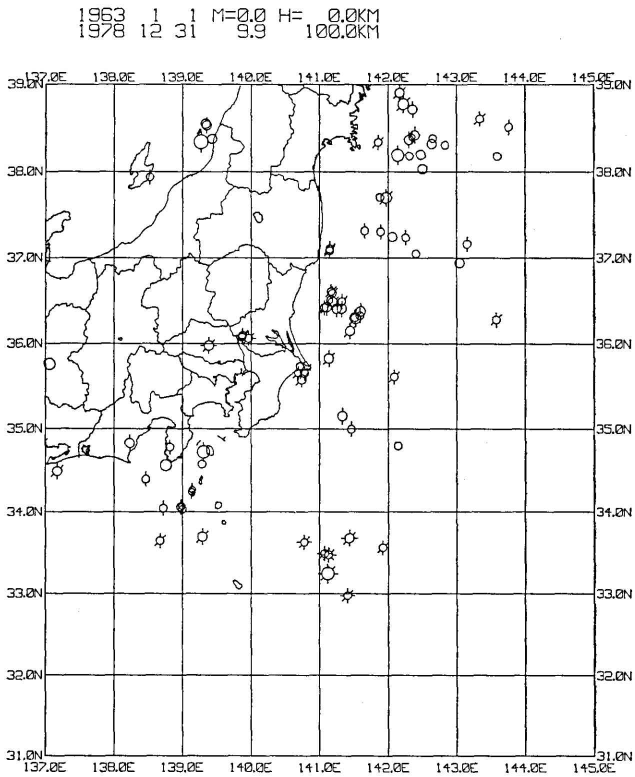


Fig. 2. Epicenter distribution of 83 earthquakes used for the study of P_n residuals. Radii of circles are proportional to their earthquake magnitude given by JMA, and focal depths are distinguished by the number of pairs of sticks for every 20 km. Epicentral coordinates adopted here are those relocated by correcting the mean P_n residuals at each station (see text).

shorter distances, say one or two hundreds kilometers, P_n velocities obtained by the first relation show instabilities from one earthquake to another. For longer distances where the P_n velocities were well-observed, the velocity increase with depth attributable to the third term in the second relation cannot be ignored. Since a majority of the 83 earthquakes have focal depths near and below the Moho discontinuity, P_n arrivals were observable even near 100 km.

Examples of the observed travel times are shown in Fig. 3. Epicentral distances and travel times are given referring to the epicentral coordinates and origin times by JMA, as in the figures. Travel time curves are iteratively fitted to the cubic equations by the least squares method using only the data of residuals less than 3 seconds. They are shown by thick lines. Rates of velocity increase with depth are obtained from the coefficients of the fitted travel time curves by the same method as BATE and HALL (1975).

Examples with the normal P_n velocity of about 7.7 km/sec in Japan are seen in Figs. 3a and 3b. Figs. 3c and 3d show low P_n velocities of 7.4 to 7.5 km/sec. Crustal velocities are observed at short distances less than 100 km for shallow earthquakes (Figs. 3e and 3f).

Residuals from the fitted travel time curves are considered to represent relative differences of the travel times through the crust beneath the stations. Fig. 4 shows examples of the geographical distributions of the residuals from the fitted travel time curves. Boundaries between the positive (late) and negative (early) arrivals are shown by thick lines. Early arrivals on the Pacific Ocean side of Northeast Japan and late

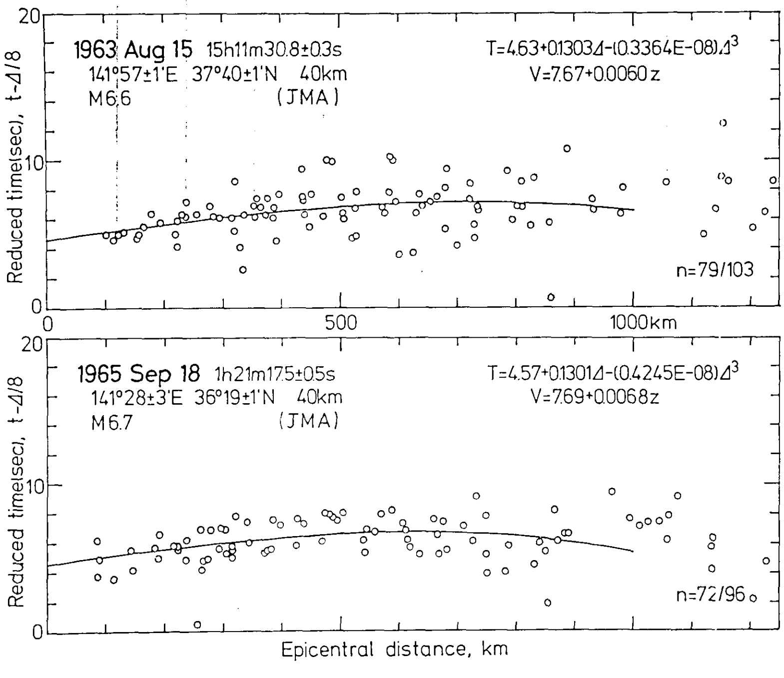


Fig. 3. Reduced travel-times of P_n arrivals, and travel-time curves fitted by the least-squares method. Formulae denote the travel-time curves and velocity variation with depth.
(a) NE off Fukushima Prefecture on August 15, 1963,
(b) Kashimanada (E off Ibaraki Prefecture) Earthquake on September 18, 1965,
(c) Niigata Earthquake on June 16, 1964,
(d) Off Miyagi Prefecture Earthquake on June 12, 1978,
(e) Off Izu Peninsula Earthquake on May 9, 1974, and
(f) Near Oshima Earthquake on January 14, 1979.

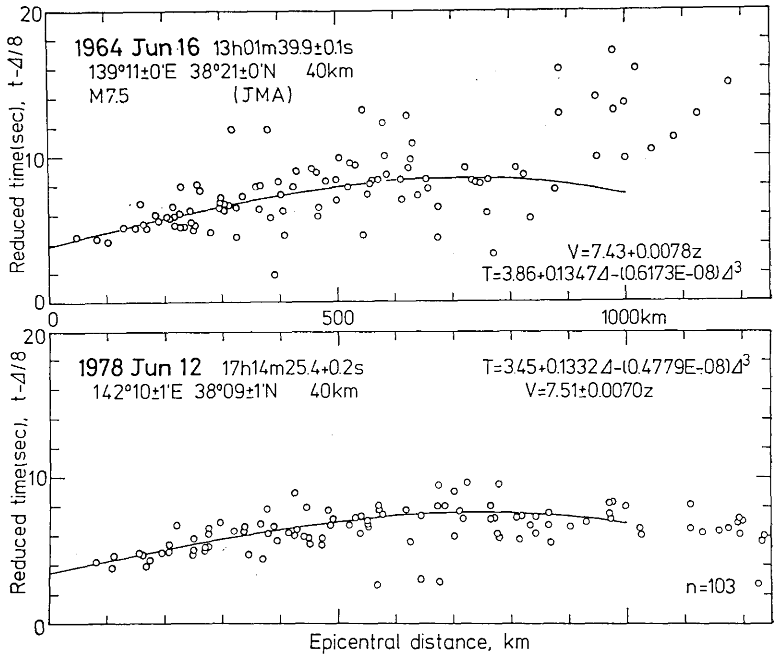


Fig. 3 c, d.

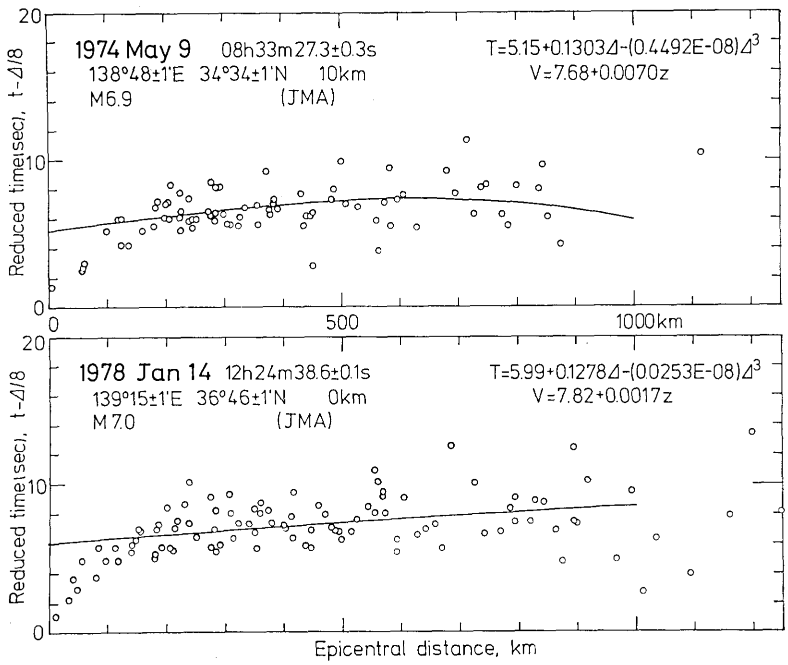


Fig. 3 e, f.

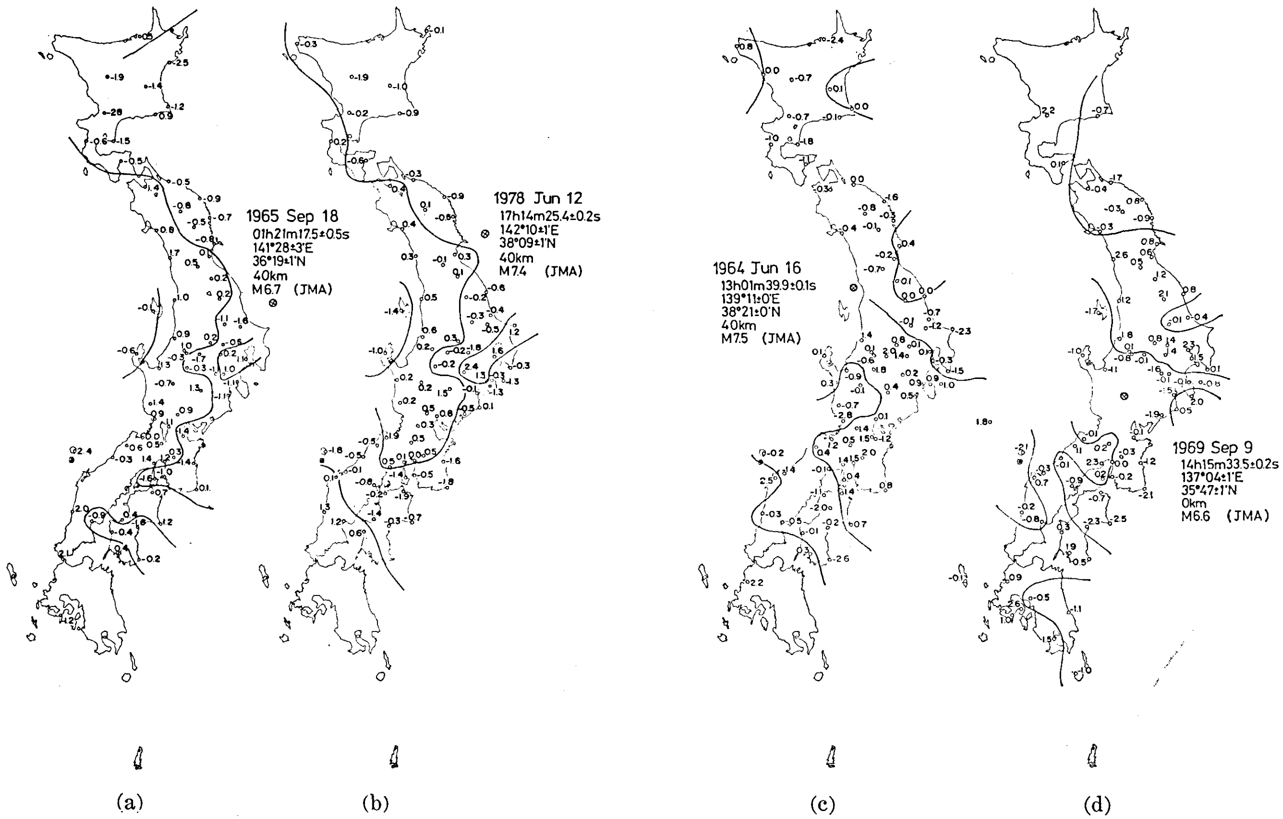


Fig. 4. Geographical distributions of P_n residuals (in seconds) for several earthquakes,
(a) Kashimanada Earthquake on September 18, 1965,
(b) Off Miyagi Prefecture Earthquake on June 12, 1978,
(c) Niigata Earthquake on June 16, 1964, and
(d) Middle Gifu Prefecture Earthquake on September 9, 1969.

arrivals on the Japan Sea side of Northeast Japan are usually observed as shown in Figs. 4a and 4b. Some confusing features are attributable to the local variation of the crustal structure and to deeper penetration of the seismic rays into the high velocity zone in the upper mantle beneath the Japanese Islands (Figs. 4c and 4d).

Table 1 summarizes the coefficients of the fitted travel time curves, velocity variations with depth, and the mean and standard deviations of the residuals for each of the 83 earthquakes. The last column denotes the focal depths by JMA. The second and third colums indicate the numbers of the travel time data compiled from the JMA Data File and those used in determining the travel time curves. A total of 5482 out of 7183 travel time data were used. The standard deviation of the residuals for each earthquake varies from 0.7 to 1.4 second with a mean of 1.0 second.

Fig. 5 shows the frequency distributions of the P_n velocities and the rates of velocity increase with depths. The P_n velocity varies from 7.4 to 8.1 km/sec. The mean P_n velocity is 7.7 km/sec, which equals the mean velocity obtained in the refraction studies from the explosions in Japan (ASADA and ASANO, 1972). The mean P_n velocity of 7.4 km/sec given by the Research Group for the Travel Time Curve (1967) is rarely observed

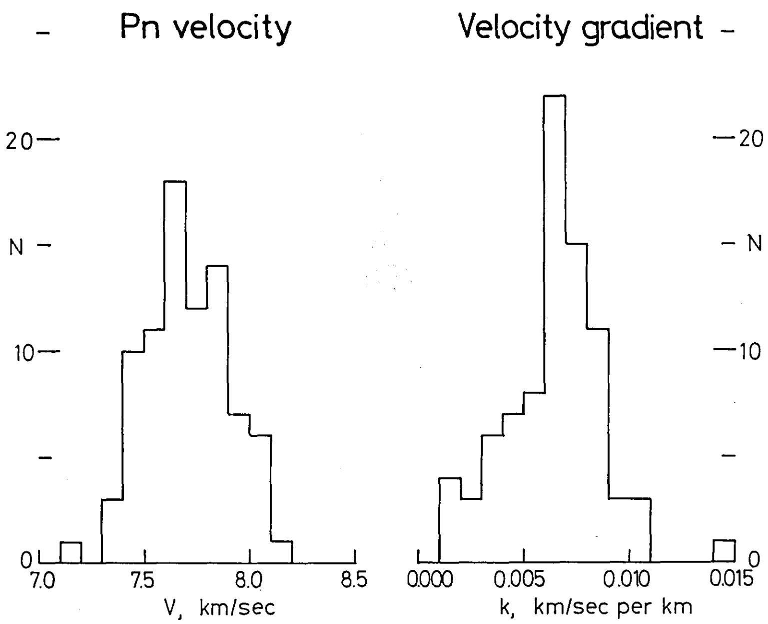


Fig. 5. Frequencies of P_n velocities (V, km/sec) and velocity gradients with depths (k, km/sec per km).

Table 1. Summary of the travel-time curves. Coefficients a (sec), b (sec/km) and c (sec/km^3) of the travel-time curves in $t=a+b\Delta+c\Delta^3$, P_n velocity v_0 (km/sec), velocity gradient k (km/sec per km) and the mean M (sec) and the standard deviation S (sec) of the residuals for the fitted travel-time curves are listed. Focal coordinates (origin time, latitude and longitude) are given in Appendix. H denotes the focal depth (km) given by JMA. N shows numbers of the travel-time data collected and used.

NO	N	A B C	VO K	M S	H
1	102/ 78	T= 4.419+0.1320*D-0.83511E-08*D**3,	V= 7.573+0.009330*Z,	RES= 0.000+/-1.312	40.0
2	94/ 77	T= 5.345+0.1269*D-0.13748E-08*D**3,	V= 7.883+0.004020*Z,	RES= 0.000+/-1.161	40.0
3	103/ 79	T= 4.633+0.1303*D-0.33637E-08*D**3,	V= 7.673+0.006039*Z,	RES= 0.000+/-1.120	40.0
4	90/ 66	T= 5.140+0.1280*D-0.13367E-08*D**3,	V= 7.814+0.003912*Z,	RES=-0.000+/-1.260	40.0
5	72/ 55	T= 4.666+0.1292*D-0.19443E-08*D**3,	V= 7.738+0.004650*Z,	RES=-0.000+/-1.144	60.0
6	89/ 65	T= 8.152+0.1304*D-0.22209E-08*D**3,	V= 7.669+0.004903*Z,	RES= 0.000+/-0.901	0.0
7	100/ 73	T= 3.971+0.1335*D-0.92942E-08*D**3,	V= 7.490+0.009681*Z,	RES= 0.000+/-1.307	40.0
8	105/ 80	T= 3.862+0.1347*D-0.61733E-08*D**3,	V= 7.426+0.007790*Z,	RES= 0.000+/-1.116	40.0
9	76/ 53	T= 7.021+0.1345*D-0.37663E-08*D**3,	V= 7.435+0.006095*Z,	RES=-0.000+/-0.954	0.0
10	81/ 60	T= 5.043+0.1357*D-0.43169E-08*D**3,	V= 7.371+0.006442*Z,	RES=-0.000+/-1.359	20.0
11	89/ 73	T= 7.704+0.1321*D-0.40734E-08*D**3,	V= 7.570+0.006513*Z,	RES= 0.000+/-1.118	0.0
12	92/ 71	T= 2.636+0.1409*D-0.63087E-08*D**3,	V= 7.097+0.007357*Z,	RES=-0.000+/-1.033	40.0
13	89/ 57	T= 7.203+0.1354*D-0.63503E-08*D**3,	V= 7.385+0.007835*Z,	RES=-0.000+/-1.404	0.0
14	75/ 53	T= 4.264+0.1304*D-0.26904E-08*D**3,	V= 7.670+0.005398*Z,	RES=-0.000+/-1.117	60.0
15	89/ 68	T= 5.907+0.1265*D-0.16720E-08*D**3,	V= 7.906+0.004453*Z,	RES=-0.000+/-1.328	20.0
16	58/ 48	T= 3.402+0.1358*D-0.11247E-07*D**3,	V= 7.363+0.010381*Z,	RES=-0.000+/-1.346	40.0
17	96/ 72	T= 4.576+0.1301*D-0.42448E-08*D**3,	V= 7.685+0.006800*Z,	RES= 0.000+/-1.107	40.0
18	97/ 75	T= 4.293+0.1312*D-0.48563E-08*D**3,	V= 7.621+0.007182*Z,	RES= 0.000+/-1.071	40.0
19	67/ 60	T= 5.695+0.1312*D-0.67910E-08*D**3,	V= 7.622+0.008495*Z,	RES=-0.000+/-1.145	20.0
20	79/ 56	T= 3.455+0.1362*D-0.19459E-07*D**3,	V= 7.342+0.013596*Z,	RES=-0.000+/-1.161	40.0
21	87/ 55	T= 7.825+0.1305*D-0.37560E-08*D**3,	V= 7.664+0.006370*Z,	RES=-0.000+/-1.445	20.0
22	66/ 51	T= 4.478+0.1317*D-0.50994E-08*D**3,	V= 7.591+0.007316*Z,	RES=-0.000+/-1.118	40.0
23	70/ 56	T= 5.224+0.1336*D-0.63785E-08*D**3,	V= 7.486+0.008322*Z,	RES=-0.000+/-1.251	20.0
24	66/ 50	T= 5.924+0.1314*D-0.68447E-08*D**3,	V= 7.613+0.008513*Z,	RES= 0.000+/-1.269	20.0
25	72/ 57	T= 4.760+0.1290*D-0.48385E-10*D**3,	V= 7.754+0.000736*Z,	RES= 0.012+/-1.023	40.0
26	93/ 41	T= 6.695+0.1245*D-0.41646E-08*D**3,	V= 8.031+0.007195*Z,	RES=-0.000+/-1.063	30.0
27	70/ 58	T= 7.025+0.1289*D-0.30698E-08*D**3,	V= 7.756+0.005862*Z,	RES=-0.000+/-1.113	10.0
28	72/ 60	T= 7.152+0.1285*D-0.32053E-08*D**3,	V= 7.785+0.006024*Z,	RES=-0.000+/-1.286	10.0
29	76/ 57	T= 4.774+0.1280*D-0.15760E-08*D**3,	V= 7.810+0.004245*Z,	RES=-0.000+/-1.162	40.0
30	80/ 61	T= 4.888+0.1286*D-0.15434E-08*D**3,	V= 7.774+0.004172*Z,	RES=-0.000+/-1.099	50.0
31	89/ 72	T= 5.113+0.1270*D-0.76224E-09*D**3,	V= 7.872+0.002987*Z,	RES= 0.000+/-1.024	50.0
32	68/ 51	T= 3.862+0.1319*D-0.63090E-08*D**3,	V= 7.583+0.008126*Z,	RES=-0.000+/-0.617	60.0
33	92/ 70	T= 5.037+0.1244*D-0.10459E-09*D**3,	V= 8.038+0.001142*Z,	RES= 0.031+/-0.954	50.0
34	89/ 67	T= 3.629+0.1329*D-0.36914E-08*D**3,	V= 7.524+0.006142*Z,	RES= 0.000+/-1.132	50.0
35	71/ 52	T= 5.905+0.1345*D-0.97395E-08*D**3,	V= 7.434+0.009799*Z,	RES=-0.000+/-0.951	10.0
36	63/ 52	T= 7.752+0.1316*D-0.54138E-08*D**3,	V= 7.600+0.007553*Z,	RES=-0.000+/-0.949	0.0
37	68/ 59	T= 3.871+0.1354*D-0.88421E-08*D**3,	V= 7.384+0.009244*Z,	RES=-0.000+/-0.916	40.0
38	91/ 73	T= 7.499+0.1344*D-0.50552E-08*D**3,	V= 7.442+0.007072*Z,	RES=-0.000+/-1.225	0.0
39	56/ 48	T= 3.857+0.1327*D-0.53170E-08*D**3,	V= 7.536+0.007389*Z,	RES=-0.000+/-0.899	60.0
40	86/ 64	T= 3.994+0.1321*D-0.35461E-08*D**3,	V= 7.568+0.006074*Z,	RES= 0.000+/-0.907	40.0
41	69/ 62	T= 4.528+0.1292*D-0.36015E-08*D**3,	V= 7.739+0.006330*Z,	RES=-0.000+/-1.110	50.0
42	78/ 61	T= 4.119+0.1289*D-0.10113E-08*D**3,	V= 7.760+0.003368*Z,	RES= 0.156+/-1.000	40.0

Table 1 (Continued).

NO	N	A B C	VO K	M S	H
43	80/ 62	T= 3.928+0.1323*D-0.43358E-08*D**3,	V= 7.560+0.006705*Z,	RES=-0.000+/-0.976	50.0
44	62/ 54	T= 7.550+0.1239*D-0.64360E-09*D**3,	V= 8.071+0.002850*Z,	RES= 0.152+/-1.096	20.0
45	62/ 50	T= 7.386+0.1272*D-0.48550E-09*D**3,	V= 7.863+0.002380*Z,	RES= 0.145+/-1.189	20.0
46	73/ 56	T= 5.609+0.1264*D-0.19153E-08*D**3,	V= 7.912+0.004771*Z,	RES= 0.000+/-0.898	30.0
47	97/ 72	T= 5.637+0.1255*D-0.29304E-09*D**3,	V= 7.971+0.001887*Z,	RES= 0.149+/-0.903	50.0
48	69/ 51	T= 3.970+0.1311*D-0.36504E-08*D**3,	V= 7.630+0.006238*Z,	RES=-0.000+/-1.064	40.0
49	67/ 52	T= 3.492+0.1368*D-0.88296E-08*D**3,	V= 7.311+0.009100*Z,	RES=-0.000+/-0.745	20.0
50	81/ 67	T= 4.661+0.1255*D-0.54435E-09*D**3,	V= 7.970+0.002572*Z,	RES= 0.174+/-1.046	50.0
51	70/ 58	T= 4.446+0.1293*D-0.15143E-08*D**3,	V= 7.732+0.004099*Z,	RES=-0.000+/-1.267	60.0
52	76/ 52	T= 3.920+0.1301*D-0.34455E-08*D**3,	V= 7.685+0.006127*Z,	RES=-0.000+/-1.056	50.0
53	75/ 54	T= 3.900+0.1295*D-0.32790E-08*D**3,	V= 7.724+0.006022*Z,	RES=-0.000+/-1.102	60.0
54	91/ 72	T= 5.150+0.1303*D-0.44920E-08*D**3,	V= 7.677+0.006984*Z,	RES=-0.000+/-1.143	10.0
55	68/ 57	T= 5.544+0.1314*D-0.65067E-08*D**3,	V= 7.610+0.008296*Z,	RES=-0.000+/-1.091	10.0
56	91/ 66	T= 3.557+0.1311*D-0.54183E-08*D**3,	V= 7.628+0.007597*Z,	RES=-0.000+/-1.006	40.0
57	76/ 50	T= 2.431+0.1341*D-0.34324E-08*D**3,	V= 7.458+0.005846*Z,	RES=-0.000+/-1.190	50.0
58	84/ 71	T= 4.984+0.1249*D-0.87636E-09*D**3,	V= 8.007+0.003286*Z,	RES= 0.000+/-1.021	60.0
59	77/ 63	T= 4.699+0.1285*D-0.34670E-08*D**3,	V= 7.781+0.006261*Z,	RES=-0.000+/-0.982	40.0
60	68/ 50	T= 4.473+0.1308*D-0.94293E-09*D**3,	V= 7.642+0.003178*Z,	RES=-0.000+/-1.257	30.0
61	106/ 93	T= 5.557+0.1256*D-0.20031E-08*D**3,	V= 7.961+0.004925*Z,	RES= 0.000+/-1.092	40.0
62	110/ 89	T= 3.281+0.1327*D-0.44904E-08*D**3,	V= 7.533+0.006788*Z,	RES= 0.000+/-0.918	30.0
63	125/ 97	T= 3.084+0.1357*D-0.71563E-08*D**3,	V= 7.368+0.008288*Z,	RES= 0.000+/-0.890	30.0
64	99/ 77	T= 4.600+0.1281*D-0.29382E-08*D**3,	V= 7.806+0.005791*Z,	RES= 0.000+/-0.934	40.0
65	72/ 58	T= 3.344+0.1312*D-0.37740E-08*D**3,	V= 7.620+0.006330*Z,	RES=-0.000+/-0.775	50.0
66	94/ 61	T= 3.093+0.1358*D-0.39403E-08*D**3,	V= 7.366+0.006147*Z,	RES=-0.000+/-0.920	30.0
67	112/ 79	T= 3.599+0.1330*D-0.36022E-08*D**3,	V= 7.518+0.006062*Z,	RES= 0.000+/-0.930	30.0
68	124/106	T= 7.264+0.1263*D-0.27898E-08*D**3,	V= 7.916+0.005763*Z,	RES= 0.000+/-1.107	10.0
69	124/ 93	T= 4.398+0.1279*D-0.12016E-09*D**3,	V= 7.819+0.001174*Z,	RES= 0.037+/-0.957	50.0
70	143/103	T= 5.978+0.1278*D-0.25342E-09*D**3,	V= 7.822+0.001706*Z,	RES= 0.000+/-1.108	0.0
71	116/ 86	T= 5.246+0.1285*D-0.42748E-08*D**3,	V= 7.782+0.006953*Z,	RES= 0.000+/-1.159	20.0
72	145/101	T= 3.781+0.1295*D-0.30388E-08*D**3,	V= 7.720+0.005792*Z,	RES= 0.000+/-0.964	50.0
73	91/ 63	T= 4.159+0.1283*D-0.14265E-09*D**3,	V= 7.791+0.001272*Z,	RES=-0.000+/-0.772	60.0
74	74/ 51	T= 3.768+0.1338*D-0.15760E-08*D**3,	V= 7.472+0.003972*Z,	RES=-0.000+/-1.253	30.0
75	92/ 72	T= 3.307+0.1336*D-0.45756E-08*D**3,	V= 7.484+0.006784*Z,	RES=-0.000+/-0.936	40.0
76	144/103	T= 3.452+0.1332*D-0.47785E-08*D**3,	V= 7.510+0.006970*Z,	RES= 0.001+/-0.952	40.0
77	89/ 68	T= 3.456+0.1317*D-0.38305E-08*D**3,	V= 7.591+0.006341*Z,	RES=-0.000+/-1.168	40.0
78	63/ 45	T= 3.802+0.1288*D-0.19927E-08*D**3,	V= 7.763+0.004730*Z,	RES= 0.356+/-1.016	40.0
79	120/ 94	T= 3.663+0.1313*D-0.26514E-08*D**3,	V= 7.614+0.005300*Z,	RES= 0.000+/-0.977	40.0
80	77/ 69	T= 3.423+0.1340*D-0.49315E-08*D**3,	V= 7.464+0.007016*Z,	RES= 0.000+/-0.915	30.0
81	85/ 64	T= 2.343+0.1367*D-0.75688E-08*D**3,	V= 7.318+0.008437*Z,	RES=-0.000+/-1.037	50.0
82	93/ 71	T= 5.825+0.1308*D-0.37514E-08*D**3,	V= 7.647+0.006345*Z,	RES= 0.000+/-0.942	10.0
83	103/ 86	T= 4.696+0.1264*D-0.23133E-08*D**3,	V= 7.914+0.005245*Z,	RES= 0.000+/-1.034	50.0

in the present study. This might be caused by excessive effects of the Δ^3 term over longer distances up to 1500 km. Smaller rates of the velocity increase with depth are observed, compared to the results within the crust (HILL, 1971).

III. Regional variation of the P_n residuals and its geophysical implication

As stated in the previous chapter (Fig. 4), the P_n residuals show the systematic geographical variations though some different features are observed from one earthquake to another. P_n residuals are summarized for each station. Although the azimuthal variation around the station is observed for the teleseismic residuals (MAKI, 1979b), P_n residuals do not clearly show such azimuthal dependence. Frequencies of P_n residuals at each station show the normal distribution. In Table 2 the mean and the standard deviation of P_n residuals are listed for stations with 10 or more observations. The P_n residuals vary from -1.0 to $+1.0$ second, and the standard deviations are less than 1.7 second.

In Fig. 6 the geographical distribution of the mean P_n residuals is shown by the different symbols. Averaging all stations the mean P_n residuals is -0.06 second, and the standard deviation is $+0.43$ second. Solid symbols show late arrivals and open ones show early arrivals. The Pacific Ocean side of Northeast Japan from the Hokkaido to the Kanto district is characterized by the early arrival. Later arrivals are observed in Southwest Japan and on the Japan Sea side of Northeast Japan, especially in the mountain region of the central Japan.

The geographical distribution of the mean P_n residuals is compared with the crustal thickness derived from the surface wave dispersion, shown by broken lines (KAMINUMA and AKI, 1964; taken here from the SUGIMURA and UYEDA's (1973) paper). Common features are generally observed between the two, but some local variations can be seen in the P_n residuals of the present study.

Since the P_n residuals are considered to show the relative differences in the travel times through the crustal part beneath the stations, differences in the crustal thickness can be estimated by assuming the velocities in the lowermost crust and uppermost mantle. Fig. 7 shows the regional variation of the relative differences of the crustal thickness for the assumed one-layer crust with the velocities in the crust and in the uppermost mantle, 6.0 and 7.7 km/sec respectively. Only the boundaries between the positive and negative residuals are shown by solid lines.

Table 2. Station corrections of the P_n travel-times for the earthquakes in and around the Kanto district.

NO	STA	STAT.CORR.	N	NO	STA	STAT.CORR.	N	NO	STA	STAT.CORR.	N
4	ASA	-1.05+/-1.33	30	5	ABJ	-1.06+/-1.20	20	6	SAP	-0.64+/-1.69	24
7	OBI	-0.92+/-1.02	27	8	KUS	-1.40+/-1.52	13	10	SUT	0.43+/ 1.13	21
11	MRR	-1.55+/-1.22	13	13	URA	-0.37+/-1.10	49	15	HAK	-0.37+/-1.15	53
16	HRO	-1.63+/-0.90	23	17	MIZ	0.41+/-1.17	29	18	AOM	0.27+/-1.01	53
19	HAC	-0.61+/-0.95	72	20	AKI	0.60+/-0.82	81	21	MRK	-0.32+/-0.76	88
22	MIY	-0.70+/-0.92	67	23	SAK	0.96+/-0.97	30	24	YAM	-0.17+/-0.60	94
25	SEN	-0.19+/-0.71	75	26	ISN	-0.57+/-0.97	76	27	FKS	0.17+/-0.70	74
28	SHR	-0.26+/-0.76	81	29	ONA	-0.14+/-0.77	64	30	OFU	-0.65+/-0.94	75
31	WAJ	-0.46+/-0.70	49	32	AIK	-0.83+/-0.96	81	33	NII	0.73+/-0.38	64
34	KAN	0.97+/-0.78	62	35	TGY	0.70+/-0.90	40	36	NGN	0.69+/-0.83	74
37	TKD	0.60+/-0.91	69	38	UTS	-0.42+/-0.61	89	39	FUK	0.36+/-0.97	58
40	TKY	0.36+/-0.78	69	41	MTM	0.68+/-0.86	74	42	OIW	0.22+/-1.02	77
43	MAE	0.37+/-0.82	93	44	KMG	0.24+/-0.79	85	45	KAK	-0.94+/-0.71	23
46	MIT	-0.27+/-0.62	75	47	TSR	0.11+/-0.80	60	48	GIF	0.52+/-0.77	86
49	NAG	0.16+/-0.82	67	50	IID	0.70+/-0.70	94	51	KOF	-0.03+/-0.81	66
52	FUN	0.00+/-1.06	51	53	CHJ	-0.24+/-0.92	62	54	CHO	-0.02+/-0.99	67
55	KAM	0.37+/-0.86	14	56	TSU	0.41+/-1.31	38	57	HMM	0.19+/-1.10	70
58	OMA	0.34+/-1.15	39	59	SHZ	0.02+/-0.78	83	60	MIS	-0.42+/-1.04	68
61	TOK	0.48+/-0.81	62	62	OWA	-0.57+/-0.99	72	63	AJI	-0.60+/-0.74	80
64	YOK	0.76+/-0.94	75	65	TMS	0.00+/-1.04	85	66	OSH	-0.71+/-0.92	47
67	HJJ	-0.26+/-1.13	66	68	MAT	-0.43+/-0.67	75	69	SAI	-0.39+/-1.15	61
70	MTS	0.57+/-1.03	53	71	YON	0.13+/-1.05	36	72	TOT	-0.19+/-0.81	49
73	TYK	-0.16+/-0.85	70	74	MAI	0.50+/-0.97	50	75	HMD	0.02+/-1.05	71
76	KYO	-0.33+/-0.75	69	77	HIK	0.52+/-0.72	86	78	SHN	0.24+/-0.92	27
79	HIR	-0.11+/-0.99	44	80	OKA	-0.73+/-0.76	47	81	HIM	0.41+/-1.13	42
82	KOB	1.46+/-0.57	26	83	OSA	0.01+/-0.82	51	84	SUM	-0.21+/-0.92	53
85	WKY	0.37+/-1.17	52	86	SHJ	-0.71+/-1.03	75	87	NAR	0.44+/-1.22	58
89	FKK	0.08+/-1.12	28	90	SAG	0.52+/-1.13	13	91	OIT	0.92+/-1.12	25
93	NGS	-0.48+/-0.73	18	95	KUM	0.36+/-0.84	23	97	KAG	0.98+/-0.87	11
98	MYZ	0.41+/-1.16	26	100	NGB	0.08+/-0.96	15	101	ASZ	-0.15+/-1.04	34
102	MTY	0.27+/-1.22	48	103	TKM	-0.66+/-0.89	70	104	UWA	-0.14+/-1.05	24
105	KOC	0.05+/-1.09	39	106	TSS	-0.39+/-1.22	29	107	TKS	0.28+/-1.08	63
108	MRT	-0.02+/-1.10	69	112	NGT	0.05+/-1.07	16	122	SKH	0.56+/-0.68	32
123	HOJ	-0.20+/-0.99	21	124	KAMA	-1.22+/-0.66	12	125	KAKJ	-1.16+/-0.55	10
126	CHJJ	-0.39+/-0.53	10	127	IIDJ	0.71+/-0.63	13				

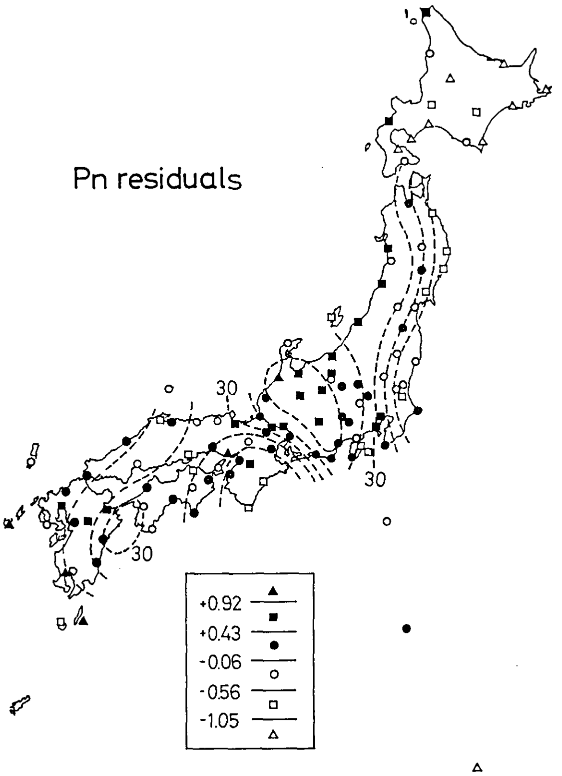


Fig. 6. Geographical distribution of the mean P_n residuals for 83 earthquakes in and around the Kanto district. P_n residuals are shown by six symbols, and closed ones show late arrivals and open ones show early arrivals. Broken lines show the contours of the crustal thickness derived from the surface wave dispersion (KAMINUMA and AKI, 1963; adopted here from SUGIMURA and UYEDA, 1973).

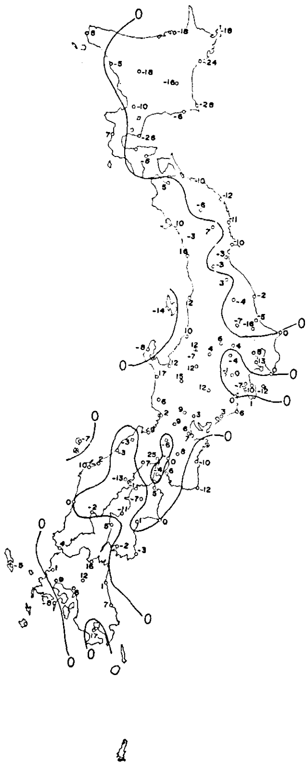
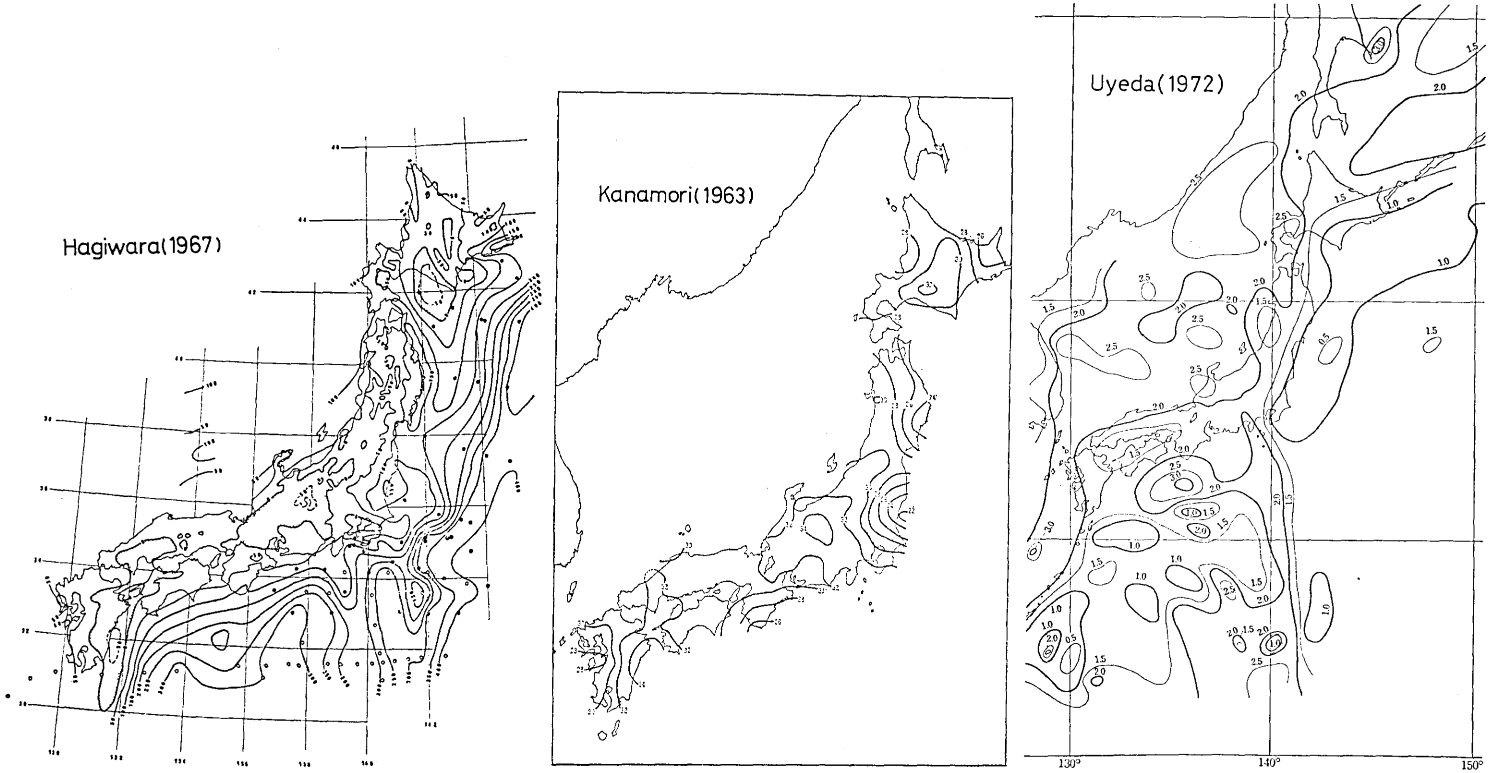


Fig. 7. Differences of the crustal thickness (in km) derived from the mean P_n residuals by assuming the velocities of the lowermost crust and uppermost mantle as 6.0 and 7.7 km/sec, respectively. Boundaries between the positive and negative ones are represented.

The Pacific Ocean side of Northeast Japan is characterized by the thin crust, and the thick crust is found in the Kyushu, Kinki and Chubu districts and on the Japan Sea side of Northeast Japan. A region of relatively thicker crust, exceeding 10 km, extends from the mountain region of Central Japan through Niigata Prefecture. Such a feature is not observed in the study of surface wave dispersion (KAMINUMA and AKI, 1964). An extremely thinner crust on the Pacific Ocean side of the Hokkaido district is apparent and might be caused by a deeper penetration of the seismic rays into the high velocity zone in the upper mantle beneath Northeast Japan.



(a) (b) (c)

Fig. 8. Geophysical features in and around the Japanese Islands;
(a) Bouguer gravity anomaly (HAGIWARA, 1967),
(b) crustal thickness derived from the gravity anomaly (KANAMORI, 1963a, b), and
(c) heat flow (UYEDA, 1972).

Fig. 8 shows previous geophysical studies implying regional variations in the crustal structures: (a) Bounguer gravity anomaly (HAGIWARA, 1967, (b) crustal thickness derived from the Bouguer gravity anomaly (KANAMORI, 1963a, b), and (c) heat flow (UYEDA, 1972). These geographical features are generally consistent with the distribution of the P_n residuals. In the regions of the negative Bouguer gravity anomaly, such as the mountain region in Central Japan, the boarder region of the Kyushu, Shikoku and Chugoku districts, and the Kanto plain, thicker crusts by 10 km or more are observed. The early arrivals or thin crusts observed at Aikawa (AIK) in Sado Island, at Wajima (WAJ) at the northern end of the Noto Peninsula and at Saigo (SAI) in Oki Islands (See Fig. 1) are consistent with the thin crust in the Sea of Japan (the Research Group for Explosion Seismology, 1977). The coastal region on the Japan Sea side is known as a region of high heat flow (UYEDA, 1972; UYEDA and HORAI, 1964), and later P_n arrivals are observed.

Fig. 9 shows the relation between the Bouguer gravity anomaly (Geographical Survey Institute, 1955, 1957, 1964, 1965, 1966) and the P_n residuals obtained in this study. An empirical relation shown by a straight line in the figure is given for the California-Nevada region by PRESS and BIEHLER (1964), but their relation is not held in Japan. Better correlation with the Bouguer gravity anomaly is observed from the P_n residuals

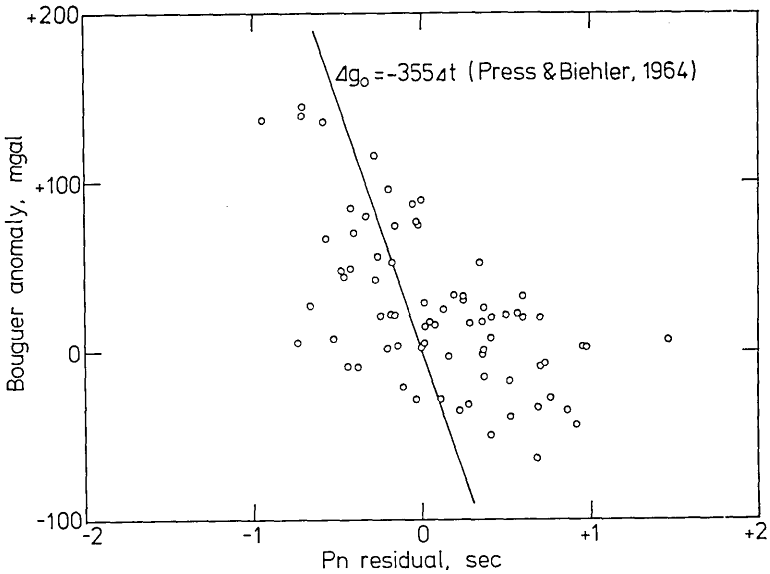


Fig. 9. Relation of the mean P_n residuals and the Bounguer gravity anomaly. Thick line denotes the relation given for the California-Nevada region by PRESS and BIEHLER (1964).

rather than the residuals for the distant and nearby-deep earthquakes (MAKI, 1978, 1979b).

In Fig. 10 the mean P_n residuals are compared with the teleseismic and nearby-deep earthquake residuals at each station. Stations in the Hokkaido district are distinguished by triangles. Nearly identical values of the means P_n residuals suggest that the travel time anomalies from the distant and nearby-deep earthquakes may be attributable mainly to the regional variations in the crustal structure beneath the stations. In the recent study of the travel times from the nearby-deep earthquakes around Japan, UTSU (1975) obtained smaller velocity contrast of about 3% over previous results in the upper mantle around the inclined seismic zone (high velocity zone). Another part of the travel time anomaly from the nearby-deep earthquakes might be caused by the crustal part. Such a result supports the idea of the large effect of the regional variation in the crustal structure.

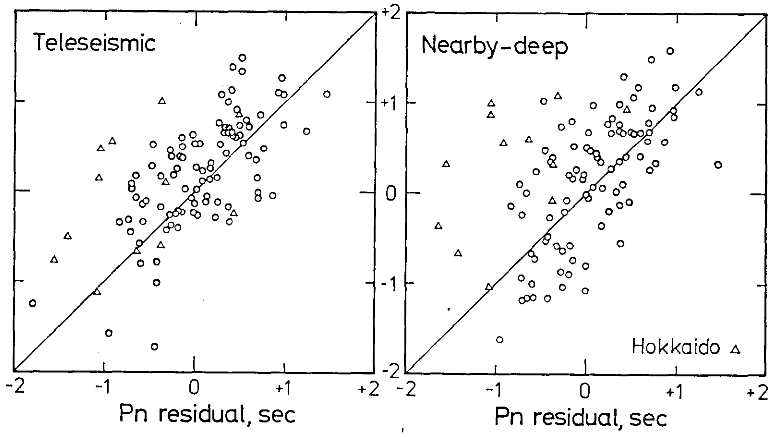


Fig. 10. Comparison of the mean P_n residuals with the teleseismic residuals (MAKI, 1979b) and with the residuals from the nearby-deep earthquakes (MAKI, 1978). Thick lines show the agreement between them. Stations in the Hokkaido region are distinguished by triangles, because they are strongly affected by the high velocity zone beneath Northeast Japan.

IV. Relocation of earthquakes in and around the Kanto district by correcting the P_n residuals

Systematic differences of the hypocenters of deep earthquakes in the vicinity of Japan, determined by various agencies, have been explained by the lateral heterogeneity of the upper mantle (UTSU, 1967, 1971, 1975). UTSU (1975) tried to redetermine hypocenters more accurately by taking into account the lateral heterogeneity.

Hypocenters of the local earthquakes are also affected by the lateral variation in the velocity structure, especially in the crust and uppermost mantle. MAKI (1979a) tried to relocate the local earthquakes in the Kanto district by the Joint Hypocenter Determination method (DOUGLAS, 1967). Maki obtained three kinds of the station corrections for the different classes of focal depths. Station corrections at some stations show a significant variation among the different classes of focal depths as shown by the Research Group for the Travel Time Curve (1967).

It is expected that the application of the station correction will make it possible to determine more accurately the hypocenter and origin times by reducing the standard deviation of the travel time residuals as shown by MAKI (1979a). In this chapter the earthquakes in and around the Kanto district are relocated by using only the P wave travel times corrected for the mean P_n residuals at each station (a computer program called HYPO80).

The JMA located 6657 earthquakes occurring during the 16 years from 1963 to 1978 in the shaded region in Fig. 1. Of these earthquakes, 1972 were excluded because of the small number of P wave travel time data with residuals less than 3 seconds. Relocated hypocenters and origin times of 83 earthquakes used in the analysis of the P_n residuals are listed in the Appendix. Focal depths have been determined to a tenth of a kilometer instead of the 10 or 20 km steps employed by JMA. Significant differences in the focal depths are sometimes observed between those determined by JMA and those relocated.

In Figs. 11a and 11b the geographical distribution of the JMA epicenters and the relocated ones in the present study are compared for earthquakes with focal depths less than 100 km. Radii of circles are proportional to their earthquake magnitude, and focal depths are denoted by the numbers of pairs of sticks for every 20 km. A tendency to cluster within small regions and a reduction in the number of earthquakes are observed off the Pacific coast extending from Ibaraki Prefecture (Kashimanada) to Sagami Bay. In Fig. 12 epicentral distributions of the relocated earthquakes are displayed for three ranges of focal depth, (a) $h=0$—30 km, (b) $h=30$—60 km, (c) $h=60$—90 km. Shallow earthquake activity observed in the off-coast region extending from Ibaraki and Chiba Prefectures, and in the inland region extending from the Izu Peninsula to the western part of Tochigi Prefecture through the eastern part of Yamanashi Prefecture and western part of Saitama Prefecture, where some destructive earthquakes have occurred.

It is a well-known fact that the foci of mantle earthquakes in the

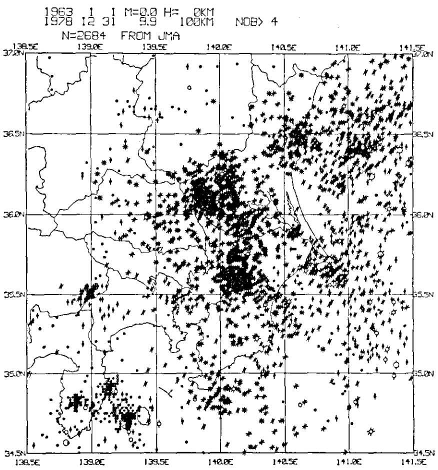


Fig. 11(a).

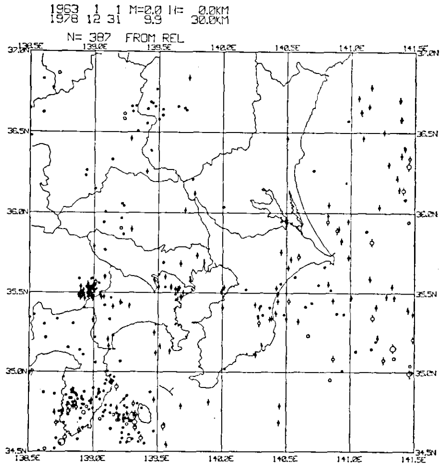


Fig. 12(a).

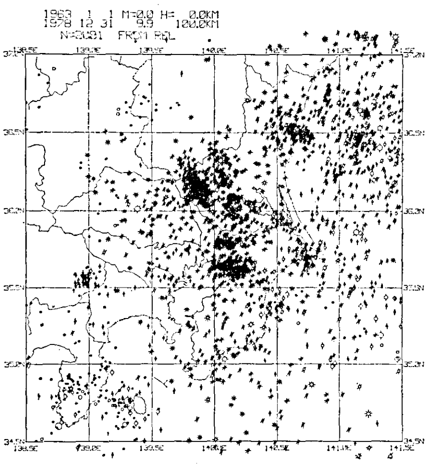


Fig. 11(b).

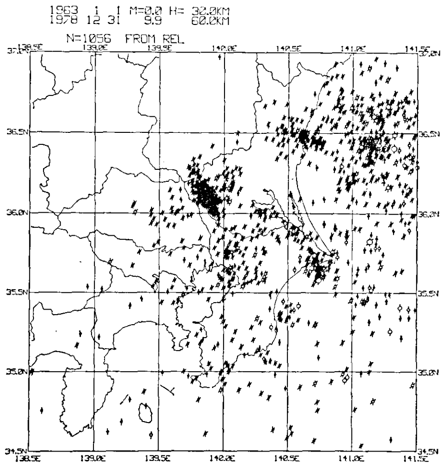


Fig. 12(b).

Fig. 11. Comparison of the epicenters for earthquakes with focal depths from 0 to 100 km given by JMA (a) and those relocated by correcting the mean P_n residuals (b). See Fig. 2 for symbols of focal depths and earthquake magnitude.

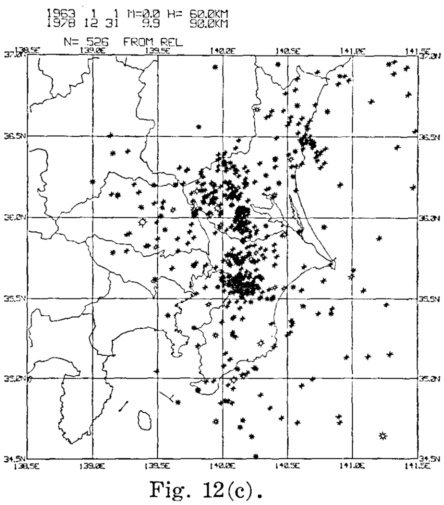


Fig. 12(c).

Fig. 12. Epicenter distributions of the relocated earthquakes for the ranges of depth; (a) h=0-30 km, (b) h=30-60 km, and (c) h=60-90 km. Symbols for depths and magnitudes are the same as in Fig. 2.

Kanto district show a strong tendency to cluster (TSUMURA, 1973 ; USAMI and WATANABE, 1975 ; MAKI *et al.*, 1978). A linear trend of the epicenters in the southwestern end of Ibaraki Prefecture at the depth range from 30 km to 60 km (Fig. 12b) and a significant clustering of the foci in a limited region in the northern and central parts of Chiba Prefecture at the depth range from 60 to 90 km, located just east of the 140°E line, were observed in the present study (Fig. 12c).

In Fig. 13 frequency distribution of focal depths by JMA and those relocated in this study are compared. Although the focal depths by JMA have been represented in 10 km steps in the recent years and in 20 km steps in earlier years, significant differences have not been observed as stated by AKI (1965) in general. Two peaks around 50 km by JMA were not observed in those relocated.

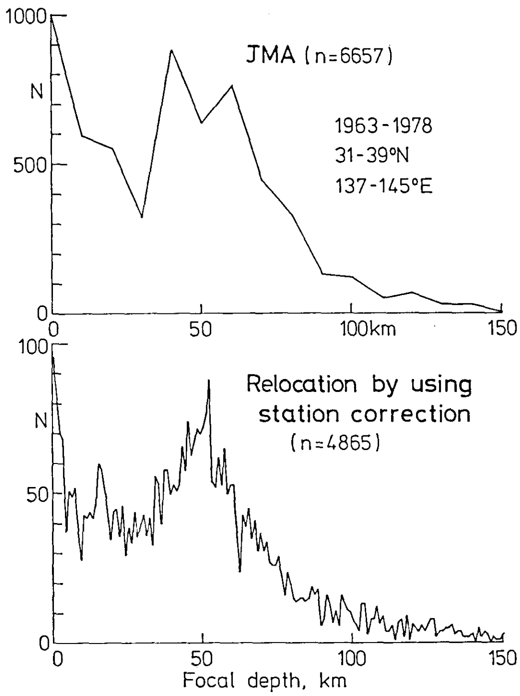


Fig. 13. Comparison of the frequency distributions of focal depths given by JMA (upper) and those relocated in the present study by correcting the mean P_n residuals (lower).

In Fig. 14 the vertical distributions of hypocenters are shown for the E-W section from 139°E to 141°E along the latitude of 36°N (a) and 35°N (b), and for the N-S section from 34°N to 37°N along the longitude of

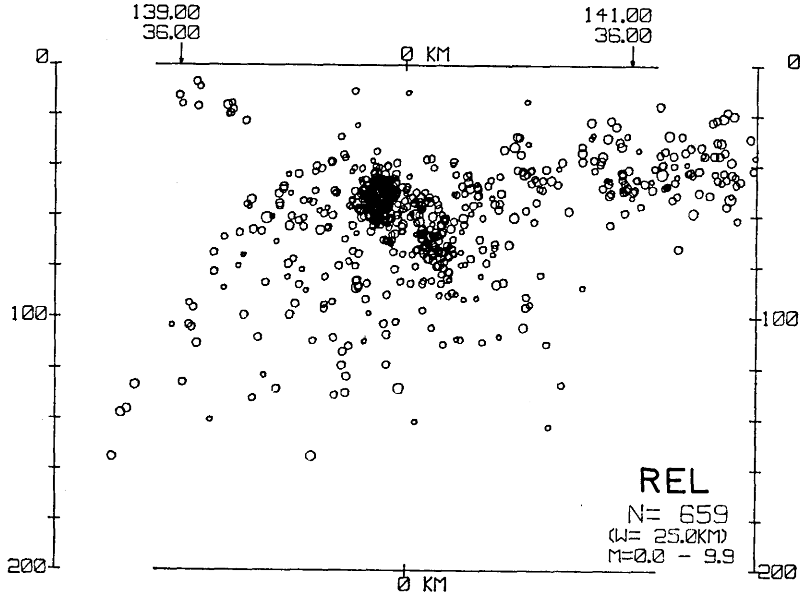


Fig. 14(a).

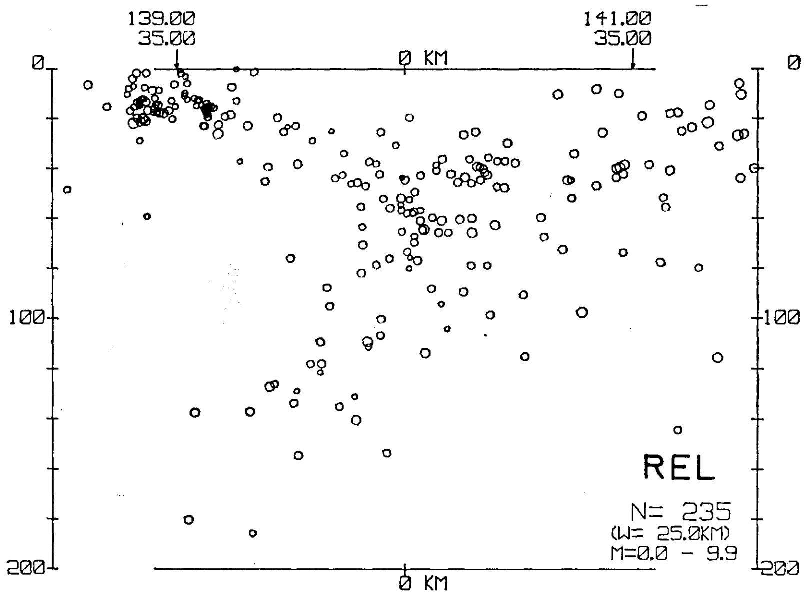


Fig. 14(b).

Fig. 14. Depth distributions of the relocated earthquakes along the E-W sections through the latitude of 36°N (a) and 35°N (b), and N-S sections through the longitude of 141°E (c) and 140°E (d).

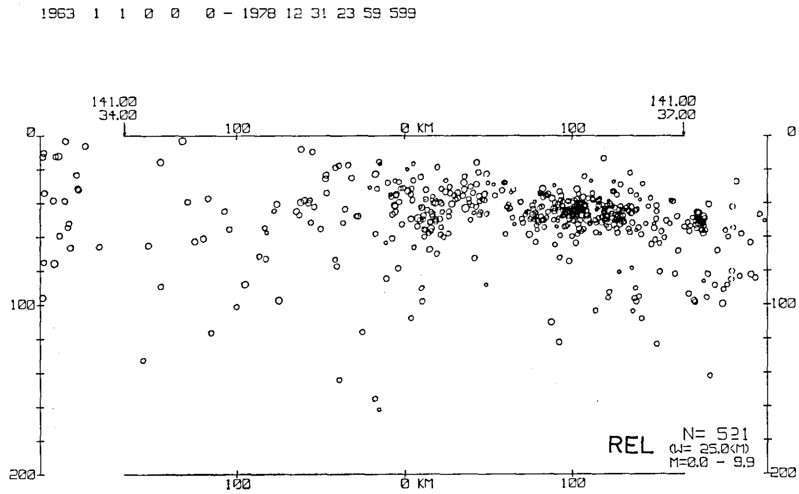


Fig. 14(c).

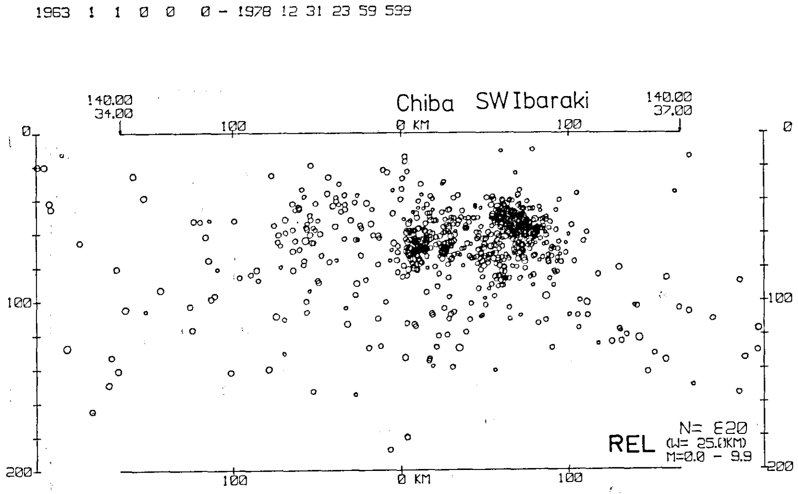


Fig. 14(d).

141°E (c) and 140°E (d). Other than the major seismic zone associated with the descending Pacific Plate from the east to the west, a minor seismic zone dipping to the east is recognized south of 36°N or beneath Chiba Prefecture. A tendency of westward thickening of the major seismic zone dipping from the east is observed (Figs. 14c and 14d).

V. Regional variation in the velocity structure of the lowermost crust and uppermost mantle

Travel time anomalies associated with the high velocity zone in the descending Pacific Plate have been noticed and an attempt has been made to explain them by constructing the velocity profiles with depths (TADA, 1972; NAGAMUNE, 1973; SUZUKI, 1978) or the travel time table for a particular region (ICHIKAWA, 1978). On the other hand, lower velocities in the lowermost crust and uppermost mantle have also been observed. According to the geothermal study in and around Japan (UYEDA and HORAI, 1964), lower velocities in the lowermost crust and uppermost mantle beneath the Japanese Islands are controlled mainly by the thermal condition in the lowermost crust and uppermost mantle.

Lower P_n velocities around 7.5 km/sec were observed in the inland regions of Japan (AOKI *et al.*, 1972; YOSHII and ASANO, 1972). For the refraction measurements along the 139°E line the P_n velocity could not be determined because the values of the refraction veiocity were too low, e.g. 6.82 km/sec by HOTTA *et al.* (1964) and 6.6 to 6.8 km/sec by ASADA and SHIMA (1968). Such velocities suggest the existence of an unusually thick "intermediate layer" (KANAMORI, 1963b, c) along the 139°E line. Recently HASHIZUME and MATSUI (1979) pointed out a gradual increase rather than a sharp contrast in the velocity variation with depths around the Moho discontinuity beneath Southwest Japan.

ARCHAMBEAU *et al.* (1969) showed a strong lateral variation in the P wave velocity in the upper mantle down to about 200 km in the tectonic region of the United States. They explained it by the regional variations in the depth, thickness and velocity contrast of the low-velocity zone and transition zones around the discontinuities in the upper mantle.

In the present study a variety of travel time curves are observed for the earthquakes in and around the Kanto district. In this chapter some velocity models of the lowermost crust and uppermost mantle will be constructed tentatively for some typical travel time curves, comparing with the standard ones adopted by JMA (ICHIKAWA and MOCHIZUKI, 1971; ICHIKAWA, 1978).

The relation of velocity gradients with depths and P_n velocities is shown in Fig. 15. A decrease of the velocity gradients with increasing P_n velocity indicates the existences of a slow increase in the velocity with depths from higher velocity and an abrupt increase from lower velocity to the nearly same velocity in the uppermost mantle. Such types of velocity variations are shown schematically in the insert of Fig. 15.

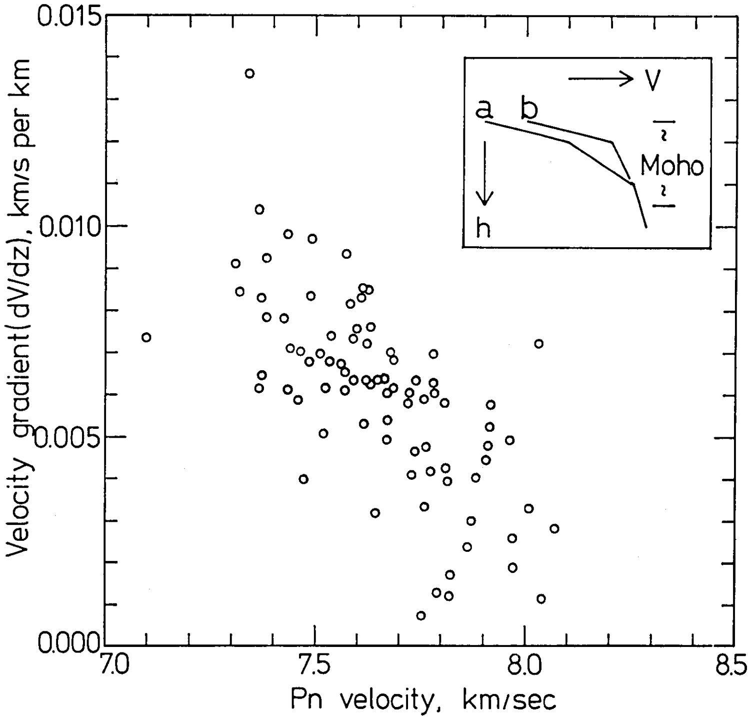


Fig. 15. Relation of the velocity gradients with depths and P_n velocities. Schematic variation of velocity with depths is also shown in the insert.

Shown in Fig. 16 are the depth variation in P_n velocity (a) and velocity gradient (b) with focal depth. Ultimate P_n velocity up to 8.1 km/sec is observed from this figure. A slow increase of the velocity (type b in Fig. 15) suggests the existence of a gradual variation of the velocity around the Moho discontinuity, as preferred by HASHIZUME and MATSUI (1979).

In Fig. 17 reduced travel time are shown for three earthquakes having the typical features of the curves. Their epicenters are shown by asterisks, A, B, C in Fig. 1. Thick lines show the travel time curves fitted by the least squares method, and thin and broken lines denote the reduced travel times from the tables by ICHIKAWA and MOCHIZUKI (1971) and ICHIKAWA (1978), respectively. The former figures represent the average travel times for the Japanese region, and the latter figures apply to the high velocity zone located on the Pacific Ocean side of Northeast Japan.

An example of a travel time curve with the low P_n velocity of 7.44 km/sec is shown in the upper figure of Fig. 17. The epicenter of this earthquake occurring on September 9, 1969 is located in the middle part

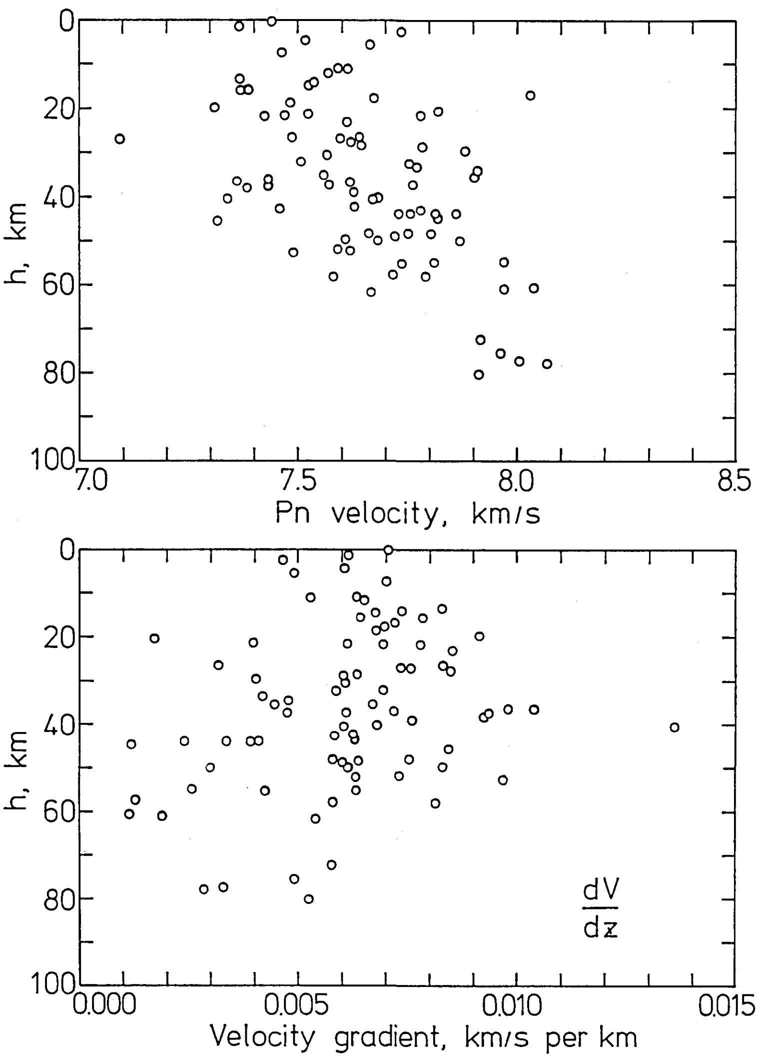


Fig. 16. Depth variation of the P_n velocities (upper) and velocity gradients (lower).

of the Gifu Prefecture, Central Honshu. The middle figure shows an example of an extremely low P_n velocity of about 7.10 km/sec. This earthquake occurred on November 27, 1964 near Sado Island. Such a low P_n velocity was also observed at epicentral distances up to 600 km or to penetration depths of the seismic rays of 60 km. The lower figure shows an example of normal velocity for the Higashi Matsuyama earthquake occurring on July 1, 1968, below the Moho discontinuity in the eastern part of Saitama Prefecture, and the observed travel times are almost identical to those by ICHIKAWA and MOCHIZUKI (1971).

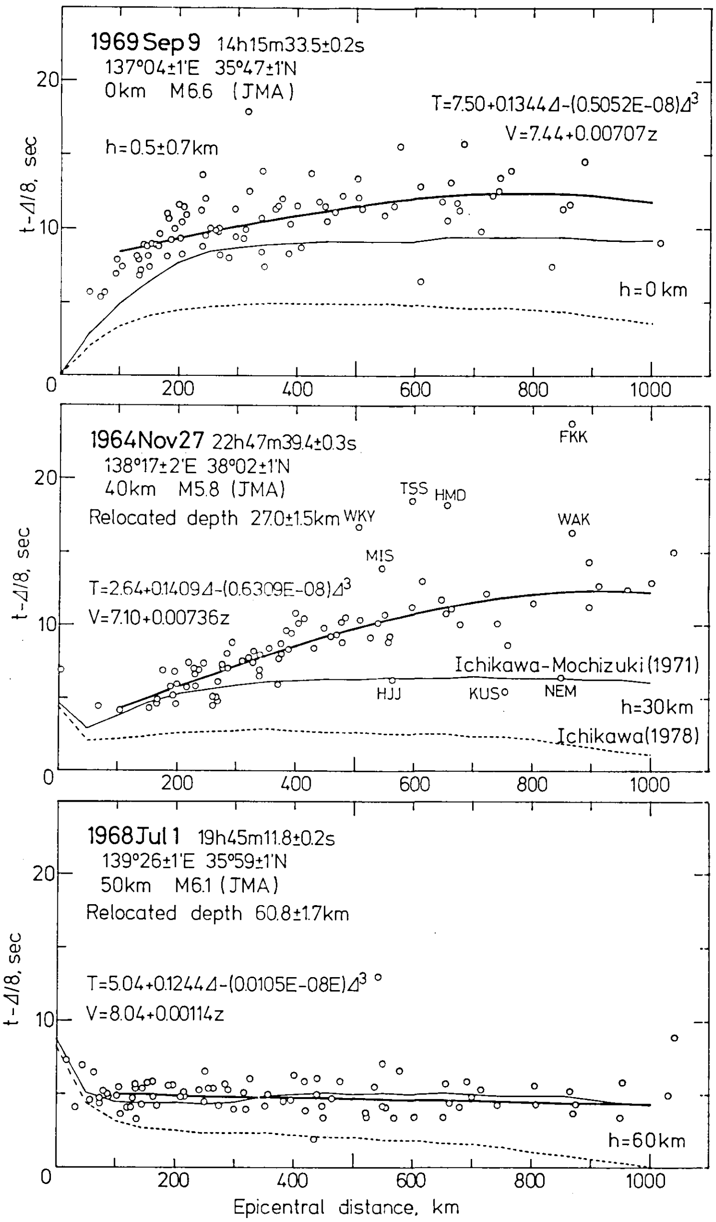


Fig. 17. Reduced travel-time curves showing low P_n velocities. Thick lines show the travel-time curves fitted by the least-squares method, and their travel-time relations and velocity increase with depths are also shown by the formulae. Thin and broken lines show, the reduced travel-times by ICHIKAWA and MOCHIZUKI (1971) and ICHIKAWA (1978), respectively. Focal depths are redetermined by correcting the mean P_n residuals.

(a) Middle Gifu Prefecture Earthquake on September 9, 1969.

(b) Near Sado Island Earthquake on November 27, 1964, and

(c) Higashi-Matsuyama Earthquake on July 1, 1968 (h=60 km), showing the normal P_n velocity.

Accordihg to the seismic ray theory (BULLEN, 1960; JULIAN and ANDERSON, 1968), travel times for given focal depths are calculated for some velocity models. In Fig. 18 the solid symbols show the calculated travel times for the velocity models of ICHIKAWA and MOCHIZUKI (1971) and the open symbols show those of ICHIKAWA (1978). Circles, triangles and squares show the travel times for the three depths of 0, 20 and 40 km, read from the above travel time tables. Ichikawa obtained the travel times by the same method of summation of the travel times over a number of spherical shells 2 km thick as DOWLING and NUTTLI (1964).

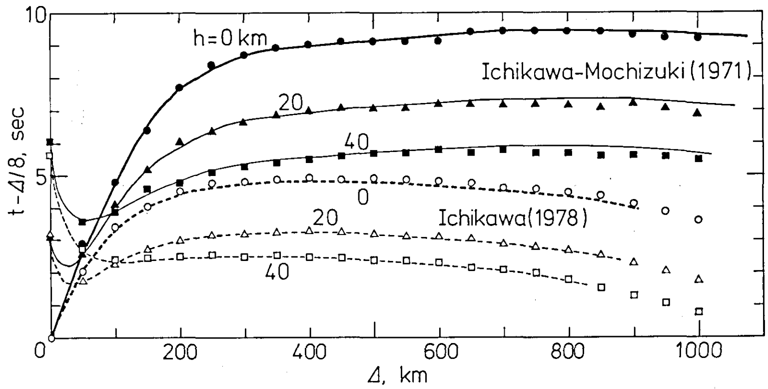


Fig. 18. Comparison of the travel-times for three depths read from the tables (circles, h=0 km; triangles, h=20 km; squares, h=40 km), and for those calculated for the velocities (thick, thin and broken lines) given by ICHIKAWA and MOCHIZUKI (1971) and ICHIKAWA (1978).

Velocity models and their travel times are shown in Fig. 19. Thick lines denote those best fitted to the observed travel time curves, while thin and broken lines show some typical less fitted out of many trials. Shaded areas denote the range bounded by the those of ICHIKAWA and MOCHIZUKI (1971) and of ICHIKAWA (1978). Circles denote the travel times fitted to those observed.

For the travel time curve of the earthquake which occurred in the middle part of the Gifu Prefecture, lower volocities by about 0.4 km/sec were required over the entire depths down to about 100 km (Fig. 19a).

A lower refraction velocity of 7.1 km/sec was observed for an earthquake near Sado Island, Central Japan, at the depth of 27.0 km (Fig. 19b). An apparent velocity of about 7.1 km/sec was observed up to distances of 600 km. Thus an unusually thick "intermediate layer" might be required. Velocity variations with depth were tentatively constructed for this travel time curve (Fig. 19b). The most distinctive feature is the absence

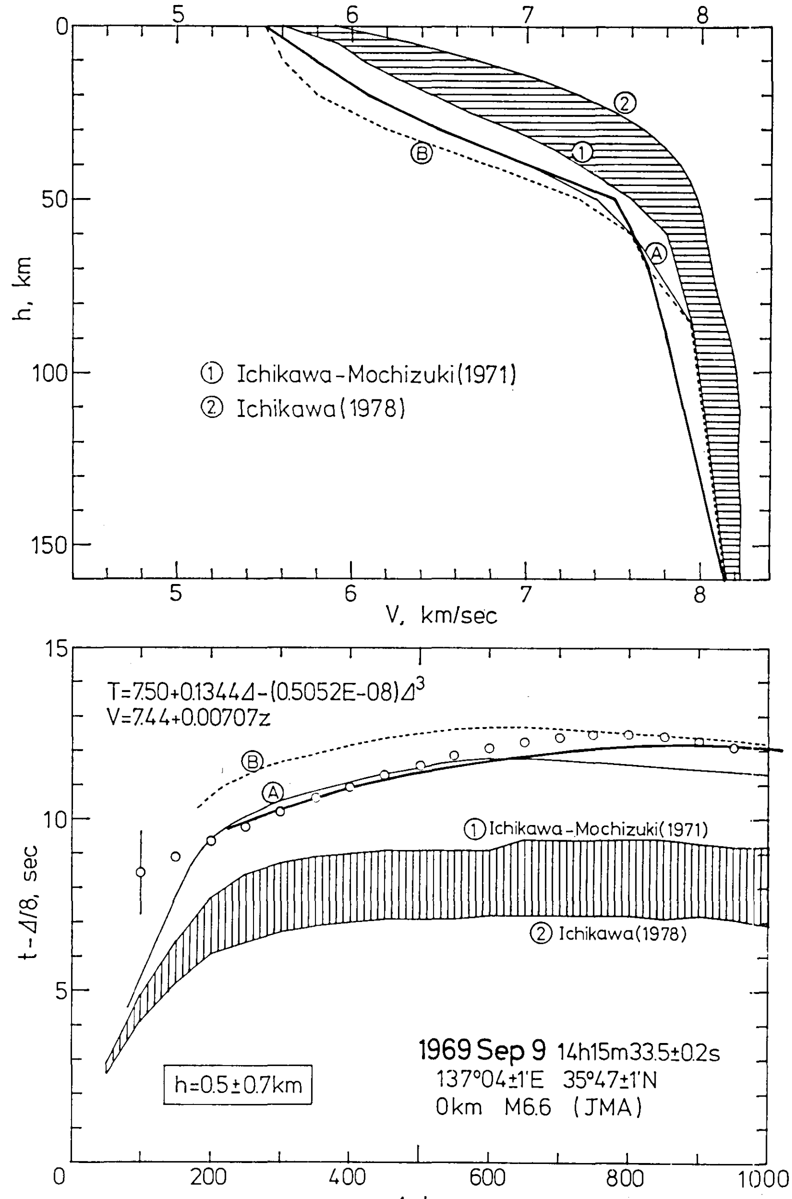
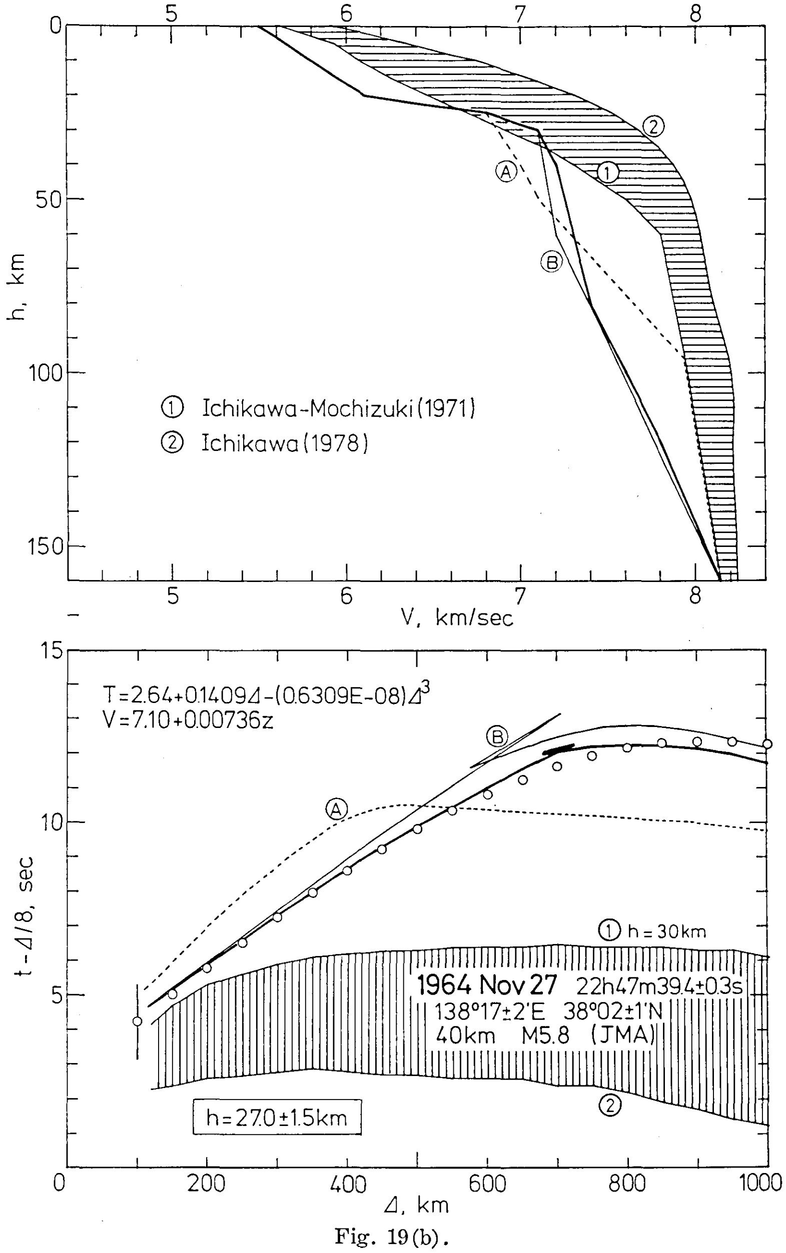


Fig. 19(a).

Fig. 19. Construction of the velocity structure and corresponding travel-times for the low P_n velocities observed for the Middle Gifu Prefecture Earthquake on September 9, 1969, (a), and the Near Sado Island Earthquake on November 27, 1964 (b). Best fitted velocity profiles and their travel-time curves to the observed travel-time curves (open circles) are shown by the thick lines. Other typical trials of the velocity profiles and their travel-times are shown by thin or broken lines. Standard travel-times and their velocity profiles given by ICHIKAWA and MOCHIZUKI (1971) and ICHIKAWA (1978) are also compared.



5
6
7
8
0
50
100
150
h, km
V, km/sec
Ⓐ
Ⓑ
① Ichikawa-Mochizuki (1971)
② Ichikawa (1978)
15
10
5
0
200
400
600
800
1000
Δ, km
t-Δ/8, sec
T=2.64+0.1409Δ-(0.6309E-08)Δ³
V=7.10+0.00736z
① h=30km
1964 Nov 27 22h47m39.4±0.3s
138°17±2'E 38°02±1'N
40km M5.8 (JMA)
h=27.0±1.5km

Fig. 19 (b).

of the Moho discontinuity with normal P_n velocities around 7.7 km/sec. A velocity of 7.4 km/sec was seen up to depths of about 80 km. The refraction velocity of about 7.1 km/sec might correspond to the "intermediate layer" and cannot be recognized as the P_n velocity.

Since this earthquakes is located in the region of the high heat flow, such an extremely low and strange velocity profile may be explained by geothermal anomaly as discussed by UYEDA and HORAI (1974).

VI. Discussion and conclusion

Cubic equations of the travel time curve were estimated from P_n arrivals for 83 well-observed shallow earthquakes which occurred in and around the Kanto district by taking the velocity increase with depths in the uppermost mantle into consideration. The P_n velocity varies from 7.4 km/sec to 8.1 km/sec, and the velocity gradient with depths has a mean of about 0.007 km/sec per km.

Critically speaking, the velocity structure in the lowermost crust and uppermost mantle, especially for P_n velocity, has not been confirmed in Japan owing to the short distances covered by the Research Graup for Explosion Seismology. The use of natural earthquakes can make it possible to study such a velocity structure. However, the errors in hypocenter locations and less accurate data of the travel times limit such studies.

Velocity gradients with depths can not be ignored for longer ranges of the epicentral distances. The existence of a high velocity zone in the upper mantle associated with the descending Pacific Plate also affects the travel time data. The very early arrivals observed at some stations in Hokkaido found in this study were caused by the deep penetration of seismic rays into such a high velocity zone. Some different features of the geographical distribution of the residuals were reported for the different ranges of the focal depths by the Research Group for the Travel Time Curve (1967).

The relation of the velocity gradients with depths and P_n velocities suggests a variety of velocity variations with depths. HASHIZUME and MATSUI (1979) preferred a slow increase in the P wave velocity around the depths of the Moho discontinuity from the refraction data in the Chugoku district, Southwest Japan. The mean value of velocity gradients with depths obtained in the present study, i.e. 0.007 km/sec per km, is lower than the one within the crust given by HILL (1971). The velocity gradients with depths obtained in the present study vary from 0.001 to 0.010

km/sec per km, and this range may be explained by the difference in the thermal gradient by about 20°C/km, as discussed by HILL (1971).

Residuals from the travel time curves fitted to individual earthquakes show geographically sytematic features. Early arrivals are observed on the Pacific Ocean side of Northeast Japan, while late arrivals are observed in Southwest Japan and on the Japan Sea side of Northeast Japan. Exceptionally early arrivals are observed in some parts of the Shikoku and Chugoku districts, as observed for the teleseismic residuals (MAKI, 1979b).

The geographical features of the mean P_n residuals coincide with those of the Bouguer gravity anomaly, crustal thickness derived from the gravity anomaly and surface wave dispersion, and heat flow in and around the Japanese Islands. Finer local variations in the crustal thickness have been tentatively derived from the mean P_n residuals by assuming the velocity contrast between the lowermost crust and uppermost mantle. The northeast extent of a thicker crust region is found in the mountain region of the central Japan. Other regions with the thick crust are also found in the Kanto and Kinki district.

The nearly identical values of the mean P_n residuals with the mean teleseismic and nearby-deep earthquake residuals suggest that most of the travel time anomalies observed in the distant and nearby-deep earthquakes can possibly be explained by the regional variations of the lowermost crust and uppermost mantle structure.

Hypocenters of the earthquakes which occurred in and around the Kanto district were accurately determined by correcting the mean P_n residuals for the observed travel times. Focal depths were determined to a tenth of a kilometer instead of the 10 or 20 km steps adopted by JMA. Relocated epicenters have a tendency of clustering in small regions. Redetermined focal depths are sometimes very different from those of JMA, especially in the case of some shallow earthquakes.

A typical low P_n velocity of 7.4 km/sec is considered to show the lower bound of the velocity structure in the Japanese region. Compared to the standard adopted by JMA, or the ICHIKAWA and MOCHIZUKI's model (1971), lower velocities by about 0.4 km/sec are required for the entire depths down to about 100 km. Such low velocities differ by about 1.0 km/sec from the high velocity model by ICHIKAWA (1978) in the depth range down to 50 km. For the depth range from 50 to 150 km, less variabilities of about 0.5 to 0.2 km/sec are observed.

UTSU (1971) showed a velocity difference of 6% between the high and low V zones associated with the descending Pacific Plate beneath the Asian continent. KANAMORI (1968) also showed a velocity contrast of 0.4

km/sec down to 250 km in the upper mantle, and he explained it in terms of a temperature contrast of about 500°C and a partial melting of about 2%.

An unusually thick "intermediate layer" has been suggested for the crustal structure along the 139°E line (HOTTA *et al.*, 1964; ASADA and SHIMA, 1968). It should be mentioned here that the Moho discontinuity could not be detected or well observed. The travel time data for an earthquake which occurred near Sado Island on November 27, 1964, shows an unusually thick "intermediate layer" with a velocity of 7.4 km/sec down to the depth of about 80 km. This suggests the absence of the Moho discontinuity with the normal velocity jump.

A velocity profile which satisfies the travel time curve fitted to this earthquake shows a velocity of 7.1 km/sec at a depth of about 30 km. Velocities greater than 7.4 km/sec are not required even to a depth of 100 km. It is not easy to interpret petrologically such a low velocity as the Moho (P_n) velocity. Other alternative ideas are the absence of the Moho discontinuity and an unusual rise of the low velocity zone of the upper mantle (absence of the lid). For a velocity profile with a pronounced low-velocity zone without the lid, the existence of the extremely high temperature in the lowermost crust and uppermost mantle or a partial melting may be supposed. Since this earthquake is located in the region with the high heat flow, such an extremely low and unsual velocity profile may be explained by the geothermal conditions. According to UYEDA and HORAI (1964) the difference of a unit of heat flow makes it possible to produce a temperature difference of several hundreds degree or a velocity reduction of several tenths of km/sec.

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Appendix. Relocated hypocenters and origin times by using the station corrections of the P_n travel-times.

NO	DATE Y	M	D	ORIGIN TIME H	M	SEC	LONGITUDE DEG	LATITUDE DEG	DEPTH KM	MAG	RESIDUAL SEC	NR/NU
1	1963	MAY	8	19	22	8.31+/-0.28	141.321+/-0.008	36.407+/-0.008	37.5+/- 2.4	6.1	0.06+/-0.91	100/ 78
2	1963	JUN	3	16	35	50.30+/-0.26	138.722+/-0.007	34.041+/-0.006	29.8+/- 1.7	5.9	0.0 +/-0.80	93/ 75
3	1963	AUG	15	15	11	31.78+/-0.34	141.966+/-0.007	37.695+/-0.008	40.7+/- 2.5	6.6	0.0 +/-0.83	101/ 79
4	1964	FEB	5	20	30	15.44+/-0.18	141.103+/-0.007	36.421+/-0.008	44.1+/- 2.2	6.0	0.03+/-0.77	90/ 65
5	1964	MAR	1	0	20	6.21+/-0.91	142.137+/-0.008	34.793+/-0.009	2.6+/- 2.8	5.5	0.0 +/-0.79	69/ 53
6	1964	APR	16	10	4	27.66+/-1.05	143.045+/-0.007	36.941+/-0.010	5.7+/- 2.3	6.0	-0.01+/-0.82	86/ 69
7	1964	MAY	30	23	30	43.25+/-0.23	141.439+/-0.008	36.143+/-0.008	52.8+/- 3.2	6.2	0.01+/-0.87	97/ 72
8	1964	JUN	16	13	1	40.61+/-0.25	139.268+/-0.010	38.343+/-0.008	21.9+/- 1.0	7.5	0.01+/-0.92	105/ 73
9	1964	JUN	16	15	53	8.77+/-0.69	139.348+/-0.011	38.529+/-0.009	37.4+/- 1.7	6.1	0.0 +/-0.80	72/ 47
10	1964	JUN	16	16	14	58.75+/-0.66	139.428+/-0.013	38.377+/-0.010	15.8+/- 1.2	6.1	0.06+/-1.00	80/ 50
11	1964	JUL	12	10	45	26.68+/-0.49	139.332+/-0.010	38.548+/-0.008	12.1+/- 0.9	6.0	0.0 +/-0.88	87/ 67
12	1964	NOV	27	22	47	41.75+/-0.21	138.520+/-0.011	37.935+/-0.008	27.0+/- 1.5	5.8	0.05+/-0.92	87/ 60
13	1964	DEC	9	2	49	42.95+/-0.22	139.285+/-0.008	34.574+/-0.007	15.8+/- 1.4	5.8	0.05+/-0.78	86/ 49
14	1965	APR	6	14	31	59.59+/-0.11	139.958+/-0.009	36.058+/-0.009	61.9+/- 2.0	5.5	0.0 +/-0.83	72/ 58
15	1965	APR	20	8	41	59.06+/-0.13	138.226+/-0.008	34.825+/-0.008	35.5+/- 1.7	6.1	-0.06+/-0.93	89/ 79
16	1965	SEP	18	0	18	35.27+/-0.41	141.511+/-0.009	36.300+/-0.009	36.7+/- 3.2	5.7	0.0 +/-0.81	57/ 47
17	1965	SEP	18	1	21	17.97+/-0.36	141.520+/-0.007	36.294+/-0.008	40.4+/- 2.9	6.7	0.01+/-0.84	92/ 73
18	1965	SEP	23	7	7	58.96+/-0.43	141.598+/-0.007	36.374+/-0.009	37.0+/- 2.6	6.2	0.0 +/-0.91	96/ 79
19	1965	NOV	6	17	57	12.18+/-0.31	138.998+/-0.008	34.028+/-0.007	27.7+/- 2.2	5.6	0.0 +/-0.81	66/ 59
20	1965	NOV	14	14	54	12.42+/-0.27	141.323+/-0.008	36.490+/-0.008	40.5+/- 2.6	5.6	0.01+/-0.81	76/ 57
21	1966	APR	3	13	43	38.30+/-0.25	141.132+/-0.007	36.584+/-0.008	48.7+/- 2.5	5.8	0.0 +/-0.79	82/ 66
22	1966	APR	22	0	45	22.35+/-0.49	142.084+/-0.008	35.607+/-0.011	52.0+/- 5.2	5.8	0.0 +/-0.82	57/ 47
23	1966	MAY	15	1	59	49.05+/-0.25	138.990+/-0.008	34.070+/-0.006	26.7+/- 1.7	5.4	0.0 +/-0.71	69/ 55
24	1966	MAY	15	2	3	54.39+/-0.31	138.973+/-0.010	34.057+/-0.007	23.2+/- 1.9	5.5	0.0 +/-0.82	63/ 48
25	1966	DEC	27	10	22	17.44+/-0.19	141.145+/-0.010	37.102+/-0.009	48.3+/- 2.8	5.5	0.01+/-0.92	71/ 57
26	1967	JAN	17	20	59	28.06+/-0.84	142.473+/-0.009	38.198+/-0.009	17.0+/- 1.8	6.3	0.04+/-0.92	92/ 68
27	1967	APR	6	15	17	29.63+/-0.21	139.129+/-0.007	34.236+/-0.007	32.7+/- 1.8	5.3	-0.02+/-0.74	68/ 59
28	1967	APR	7	8	23	52.03+/-0.27	139.144+/-0.009	34.261+/-0.008	29.0+/- 2.1	5.2	0.01+/-0.93	70/ 63
29	1967	SEP	15	9	28	38.26+/-0.22	140.781+/-0.009	35.648+/-0.010	55.4+/- 2.7	5.6	0.0 +/-0.87	72/ 55
30	1967	NOV	4	22	26	45.69+/-0.41	141.889+/-0.007	37.303+/-0.008	33.6+/- 2.4	5.8	0.04+/-0.75	77/ 59
31	1967	NOV	19	21	7	0.31+/-0.17	141.191+/-0.006	36.482+/-0.007	50.1+/- 2.3	6.0	0.03+/-0.70	88/ 76
32	1968	APR	21	17	34	0.88+/-0.27	143.336+/-0.005	38.604+/-0.007	58.1+/- 4.0	5.8	0.0 +/-0.52	64/ 51
33	1968	JUL	1	19	45	12.13+/-0.08	139.384+/-0.007	35.973+/-0.007	60.8+/- 1.7	6.1	0.01+/-0.78	88/ 79
34	1968	JUL	5	20	28	10.31+/-0.67	142.384+/-0.009	38.420+/-0.011	21.7+/- 2.4	6.4	0.02+/-0.90	86/ 63
35	1968	AUG	8	13	55	8.35+/-0.33	141.587+/-0.006	36.323+/-0.008	36.3+/- 2.5	5.6	0.0 +/-0.69	68/ 57
36	1968	AUG	16	19	39	13.38+/-2.26	143.761+/-0.008	38.512+/-0.011	27.1+/- 3.6	5.9	-0.05+/-0.81	61/ 54
37	1969	JUL	23	22	14	34.13+/-0.32	141.656+/-0.008	37.313+/-0.010	38.2+/- 3.1	5.5	0.06+/-0.80	64/ 59
38	1969	SEP	9	14	15	35.54+/-0.29	137.057+/-0.007	35.758+/-0.007	0.5+/- 0.7	6.6	0.02+/-0.85	90/ 73
39	1969	OCT	31	16	0	9.23+/-0.90	142.400+/-0.007	37.048+/-0.010	14.4+/- 2.8	5.5	-0.06+/-0.70	54/ 47
40	1970	SEP	14	18	44	52.75+/-0.59	142.353+/-0.009	38.715+/-0.010	30.7+/- 2.5	6.2	-0.03+/-0.85	83/ 63
41	1971	JAN	3	19	11	40.94+/-0.19	138.674+/-0.007	33.641+/-0.007	55.3+/- 4.4	5.5	0.06+/-0.71	67/ 58
42	1971	JAN	5	6	8	53.05+/-0.12	137.172+/-0.007	34.488+/-0.008	44.0+/- 2.0	6.1	0.0 +/-0.76	77/ 62

Appendix. (Continued)

NO	DATE Y	M	D	H	M	ORIGIN TIME SEC	LONGITUDE DEG	LATITUDE DEG	DEPTH KM	MAG	RESIDUAL SEC	NR/NU
43	1971	APR	5	3	39	37.55+/-0.35	142.300+/-0.007	38.368+/-0.008	35.4+/- 2.3	6.0	0.0 +/-0.72	77/ 65
44	1972	MAR	3	5	10	7.75+/-0.43	141.073+/-0.008	33.483+/-0.008	78.1+/- 5.0	5.5	0.0 +/-0.69	60/ 52
45	1972	MAR	19	8	17	33.01+/-2.89	141.921+/-0.011	33.560+/-0.030	44.1+/-25.5	5.7	0.0 +/-0.73	58/ 30
46	1972	OCT	6	20	31	1.81+/-0.17	138.463+/-0.007	34.389+/-0.007	34.6+/- 1.6	5.5	0.0 +/-0.73	69/ 61
47	1972	DEC	4	19	16	8.63+/-0.37	141.118+/-0.006	33.241+/-0.007	61.2+/- 5.6	7.2	0.04+/-0.62	90/ 71
48	1973	JUL	20	17	12	53.89+/-0.20	141.067+/-0.007	36.416+/-0.008	42.5+/- 2.5	5.9	0.0 +/-0.71	65/ 51
49	1973	AUG	24	8	50	29.57+/-0.95	142.250+/-0.009	37.233+/-0.013	20.0+/- 3.0	5.8	0.0 +/-0.82	63/ 54
50	1973	SEP	30	15	17	52.02+/-0.15	140.683+/-0.005	35.655+/-0.007	55.1+/- 2.0	5.9	0.0 +/-0.65	78/ 70
51	1973	OCT	1	23	16	22.75+/-0.23	140.708+/-0.009	35.735+/-0.011	44.2+/- 3.0	5.8	0.03+/-0.96	70/ 59
52	1973	NOV	19	22	1	55.50+/-0.19	142.164+/-0.009	38.902+/-0.009	50.2+/- 2.8	6.4	0.05+/-0.76	70/ 53
53	1974	MAR	3	13	50	49.26+/-0.18	140.737+/-0.007	35.580+/-0.007	49.0+/- 2.2	6.1	0.0 +/-0.69	68/ 55
54	1974	MAY	9	8	33	27.22+/-0.20	138.759+/-0.007	34.558+/-0.007	17.9+/- 1.3	6.9	0.0 +/-0.84	86/ 74
55	1974	JUN	27	10	49	9.21+/-0.20	139.290+/-0.009	33.690+/-0.007	49.8+/- 4.8	6.1	0.0 +/-0.77	64/ 56
56	1974	JUL	8	14	45	37.36+/-0.24	141.247+/-0.006	36.406+/-0.008	39.2+/- 2.4	6.3	0.0 +/-0.74	85/ 70
57	1974	AUG	4	3	16	35.06+/-0.13	139.865+/-0.010	36.069+/-0.010	42.8+/- 2.5	5.8	0.0 +/-0.97	73/ 51
58	1974	SEP	27	12	10	6.72+/-0.21	141.432+/-0.006	33.675+/-0.007	77.5+/- 3.3	6.4	0.0 +/-0.62	81/ 69
59	1974	NOV	16	8	32	42.77+/-0.21	141.134+/-0.005	35.824+/-0.007	43.2+/- 2.1	6.1	0.0 +/-0.62	74/ 65
60	1975	JAN	21	2	31	8.41+/-0.69	141.461+/-0.011	34.991+/-0.012	26.7+/- 3.1	5.9	0.0 +/-0.99	67/ 42
61	1975	APR	2	17	43	58.43+/-0.25	140.775+/-0.007	33.626+/-0.007	75.7+/- 3.8	5.8	-0.10+/-0.85	104/ 90
62	1975	APR	8	15	27	11.06+/-0.46	141.875+/-0.008	37.702+/-0.007	14.6+/- 1.5	5.9	0.0 +/-0.96	104/ 93
63	1975	MAY	4	18	31	58.94+/-0.49	142.058+/-0.006	37.240+/-0.007	13.6+/- 1.6	6.0	-0.01+/-0.84	120/ 85
64	1975	JUN	15	8	36	27.11+/-0.45	143.575+/-0.005	36.277+/-0.007	48.4+/- 5.3	5.9	0.0 +/-0.65	92/ 77
65	1975	AUG	15	3	9	28.58+/-0.13	141.142+/-0.006	37.080+/-0.007	52.3+/- 1.7	5.5	0.0 +/-0.64	68/ 64
66	1976	JUN	4	13	23	30.01+/-0.61	142.829+/-0.009	38.305+/-0.009	1.5+/- 1.8	5.8	0.0 +/-0.91	86/ 57
67	1976	NOV	8	17	19	23.39+/-0.57	142.494+/-0.007	38.032+/-0.008	4.6+/- 1.6	6.2	0.0 +/-0.86	105/ 77
68	1977	FEB	19	5	51	26.86+/-0.31	141.408+/-0.004	32.973+/-0.005	72.5+/- 2.7	5.7	0.0 +/-0.48	118/ 97
69	1977	DEC	17	0	10	28.03+/-0.15	141.163+/-0.006	36.604+/-0.006	44.9+/- 1.9	5.6	0.0 +/-0.79	113/100
70	1978	JAN	14	12	24	38.60+/-0.14	139.305+/-0.005	34.719+/-0.005	20.7+/- 0.8	7.0	0.0 +/-0.76	137/110
71	1978	JAN	15	7	31	46.77+/-0.11	138.816+/-0.006	34.776+/-0.006	21.8+/- 0.9	5.8	-0.02+/-0.76	111/ 93
72	1978	FEB	20	13	36	57.61+/-0.14	142.220+/-0.007	38.775+/-0.006	58.0+/- 2.2	6.7	0.0 +/-0.77	136/102
73	1978	MAR	20	19	24	13.69+/-0.06	139.872+/-0.005	36.091+/-0.005	57.4+/- 1.3	5.5	0.02+/-0.55	88/ 73
74	1978	APR	7	8	29	49.97+/-0.40	141.330+/-0.008	35.148+/-0.008	21.6+/- 1.8	6.1	0.0 +/-0.71	68/ 47
75	1978	JUN	12	17	6	8.66+/-0.59	142.309+/-0.009	38.181+/-0.008	18.8+/- 1.7	5.8	0.0 +/-0.94	84/ 70
76	1978	JUN	12	17	14	26.26+/-0.37	142.136+/-0.007	38.189+/-0.007	32.2+/- 1.9	7.4	0.0 +/-0.82	138/ 95
77	1978	JUN	12	18	12	52.63+/-0.60	142.648+/-0.007	38.381+/-0.008	11.2+/- 1.4	5.7	0.05+/-0.77	82/ 69
78	1978	JUN	12	18	40	29.00+/-0.38	142.346+/-0.009	38.397+/-0.009	37.4+/- 2.4	5.1	0.05+/-0.79	57/ 49
79	1978	JUN	14	20	34	16.44+/-0.53	142.634+/-0.006	38.318+/-0.007	11.2+/- 1.4	6.3	0.03+/-0.80	115/ 96
80	1978	JUN	16	14	33	26.06+/-0.68	143.589+/-0.005	38.178+/-0.007	7.5+/- 1.7	5.9	0.0 +/-0.61	75/ 67
81	1978	JUN	21	19	54	23.50+/-0.24	141.852+/-0.009	38.340+/-0.009	45.8+/- 2.6	5.8	0.05+/-0.84	78/ 62
82	1978	JUN	28	4	10	28.98+/-1.22	143.150+/-0.004	37.158+/-0.006	28.6+/- 3.3	5.9	0.0 +/-0.50	88/ 69
83	1978	OCT	11	10	48	59.61+/-0.16	141.131+/-0.004	33.469+/-0.005	80.4+/- 2.1	5.7	0.0 +/-0.51	91/ 79

16. P_n 走時残差の地域的変化

東京大学地震研究所　牧　　正

P_n 走時を用いて地殻最下部・最上部マントル構造の地域性が調べられた．関東地方周辺に発生した浅い地震のうち，良く観測されている83個の地震の観測走時（気象庁）のデータから，3次項を加えた走時曲線を求めた．平均的な結果として，P_n 速度は 7.4 から 8.1 km/sec，最上部マントルの速度勾配は 0.007 km/sec/km が得られた．走時曲線からの残差（P_n 残差）は観測点下の地殻構造の違いを表わす．一般的傾向としては，東北日本の太平洋側では負の P_n 残差（相対的にうすい地殻），東北日本の日本海側および西南日本では正の P_n 残差（厚い地殻）がみられる．

P_n 残差が，深発地震に対する残差と大体等しいことから，いわゆる“走時異常”の大部分は地殻構造の地域性によると考えられる．

求められた P_n 走時残差を観測走時から補正して関東地方と周辺におこった地震（1963年から1978年，n=4865個）が再決定された．震源の深さが良く決められた．又震央は従来よりせまい範囲に集中する傾向がみられる．

いくつかの走時曲線に対応する速度構造がしらべられた．最も低い P_n 速度 7.1 km/sec が佐渡附近に起こった地震（1964年11月27日，深さ 27 km）にみられた．速度構造は，通常のモホ面がないこと，或いは異常に厚い“中間層”が考えられる．この P_n 速度は 7.4 km/sec（岐阜県中部地震，1969年9月9日，深さ 0.5 km）の走時曲線に対しても，市川，望月（1971）のものより深さ 100 km まで 0.4 km/sec 低い．