BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 57 (1982), pp. 49-82

2. *Effects of Observational Conditions on Hypocenter Location of Intermediate-Depth Earthquakes in Central Japan.*

By Tadashi MAKI,

Earthquake Research Institute, University of Tokyo.

(Received February 16, 1982)

Abstract

Effects of observational conditions (errors in travel times, station numbers, and distance and azimuthal coverages of stations) on hypocenter location have been studied for an intermediate-depth earthquake of September 21, 1971, which occurred at the depth of 190 km beneath Niigata Prefecture, Central Japan.

Distance range and configuration of stations relative to epicenters usually have greater effects on hypocenter location than observational errors in travel times. Especially when determined from station subsets located within limited ranges of azimuth and distance, great shifts are observed in focal depth. Such an effect might be fatal in hypocenter location of microearthquakes by a very small number of stations.

A systematic reduction of travel-time residuals by using station corrections could make it possible to obtain a more accurate hypocenter location, especially in a region of anomalous structure associated with the descending lithospheric plate, such as the Japanese Islands. Differences among the mean residuals at individual stations observed for 40 intermediate-depth earthquakes beneath Central Japan are statististically significant.

1. Introduction

The accuray of hypocenter locations has been represented by the standard errors of focal coordinates (AKI, 1965; SATO *et al.*, 1967; ICHIKAWA, 1969). However, the differences between seismologically determined locations of artificial explosions and true ones often exceed the standard errors of the focal coordinates (RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, 1977; OKADA *et al.*, 1978; YOSHII *et al.*, 1981).

It is also well known that some nuclear explosions, such as the

LONGSHOT, were located at positions different from the true ones by the seismological location methods (FLINN, 1965; HERRIN and TAGGART, 1966, 1968b; CLEARLY, 1967; DOUGLAS, 1967; BLAMEY and GIBBS, 1968; EVERNDEN, 1969a, b; ESPINOSA, 1971).

In order to discuss geometrical features of seismic zones, seismicity gaps and developments of aftershock regions, focal coordinates must be accurately determined. JAMES *et al.* (1969) showed the large instabilities in hypocenter locations, and tried to reduce such instabilities by the prior determination of origin times from the relation of P times with S-P times. Some spurious trends in epicenter distribution might be produced by observational errors in travel times (DEWEY, 1972). In order to reduce location errors, DOUGLAS (1967) proposed the "joint hypocenter determination" method. EVERNDEN (1969a) also developed the "master event" technique. These methods reduce effectively travel-time residuals by correcting the station biases. The station biases in travel times have been obtained by CLEARLY and HALES (1966), DOUGLAS (1967), HERRIN and TAGGART (1968a), UNDERWOOD and LILWALL (1969), LILWALL and DOUGLAS (1970), LILWALL and UNDERWOOD (1970), VEITH (1975), and SENGUPTA and JULIAN (1976) for many stations in the world.

FLINN (1965) employed the confidence region to represent the errors in focal coordinates. His confidence regions were defined by taking account for not only the travel-time errors but also station configuration around the sources. But EVERNDEN (1969a) estimated the probable errors in terms of observational errors in travel times alone, because too large effects were observed for various configurations of network as shown by FLINN (1965). Other methods of estimating errors in focal coordinates were discussed in some different fashions by PETER and CROSSON (1972) and BULAND (1976).

Errors of hypocenter location must be defined by taking observational errors in travel times, conditions of observational stations (number, and distance and azimuth coverages) and variability of the earth's structure around stations, source and along paths into consideration. Regional variations of crustal structure and especially anomalous structure in the upper mantle associated with the descending oceanic lithosphere have large effects on travel time variation and then produce errors in focal coordinates. VEITH (1975) studied the combined effects of the station and source corrections. MITRONOVAS and ISACKS (1971) excluded the anomalous stations for obtaining better hypocentral locations. UTSU (1975) determined hypocenter locations of nearbydeep earthquakes under the Japanese Islands by using station corrections, taking account of the velocity contrast within and around the inclined seismic zones. Statistical studies of hypocenter locations have been made by ICHIKAWA (1975, 1978c) for solving these problems.

In the present study, effects of observational errors in travel-times and conditions of observational stations on hypocenter location will be studied for an intermediate-depth earthquake which occurred beneath Niigata Prefecture, Central Japan, on September 21, 1971. This earthquake was observed by the largest number of stations in recent years in this region. Variation of focal coordinates will be discussed with respect to errors in travel times, station numbers and distance and azimuth coverages of stations. In the remaing part of this paper, the mean residuals at each station for 40 intermediate-depth earthquakes which occurred beneath Central Japan during 12 years from 1965 to 1976 will be studied statistically.

2. Method of hypocentral location and the source of data

The program of hypocenter location was written according to Geiger's method (BOLT, 1960; FLINN, 1960; ENGDAHL and GUNST, 1966). The travel time observed at a station, T, is represented by Taylor's expansion for a given set of focal coordinates (t_o: origin time, z_o: focal depth, Δ: epicentral distance) as follows,

$$T=f(t_o, z_o, \Delta) + \left(\frac{\partial T}{\partial t}\right)_{\Delta, z_o}\delta t + \left(\frac{\partial T}{\partial x}\right)_{\Delta, z_o}\delta x + \left(\frac{\partial T}{\partial y}\right)_{\Delta, z_o}\delta y + \left(\frac{\partial T}{\partial z}\right)_{\Delta, z_o}\delta z \qquad (1)$$

where δt, δx, δy and δz denote adjustments of origin time, distance in longitude and latitude, and focal depth from the given coordinates, respectively. $f(t_o, z_o, \Delta)$ denotes the theoretical travel time derived from the standard travel-time table. In this formula,

$$\frac{\partial T}{\partial t}=-1\,, \quad \frac{\partial T}{\partial x}=-\sin\theta\frac{\partial T}{\partial \Delta}, \quad \frac{\partial T}{\partial y}=-\cos\theta\frac{\partial T}{\partial \Delta}\,, \qquad (2)$$

where θ denotes the azimuth around the epicenter, measured clockwise from the north. Then travel-time residuals, observed at the i-th station of the epicentral distance Δ_i and azimuth θ_i, are represented as follows,

$$r_i=f(t_o, z_o, \Delta_i)-T_i = \delta t+\sin\theta_i\left(\frac{\partial T}{\partial \Delta}\right)_{\Delta_i, z_o}\delta x+\cos\theta_i\left(\frac{\partial T}{\partial \Delta}\right)_{\Delta_i, z_o}\delta y+\left(\frac{\partial T}{\partial z}\right)_{\Delta_i, z}\delta z\,. \qquad (3)$$

Solving by the least-squares method for the observational data set, the adjustments δt, δx, δy and δz from the given coordinates, t_o, x_o, y_o and z_o, are obtained. After some iterations the final solutions are determined when the adjustments become less than 1.0 km for δx, δy and δz, and 0.1 sec for δt.

Partial derivatives of travel times with respect to epicentral distance and focal depth, $\partial T/\partial \Delta$ and $\partial T/\partial z$, were obtained by the numerical differentiation of travel times of ICHIKAWA and MOCHIZUKI's table (1971). The use of smoothed travel-time table prevents the abrupt changes of partial derivatives and then stable locations can be obtained.

The focal depths are determined at intervals of 10 or 20 km by JMA. Such procedure might affect epicentral locations and origin times. In the present study, four focal coordinates are determined simultaneously. Travel-time data are limited to those within a epicentral distance of 500 km

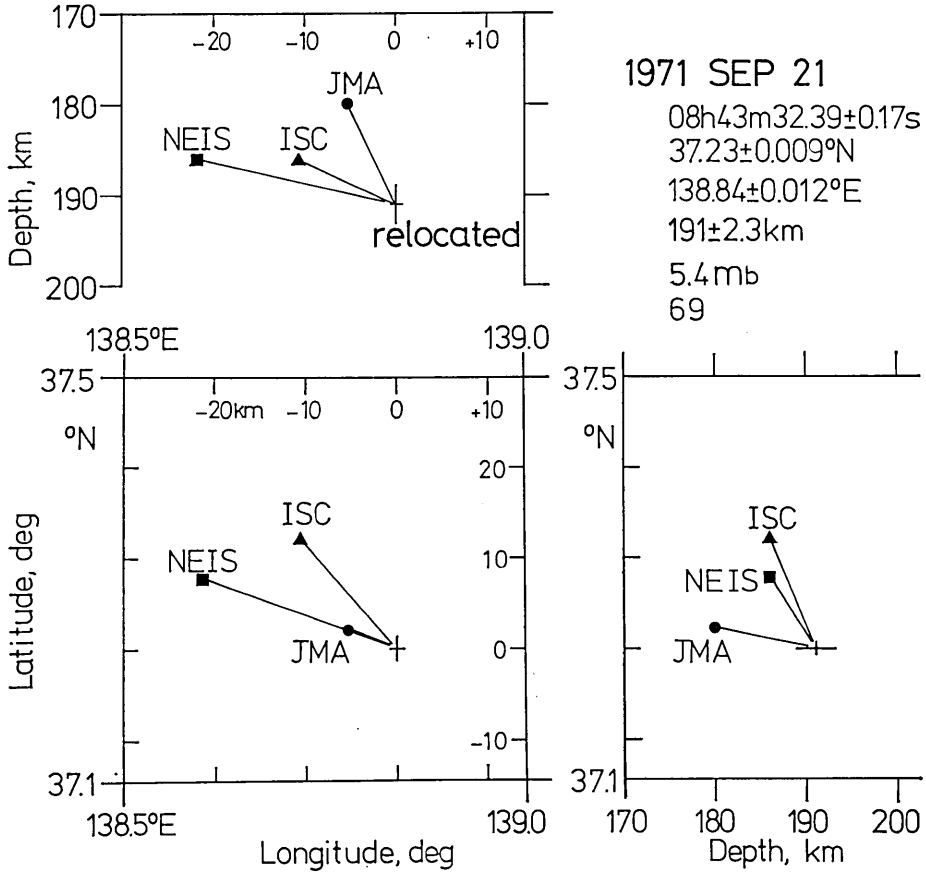

Fig. 1. Comparison of the focal coordinates of an intermediate-depth earthquake on September 21, 1971 beneath Niigata Prefecture, Central Japan. The focal coordinates determined by JMA, ISC and NEIS are represented by the solid circles, triangles and squares with the name of agency, respectively. The redetermined focal coordinates are also denoted by the crosses with different lengths according to their standard errors and are employed as the origin of the coordinates.

or less, and with travel-time residuals of less than 10 seconds.

The focal coordinates (origin time, latitude, longitude and focal depth) of an intermediate-depth earthquake of Niigata Prefecture, Central Japan, on September 21, 1971, determined by the different agencies are compared with the redetermined ones in the present study in Table 1 and Fig. 1. The redetermined focal coordinates are shown by crosses with varied lengths according to their standard errors. The epicenter determined only by the data at nearby stations, or by JMA and the present study, show a shift to the southeast. Shallower depths are found from the teleseismic data, or by ISC and NEIS. The systematic shifts of the epicenters deter-

Table 1. Focal coordinates of the Niigata intermediate-depth earthquake of September 21, 1971, determined by several agencies.

Origin time			Lat (°N)	Long (°E)	Depth	N	Mag	Agency
h	m	s			km			
08	43	32.0±0.076	37.34±0.012	138.72±0.016	186±0.96	273	5.4	ISC
08	43	32.2±0.1	37.25±0.02	138.78±0.02	180		5.7	JMA
08	43	31.9	37.3	138.6	186			NEIS
08	43	32	37.7	138.5	180		5.7	MOS
08	43	32.39±0.17	37.23±0.009	138.84±0.012	191±2.3	63		this study

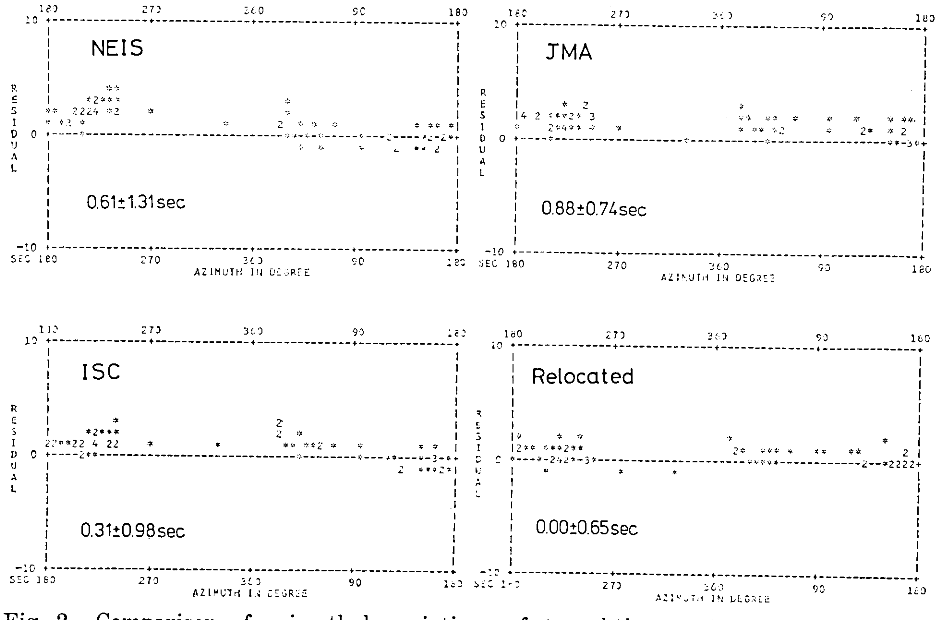

Fig. 2. Comparison of azimuthal variations of travel-time residuals for the focal coordinates determined by NEIS (a), ISC (b), JMA (c) and in this study (d). The mean residuals and standard deviations are shown in each figure.

mined by the nearby and teleseismic data have been indicated for earthquakes arround island arcs by UTSU (1967, 1971, 1975) and MITRONOVAS and ISACKS (1971), and for the LONGSHOT by ESPINOSA (1971).

In Fig. 2 azimuthal variations of travel-time residuals for the focal coordinates by NEIS, ISC, JMA and this study are compared. The mean and standard deviation of travel-time residuals are 0.61 ± 1.31 sec for NEIS, 0.31 ± 0.98 sec for ISC, and 0.881 ± 0.74 sec for JMA, respectively. The least values, or 0.0 ± 0.65 sec, were obtained in this study. The travel-time residuals for the focal coordinates by NEIS and ISC show an azimuthal dependence. The residuals for the focal coordinates by JMA show some bias. This might be due to the depth representation of intervals of 10 or 20 km by JMA. These suggest that focal coordinates are required to be more accurately redetermined.

3. Effects of travel-time errors on hypocenter locations

The observational errors in travel times are one of the major sources of mislocations. In this chapter effects of observational errors in travel times on hypocenter location are studied by supperposing normal random errors to observed travel-time data. For sampling stations uniform random numbers are used, and normal random errors are used for simulating errors in travel times.

The standard deviations of observed travel-time residuals sometimes exceed one second for each earthquake. SATO *et al.* (1967) employed a small standard deviation of 0.1 second and EVERNDEN (1969b) used the one of 0.4 second. ICHIKAWA (1975) showed a standard deviation of 0.2 second for arrival times with clear onsets. However, rather large residuals have also been observed by ICHIKAWA (1965), RESEARCH GROUP FOR THE TRAVEL TIME CURVE (1967), DOUGLAS and LILWALL (1968, 1972), JEFFREYS and SINGH (1973), UTSU (1975), VEITH (1975) and MAKI (1977, 1979). Even for the travel-time residuals from nuclear explosions a large standard deviation of 2.12 seconds has been indicated (LOMNITZ, 1971).

In the simulation study of hypocentral location, ICHIKAWA (1978c) showed that the shifts of hypocentral locations were affected by the amount of standard deviations to be used. In this study standard deviation of 1.0 second will be adopted.

In Fig. 3a azimuthal variations of travel-time residuals are shown. Solid squares denote residuals which are superposed with the random errors to the observed data at stations shown by triangles. Triangles and solid circles are the raw data, and the latter show the ones which are not selected for superposing the random errors. Solid squares and triangles connected by the lines refer to the same stations. In the figure normally distributed random errors are superposed on 40 stations which

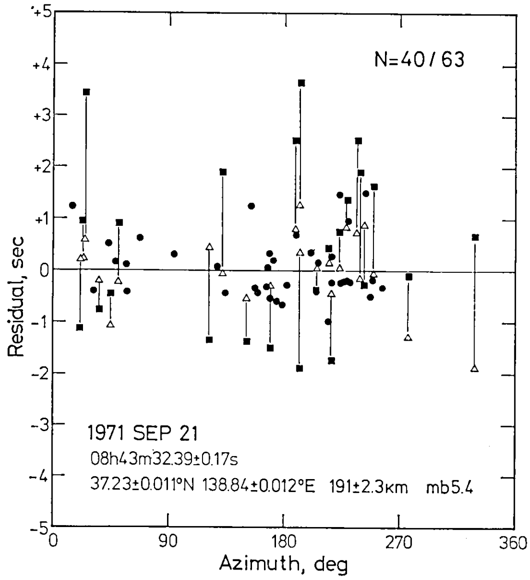

Fig. 3a. Azimuthal variation of travel-time residuals for the focal coordinates obtained in this study. Triangles and solid circles show raw residuals, and solid squares show the residuals superposed with normal random errors (n=40 out of 63 stations).

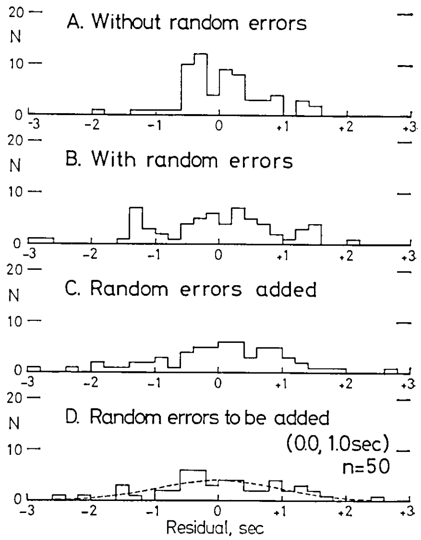

Fig. 3b. Comparison of frequency distributions of travel-time residuals, for the focal coordinates determined by all data (A), (B) residuals superposed with normal random errors shown in (D), (C) residuals for the focal coordinates determined for the case (B), (D) 50 random errors with the mean of 0 second and standard deviation of 1.0 second.

are chosen randomly out of 63 stations.

Fig. 3b shows frequency distributions of residuals in several cases. Case (A) shows frequency distribution of raw data. Case (B) shows the one which is superposed on 50 stations by normally distributed random errors shown in (D) (the mean and standard deviation equal to 0.0 and 1.0 sec). Case (C) shows frequency distribution of residuals for the redetermined focal coordinates by using the residuals of case (B). The mean and standard deviation of residuals change from $\mu=0.04\pm0.65$ sec for case (A), through $\mu=0.22\pm1.13$ sec for the case (B), to $\mu=0.00\pm1.09$ sec for the case (C). These redetermined focal coordinates have the shifts of $dt=+0.2$ second in the origin time, $dx=-0.05°$E in the longitude, $dy=+0.05°$N in the latitude and $dz=+4.9$ km in the focal depth between the case (A) and (C).

Effects of observational errors in travel times on hypocenter location are studied by determining focal coordinates by using travel times superposed with normal random errors as mentioned above. Fig. 4 displays

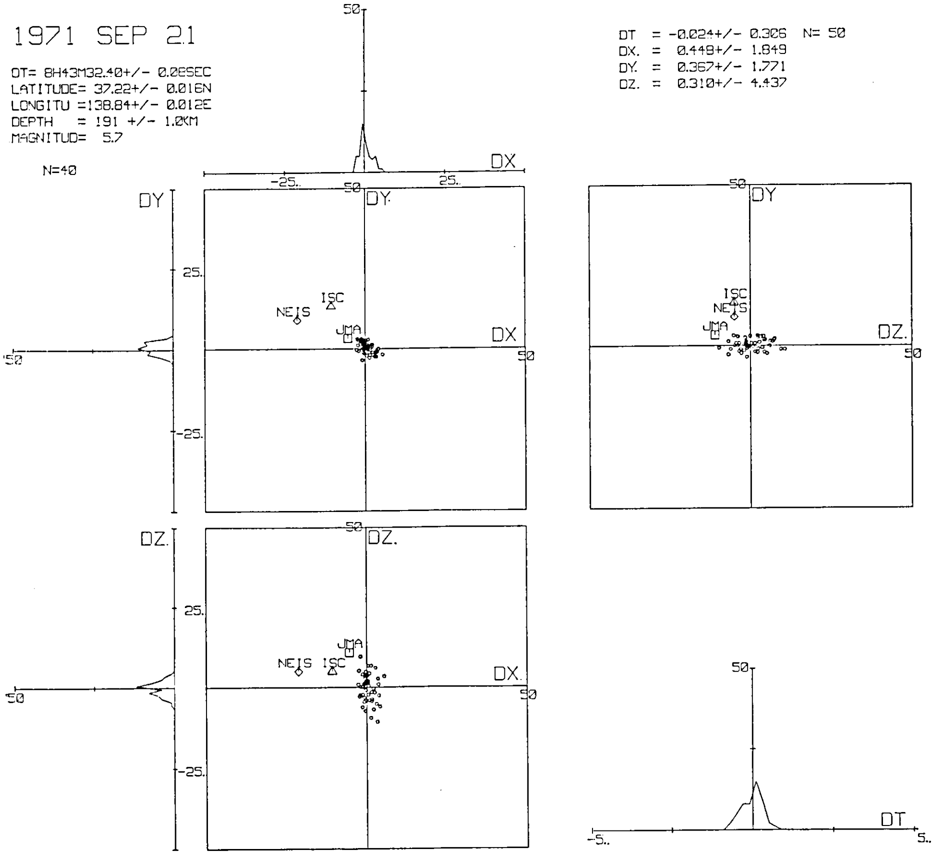

Fig. 4. Shifts in focal coordinates, dx, dy, dz and dt, which are determined for data sets with normal random errors ($\mu=0.0$, $\sigma=1.0$ sec). For each trial, 40 stations are uniformly sampled out of 69 stations. Shifts are measured from the focal coordinates determined by all data. The focal coordinates by JMA, ISC and NEIS are also shown by different symbols. Frequency distributions of shifts are also presented.

the shifts of focal coordinates (dx, difference in the longitude; dy, in the latitude; dt, in the origin time; dz, in the focal depth) determined for travel times superposed by normal random errors with the mean of 0.0 sec and standard deviation of 1.0 second. For each trial 40 stations are selected. Frequency distribution of shifts of focal coordinates (50 trials) appears to be almost normally distributed as shown in the insets of Fig. 4. The mean shifts and standard deviations are also represented in the upper part on the right-hand side. The differences of the focal coordinates determined by several agencies are also denoted by the different symbols. Their shifts are very large and sometimes exceed the range observed for the shifts obtained by superposing random errors. Larger shifts are also

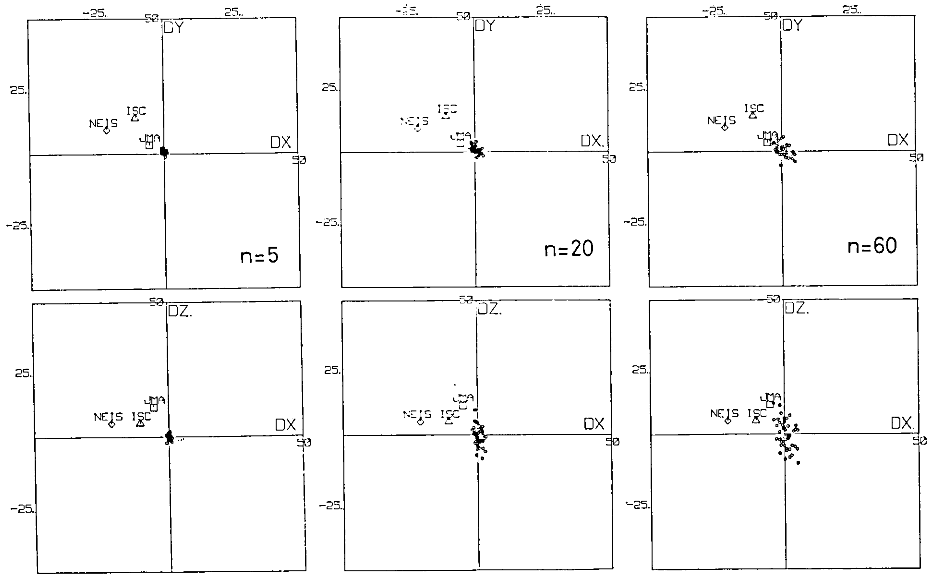

Fig. 5. Variation of epicentral shifts with station number n, to which normal random errors are superposed, (a) n=5, (b) n=20 and (c) n=60.

observed in the focal depths as mentioned by ICHIKAWA (1978c).

Fig. 5 summarizes the shifts in hypocenter location for cases in which the normal random errors with the mean of 0.0 sec and standard deviation of 1.0 second are superposed to various numbers of stations n, (a) $n=5$, (b) $n=20$, and (c) $n=60$. Table 2 also summarizes the mean and standard deviation of these shifts.

In spite of the large standard deviations of 1.0 sec, the mean shifts of focal coordinates are rather small. The standard deviations of shifts

Table 2. Summary of shifts in focal coordinates determined by travel times superposed with normal random errors ($\mu=0.0$, $\sigma=1.0$ sec).

Number of sampling stations	Trials	dt (sec)	dx (km)	dy (km)	dz (km)
1	26	−0.01±0.05	+0.13±0.31	+0.91±0.31	+0.19±0.62
5	34	+0.01±0.09	+0.15±0.52	+0.76±0.68	−0.03±0.95
10	50	+0.01±0.12	+0.23±1.01	+0.70±1.02	−0.12±1.57
20	50	−0.06±0.24	+0.46±1.21	+0.72±1.26	+0.56±3.61
30	50	+0.03±0.23	+0.23±1.40	+0.70±1.59	+0.07±3.32
40	50	−0.02±0.31	+0.45±1.85	+0.37±1.77	+0.31±4.44
50	50	−0.03±0.34	+0.40±2.10	+0.61±2.29	+0.41±5.10
60	50	0.00±0.37	+0.43±2.25	+0.43±2.35	+0.10±5.26
69	50	−0.05±0.39	+0.72±2.42	+0.11±2.80	+0.97±5.41

are comparable to the standard errors of focal coordinates, even for cases where almost all stations are superposed with the random errors. A linear trend of epicenter alignment from the southeast to northwest shows the existence of some correlation between the shifts in the longitude and latitude, as indicated by JAMES *et al.* (1969) and EVERNDEN (1969a). Focal depths are more affected than epicentral coordinates.

The differences of the focal coordinates by NEIS, ISC and JMA are so great that observational errors in travel times alone are not sufficient to estimate errors of hypocenter locations.

4. Effects of station coverages on hypocenter location

Configurations of network, or station number and distance and azimth coverages of stations have some important effects on determination of

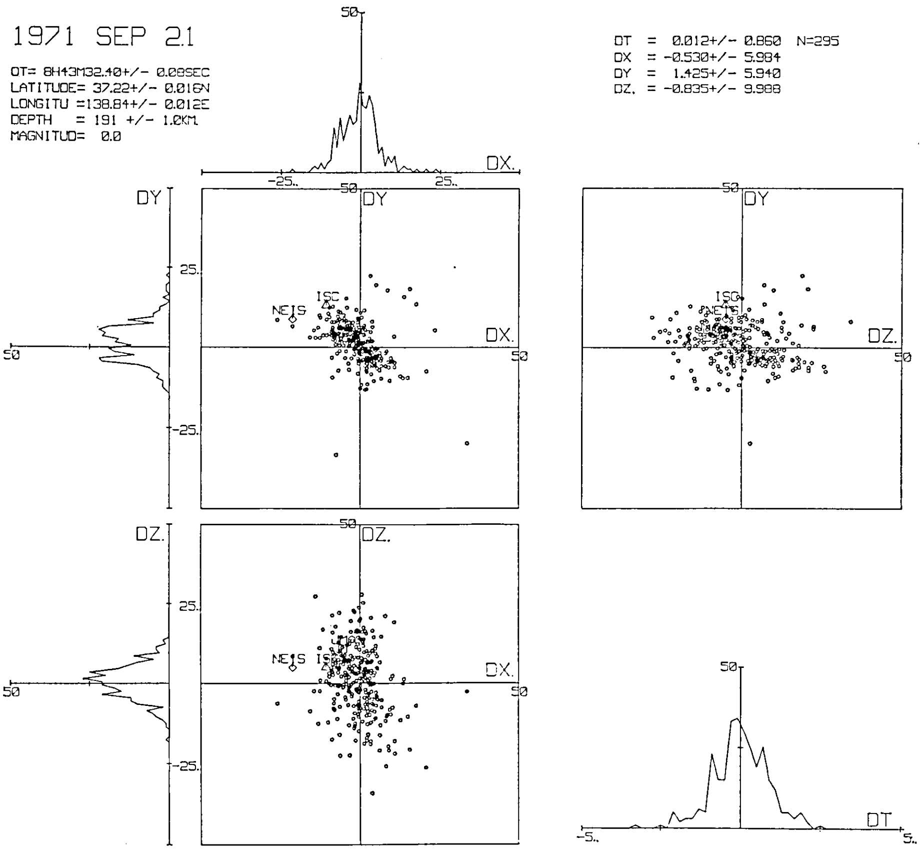

Fig. 6(a)

Fig. 6. Shifts of focal coordinates determined by subsets of n stations, which are selected randomly out of 69 stations, (a) n=10, (b) n=20 and (c) n=30.

focal coordinates. But quantitative estimates of such effects have not been made systematically. EVERNDEN (1969a) preferred the error estimation based on the errors in travel times alone, because of great effects of station configuration as shown by FLINN (1965). The effects of station configuration on hypocenter locations have been indicated for local earthquakes around the San Andreas Fault by JAMES *et al.* (1969), and for the LONGSHOT detonation by ESPINOSA (171) using the teleseismic data.

FLINN (1965) indicated the relation between the errors in epicentral coordinates and station numbers. We occasionally meet with cases for locating earthquakes by using a very small number of travel-time data covering a limited range of distance and azimuth. Different focal coordinates were obtained for two data sets within and without a certain range of distance by JAMES *et al.* (1969) and ESPINOSA (1971). TUCKER *et al.* (1968) indicated that the extension of confidence region increased several times as the number of stations decreased.

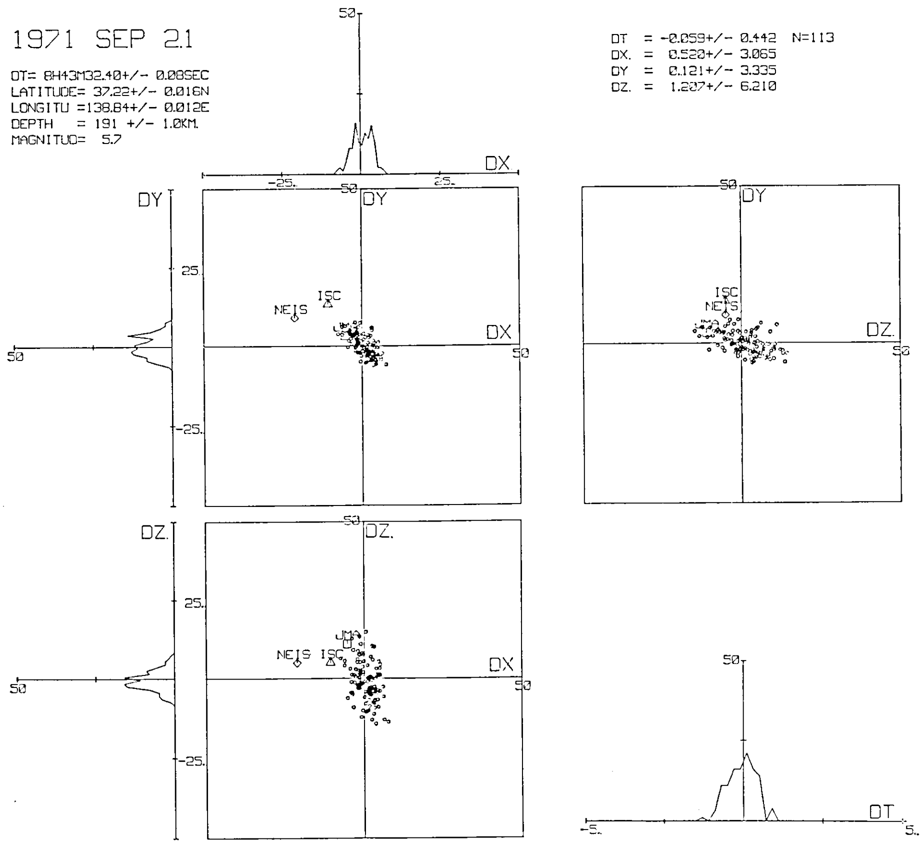

Fig. 6(b)

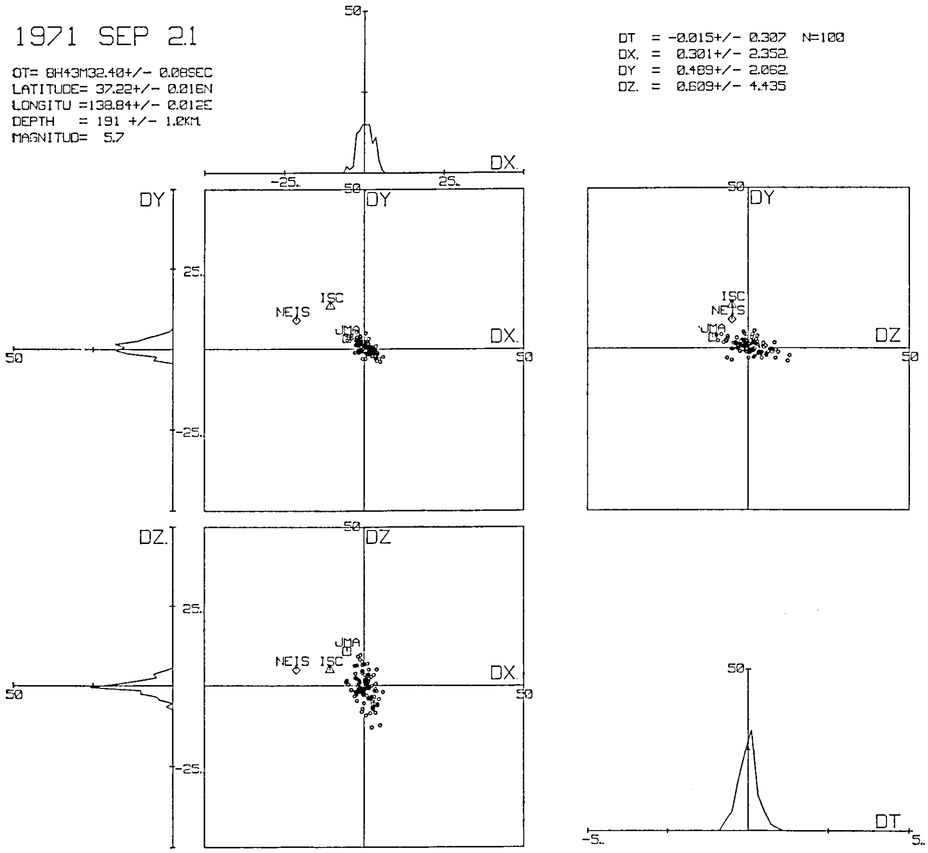

Fig. 6(c)

Shifts in focal coordinates obtained for subsets of various station numbers n are represented in Fig. 6, (a) $n=10$, (b) $n=20$ and (c) $n=30$. These station subsets are randomly selected out of 69 stations using uniform random numbers. Frequency distributions of these shifts are represented in the same figure. The focal coordinates given by NEIS, ISC and JMA are also shown by different symbols. Larger shifts are observed in focal depth. Great differences are observed for some subsets composed of a small number of stations. Dependence between shifts in the longitude and latitude is observed. DEWEY (1972) mentioned that the spurious trend in spatial distribution of earthquakes can be produced by the random errors in P-wave travel times. In Table 3 effects of station numbers on hypocenter location are summarized. A large number of stations tends to show smaller shifts of focal coordinates. On the other hand, greater shifts are observed when a smaller number of stations are used.

In Fig. 7 variations of mean shifts of focal coordinates, dt, dx, dy and

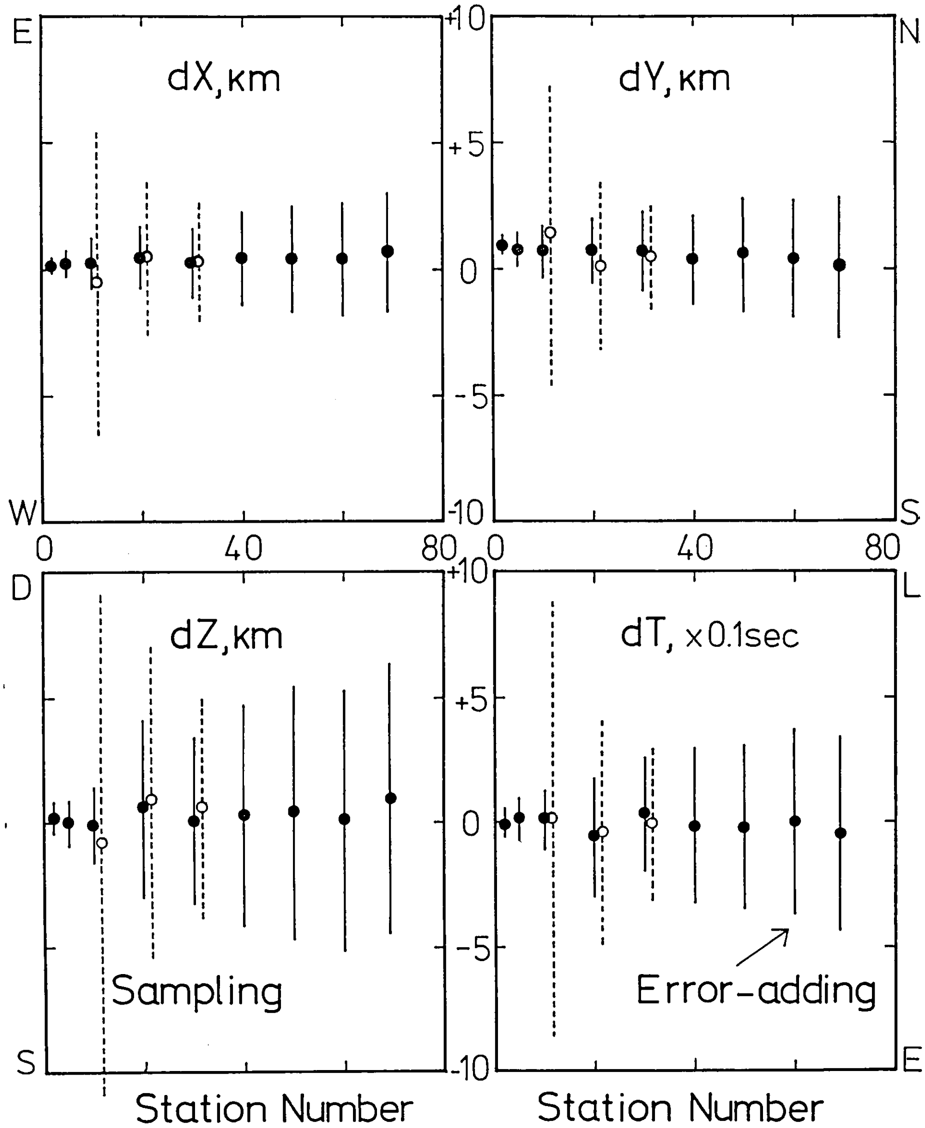

Fig. 7. Summary of the mean shifts (dx, dy, dz, dt) of focal coordinates, determined for travel times superposed with random errors (solid circles), and for subsets of sampled stations (open circles). Standard deviations are represented by solid and broken lines, respectively.

dz, are represented as a function of number of stations selected. Solid circles show the mean shifts for cases where normal random errors are superposed to a given number of stations (ordinates), and open ones denote cases in which station subsets are selected out of 69 stations. Vertical

Table 3. Shifts of focal coordinates determined by subsets of stations sampled out of 69 stations.

	Number of stations sampled		
Shifts	n=10	n=20	n=30
dx (km)	−0.53±5.98	+0.52±3.07	+0.30±2.35
dy (km)	+1.43±5.94	+0.12±3.34	+0.49±2.06
dz (km)	−0.84±9.99	+1.21±6.21	+0.61±4.44
dt (sec)	+0.01±0.86	−0.06±0.44	−0.02±0.31
Trials	295	113	100

bars of solid and broken lines denote the standard deviations for the above two cases, respectively. When the normal random errors are superposed to a large number of stations, large standard deviations are observed. In other words, cumulative effects of observational errors in travel times are predominant for focal coordinates which are determined by a large number of stations. When determined by only a small number of stations, great shifts of focal coordinates are also observed although the probable errors of focal coordinates are very small. The smallest shift by the combined effects are observed for the number of stations from 20 to 30. Such an effective number of stations for the stable location is consistent with the ones by FLINN (1965). UNDERWOOD and LILWALL (1969) also mentioned that 20 to 50 stations in the teleseismic distance are sufficient for the stable location.

In the previous trials several extremely large shifts of focal coordinates have been observed for particular subsets of stations. Also a systematic trend from the southeast to northwest has been observed in the shifts of epicenters. We occasionally meet with locating earthquakes by only travel-time data at distant stations located within a limited range of azimuth, such as earthquakes located far off Northeast Japan. For such conditions some systematic departures from the true positions and spurious trends must exist.

Typical mislocations of explosions detonated at seas were indicated by OKADA *et al.* (1978) and YOSHII *et al.* (1981). They interpreted by distinctive regional variation in crustal structure. In Fig. 8 the geographical distribution of travel-time residuals is represented by different symbols for the Niigata intermediate-depth earthquake. The epicenter is represented by an encircled cross. Earlier arrivals are observed in the coast regions on the Pacific side from the Kanto to Northeast Japan. Later arrivals are observed in Southwest Japan and on the Japan Sea side of Northeast Japan. Other exceptional earlier arrivals are observed in Southwest Japan. Such a systematic distribution of travel-time residuals is interpreted by the existance of the inclined high velocity zone in the

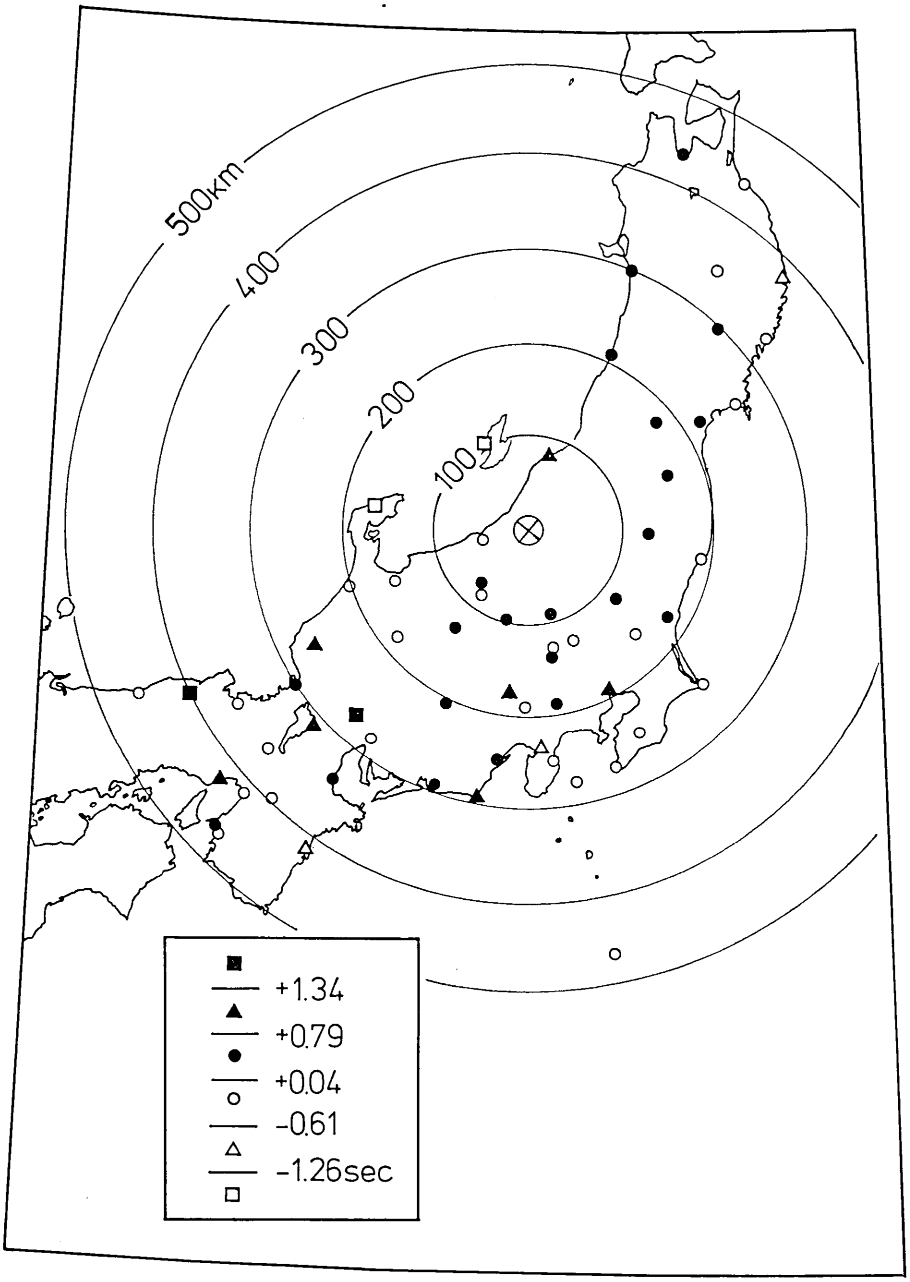

Fig. 8. Geographical distribution of travel-time residuals of the Niigata intermediate-depth earthquake for the focal coordinates determined by all data. Residuals are classified according to departure from the mean, or $\mu=+0.04$ sec.

upper mantle and regional variation in crustal structure.

For smaller earthquakes travel times are observed only at nearby stations. For off-shore earthquakes, as those occurring near the Japan Trench, travel times could not be observed at nearby distances. Japanese stations are located within a narrow range of azimuth for such source regions as the Kurile Islands. Distinct systematic discrepancies in epicentral locations have been indicated by UTSU (1967, 1971, 1975) for deep earthquakes around the Japanese Islands and for earthquakes in the Kurile Islands and Northeast Japan by UTSU (1967) and ICHIKAWA (1978a, b, 1979). Hereafter effects of station coverages in distance and azimuth are studied for data sets as being experienced in practice. Variations of shifts in focal coordinates determined by subset of travel times observed within a limited range of distance is shown in Fig. 9. The left figure shows 22 subsets of stations covering the epicentral distances shown by solid lines assigned with numbers. Broken lines Nos. 14, 20 and 22 denote cases in which focal coordinates could not be determined.

The upper right figure shows shifts in epicentral location. Nearby stations tend to shift epicenters to the northwest and distant stations shift epicenters to the southeast. Such systematic shifts are interpreted by the existence of the high velocity zone in the upper mantle beneath Central Japan associated with the subducting Pacific plate, as mentioned for the Tonga-Kermadec region (MITRONOVAS and ISACKS, 1971).

The lower right figure shows shifts of focal depths. Extremely large differences of focal depths are observed for short ranges of epicentral distance in cases No. 9, 17, 21, 15, 2 and 5. For a subset of stations far from the epicenter (No. 21), which are also located within a narrow range of distance, the shift of focal depth exceeds 50 km. Such large shifts of focal depths have been shown also by HERRIN and TAGGART (1966). Triangles in the figure show shifts for station subsets located in some azimuth ranges. In Fig. 10 focal coordinates determined only by the nearest 5 stations are represented by solid circles marked with "1". A southward shift as large as 80 km was observed for this subset. Residuals of these 5 stations show a distinct azimuthal dependence as represented by the solid circles on the left-hand side of Fig. 10. It seems dangerous to locate only by using such close stations.

Five subsets of stations located within a limited range of azimuth and their epicenter shifts are shown on the right-hand side of Fig. 10 in a different scale from Fig. 9. Larger differences are observed for these azimuth subsets than distance subsets. A tendency of northward shifts is observed for station subsets located on the northern side of the epicenter.

In this chapter effects of conditions of network on hypocenter location have been studied. For data sets from a large number of stations, the

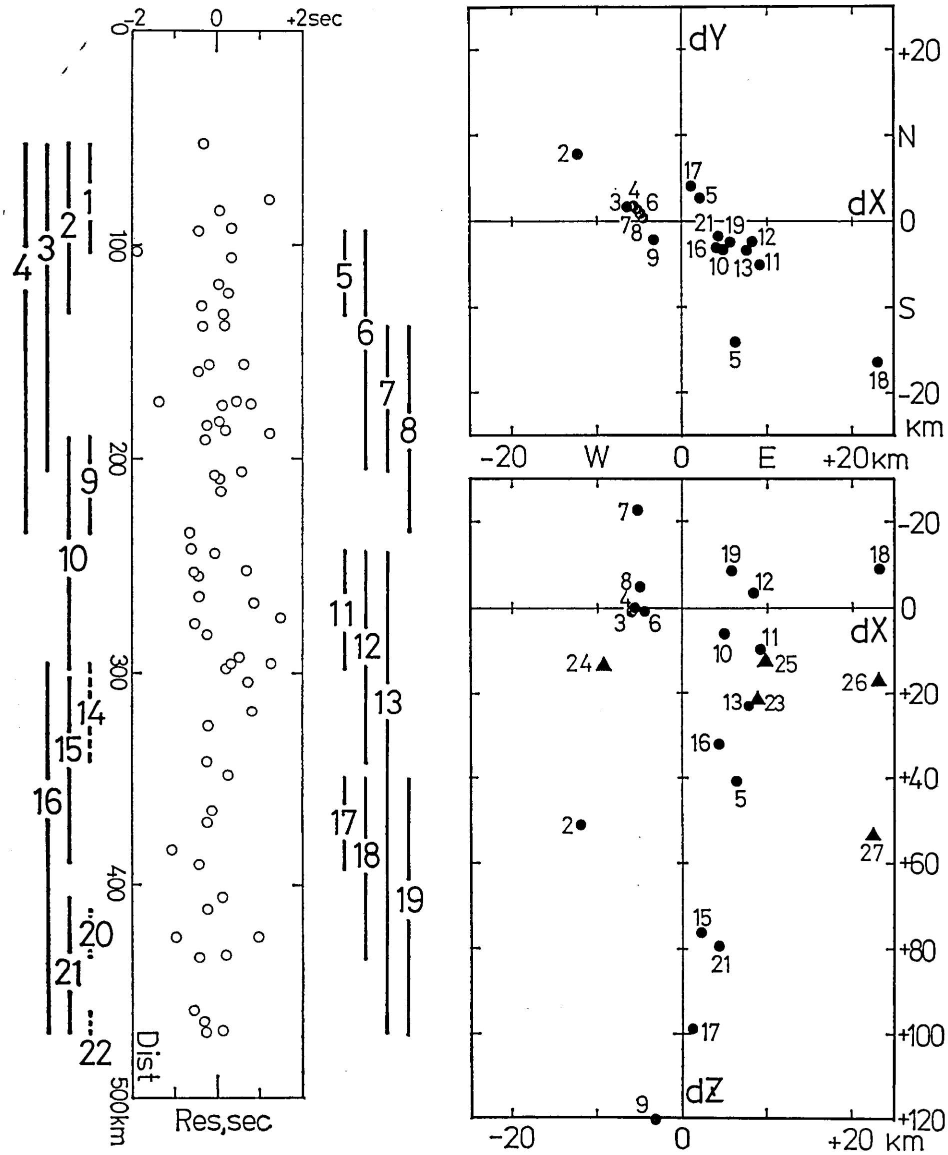

Fig. 9. Shifts in epicenter and focal depth determined for subsets in certain ranges of epicentral distances (solid circles on the right-hand side). The left-hand side shows residuals against distance, and the range of distance of each subset (solid line). Broken lines denote the cases in which the focal coordinates could not be obtained. Triangles denote subsets of stations covering the limited azimuths shown in Fig. 10. Numerals mean the number of trials.

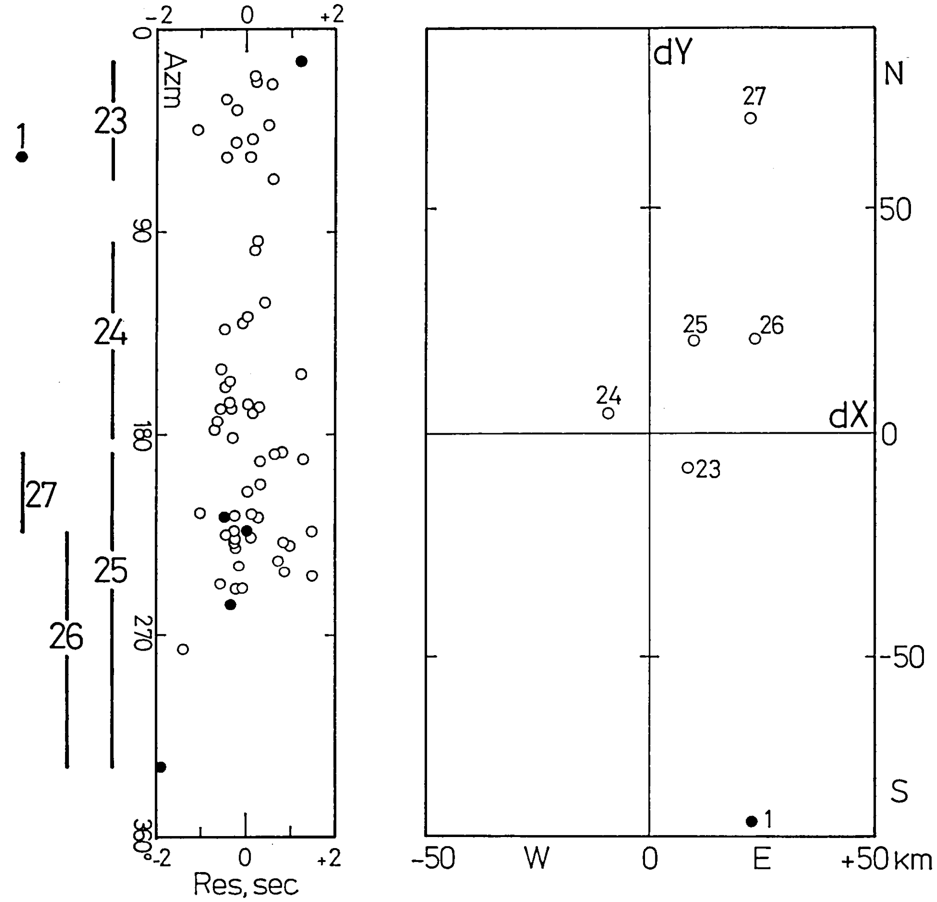

Fig. 10. Shifts in epicenter determined for subsets of stations covering limited azimuths (on the right-hand side). The left-hand side shows the relation between residual and azimuth. Solid circles, marked with "1", are shown for that obtained by the stations nearest from the epicenter.

cumulative effects of observational errors in travel times are predominant. On the other hand, for data sets from a small number of stations, focal coordinates are affected by the individual errors at each station. Smaller shifts by the combined effects may appear in cases where number of stations is about 20 to 30. It might be most dangerous to locate only by using a small number of closest stations. Great differences of the focal depths exceeding 50 km have been sometimes observed for travel times observed within narrow ranges of distance and azimuth.

5. Travel-time residuals for intermediate-depth earthquakes occurring beneath Central Japan

Instabilities in determination of focal coordinates are caused by observational errors in travel times, configuration of network, and the inadequacy of travel-time tables in use. In Central Japan travel-time data are significantly affected by the high velocity zone associated with the subducting lithospheric plate, and then the relation between the errors in hypocentral location and lateral variation in the upper mantle structure must be clarified.

The travel-time residuals are devided into three parts, caused by anomalous structure around stations and sources and along paths. It is rather easy to separate teleseismic travel-time residuals into such parts. The azimuthal variation of residuals was interpreted by regional variations under the stations (BOLT and NUTTLI, 1966; CLEARLY and HALES, 1966; TUCKER *et al.*, 1968; HERRIN and TAGGART, 1968b; LILWALL and DOUGLAS, 1970), and in terms of regional variation of structure near the sources (CLEARLY, 1967; HERRIN and TAGGART, 1968b). HERRIN and TAGGART (1962) interpreted the travel time residuals by the regional variation in *Pn* velocities. Successful use of the station corrections was described by CLEARLY and HALES (1966b), DOUGLAS (1967), LILWALL and DOUGLAS (1970), and DEWEY (1972).

Lateral velocity variation and complicated features of the high velocity zone beneath Central Japan produce a large scatter of travel-time residuals. In such regions it is required to study systematic variation of travel-time residuals. In this chapter, station biases of travel-time data are studied for intermediate-depth earthquakes beneath Central Japan.

The relocated focal coordinates of 40 intermediate-depth earthquakes beneath Central Japan are given in Table 4. These earthquakes were located by more than 20 travel-time data, and with the probable errors of origin time, epicentral distance and focal depth, less than 0.9 second, 5 km and 10 km, respectively. In Fig. 11 their epicenters are represented by different symbols according to the focal depths. Signicant differences of the focal depths from the JMA's one are observed for two earthquakes. The focal depths of 100 km for No. 15 and 110 km for No. 20 by JMA are changed to 90 and 81 km, respectively. Fig. 12a denotes the overall frequency distribution of travel-time residuals obtained for the relocated focal coordinates of these 40 intermediate-depth earthquakes. Fig. 12b denotes the frequency distribution of residual ratios, or the ratios of travel-time residual to calculated travel time.

The mean and standard deviation are equal to $+0.01\pm0.77$ sec for the travel-time residuals, and $-0.06\pm1.94\%$ for the residual ratios. The residuals observed at stations Tokyo (TOK) and Matsushiro (MAT) are

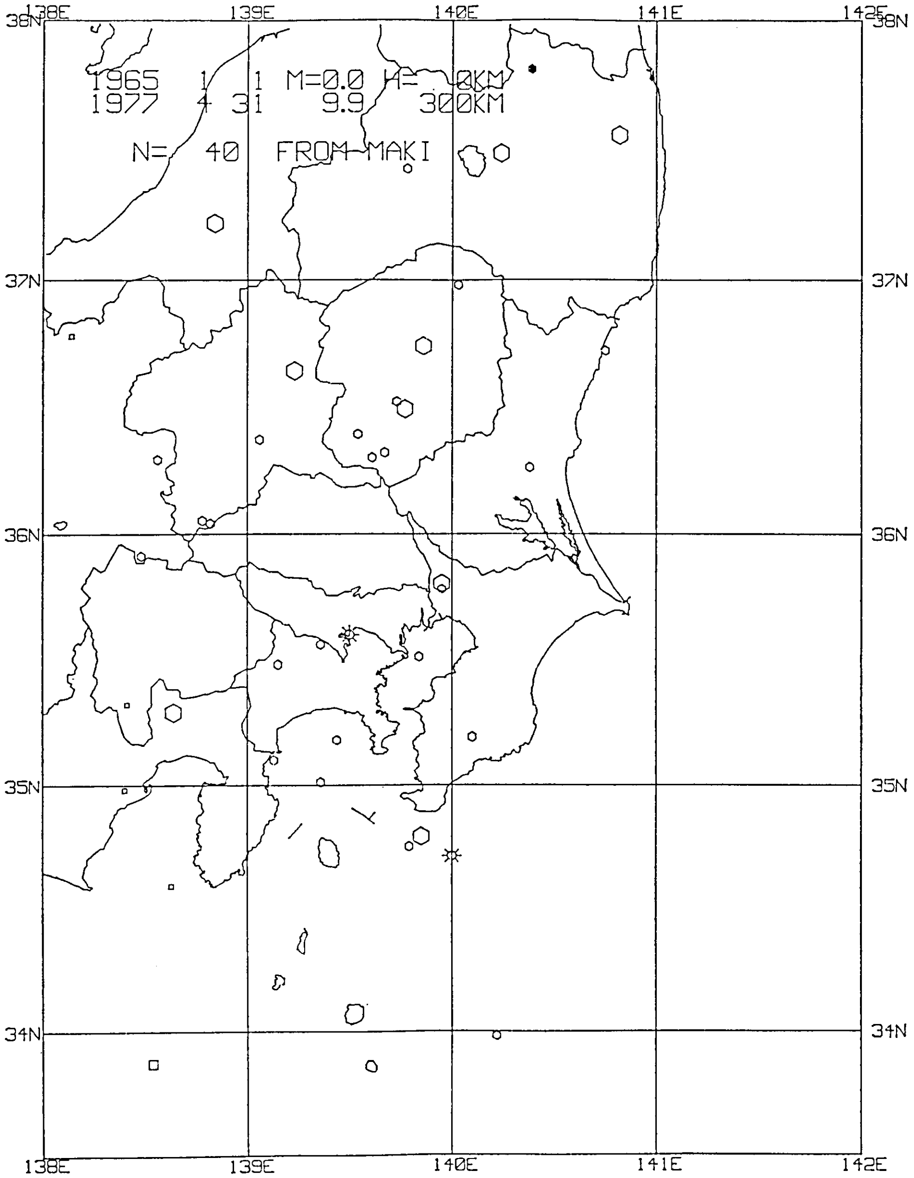

Fig. 11. Relocated epicenters of 40 intermediate-depth earthquakes in Central Japan. Focal depths are represented by circles for the depth range form 0 to 99 km, hexagons for h=100-199 km and squares for h=200-299 km.

also compared in Fig. 12a. At TOK later arrivals with the mean of $+0.82 \pm 0.35$ sec are observed, and at MAT earlier arrivals of the mean of -0.4 ± 0.35 sec are observed. In Fig. 13 (a through f) azimuthal variations of travel-time residuals (circles) and residual ratios (triangles) at individual

Table 4. Redetermined focal coordinates of 40 intermediate-depth earthquakes in and around the Kanto region.

Y	Date M	D	H	M	Origin Time SEC	Latitude (°N)	Longitude (°E)	Depth (KM)	N	Mag
1965	Feb	21	22	28	28.00±0.48	37.44±0.021	139.78±0.029	126±6.6	27	4.6
1965	May	31	8	38	7.00±0.20	35.81±0.013	139.95±0.017	123±2.4	62	5.4
1965	Jun	14	14	28	18.60±0.26	35.57±0.014	139.36±0.016	157±2.9	40	4.7
1965	Jul	3	15	24	9.45±0.39	35.20±0.022	140.10±0.028	114±3.9	37	4.6
1965	Jul	28	5	58	32.55±0.37	36.06±0.018	138.78±0.021	146±4.3	32	4.4
1965	Oct	13	15	43	9.15±0.25	36.33±0.014	139.67±0.020	108±3.4	42	4.6
1966	Feb	19	14	19	19.91±0.43	35.33±0.023	138.41±0.020	211±4.3	35	4.1
1967	Jan	30	10	30	0.09±0.49	34.60±0.032	138.63±0.022	205±4.7	22	4.1
1967	Aug	19	13	38	16.96±0.33	36.27±0.018	140.38±0.032	107±4.6	33	4.6
1967	Oct	2	20	53	38.38±0.72	35.02±0.042	139.36±0.034	131±6.4	24	4.4
1967	Oct	16	17	26	42.11±0.30	36.05±0.016	139.82±0.019	134±3.8	23	4.6
1968	Jan	9	15	38	18.18±0.72	36.99±0.036	140.03±0.055	113±9.8	21	4.5
1968	Jul	4	0	34	12.81±0.27	34.80±0.016	139.85±0.022	103±2.7	49	5.1
1968	Sep	15	5	3	29.46±0.31	35.11±0.016	139.13±0.018	139±3.4	30	4.4
1968	Oct	8	11	49	0.88±0.39	35.61±0.017	139.50±0.024	90±5.0	21	4.2
1969	Apr	9	12	57	24.79±0.16	36.75±0.009	139.86±0.015	121±2.4	63	5.5
1969	Aug	5	18	34	32.50±0.29	37.57±0.014	140.82±0.030	117±4.1	45	5.1
1969	Aug	15	9	47	57.87±0.87	36.40±0.033	139.54±0.037	137±8.8	21	4.4
1969	Oct	30	0	5	39.17±0.23	37.50±0.010	140.24±0.020	172±3.0	52	5.0
1969	Nov	30	12	48	54.32±0.33	34.72±0.019	140.00±0.025	81±4.1	24	4.5
1969	Dec	28	17	43	5.30±0.24	35.52±0.013	139.84±0.017	134±2.7	29	4.5
1971	Jan	28	12	57	42.79±0.34	35.19±0.015	139.44±0.018	124±3.7	23	4.5
1971	Mar	11	20	10	9.31±0.60	35.49±0.027	139.15±0.024	137±6.2	26	4.5
1971	Apr	23	23	46	58.94±0.45	36.38±0.015	139.06±0.020	172±4.6	21	4.4
1971	Sep	13	1	9	54.64±0.68	33.88±0.034	138.54±0.025	264±6.6	53	5.2
1971	Sep	21	8	43	32.39±0.17	37.23±0.009	138.84±0.012	191±2.3	69	5.4
1972	May	17	18	45	13.31±0.34	37.82±0.019	140.39±0.033	100±5.3	31	4.7
1972	Sep	25	16	0	30.85±0.23	35.92±0.013	138.48±0.013	187±2.7	44	4.8
1973	Feb	20	9	27	33.24±0.44	36.31±0.020	139.61±0.026	124±4.9	22	4.4
1973	Aug	23	19	16	41.50±0.15	36.50±0.009	139.77±0.013	107±2.3	51	5.1
1973	Dec	20	20	53	16.00±0.53	33.99±0.028	140.22±0.034	131±4.9	35	4.6
1975	Mar	11	8	57	30.88±0.17	36.53±0.008	139.73±0.012	133±2.2	50	4.7
1976	Feb	6	18	38	45.69±0.33	36.30±0.013	138.56±0.019	154±3.6	25	4.5
1976	Mar	9	11	1	18.25±0.37	34.99±0.023	138.40±0.016	241±3.8	31	4.4
1976	Aug	23	6	0	59.75±0.44	35.79±0.022	139.95±0.028	107±5.0	21	4.1
1976	Oct	30	0	43	53.35±0.40	34.76±0.023	139.79±0.027	145±3.9	32	4.6
1976	Nov	6	7	57	25.04±0.18	35.30±0.010	138.64±0.010	182±2.0	53	5.1
1976	Nov	27	6	17	41.71±0.27	36.79±0.015	138.14±0.020	222±4.3	28	4.5
1976	Dec	13	2	55	59.15±0.20	36.73±0.011	140.75±0.022	105±2.8	26	4.6
1976	Dec	29	14	36	49.06±0.13	36.65±0.008	139.23±0.011	148±1.9	67	5.8

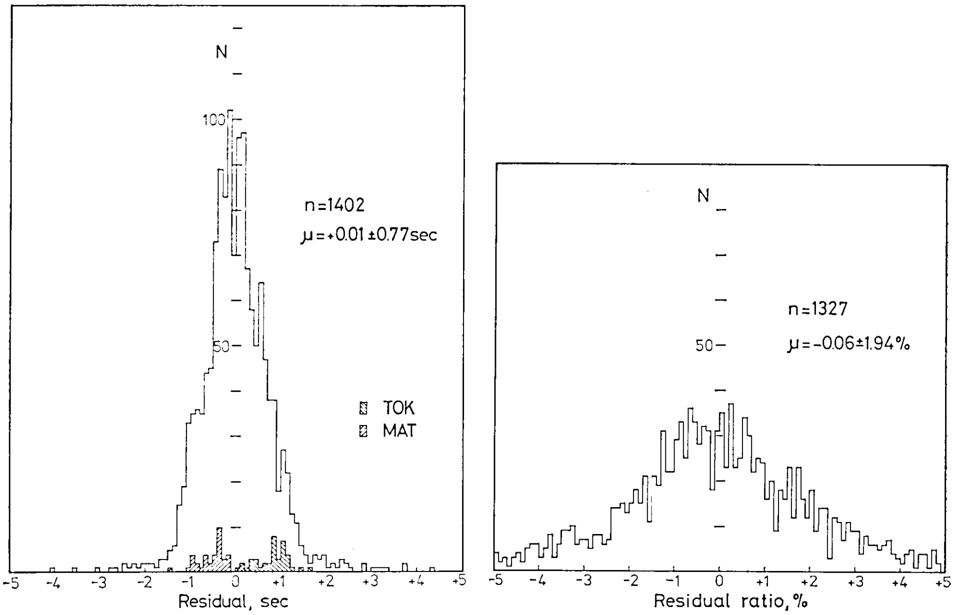

Fig. 12. Frequency distribution of travel-time residuals (a) and residual ratios (b) for 40 intermediate-depth earthquakes in Central Japan. The mean and standard deviation of residuals are equal to $+0.0\pm0.77$ second for 1402 observations. The mean residual ratio is equal to $-0.06\pm1.94\%$ for 1327 observations. Frequency distribution of travel-time residuals at TOK and MAT are denoted by two kinds of shadowed areas.

stations are shown. At stations far from the source region, for instance ONA (Onahama, Fig. 13a), a small deviation of residuals ($\sigma=0.47$ sec) is seen. At near stations, for instance CHJ (Chichibu, e), a large scatter ($\sigma=1.09$ sec) is observed.

Systematic azimuthal variations of travel-time residuals, for instance KMG (Kumagaya, d) and KOF (Kofu, f) are in harmony with the features of the Pacific plate subducting beneath Central Japan. But systematic variations with azimuth are not clearly observed at many stations. This might be caused by complicated variations of structure near the sources, along the paths and beneath the stations.

In Table 5 the means and standard deviatins of travel-time residuals at each station are represented together with the mean residual ratios. Hereafter some statistical tests are made for identifying differences of the mean residuals at individual stations. When the parameters of two normal distributions are denoted by (n_i, μ_i, σ_i) and (n_j, μ_j, σ_j), the variable

$$z=|\mu_i-\mu_j|/\sqrt{\sigma_i^2/n_i+\sigma_j^2/n_j} \qquad (4)$$

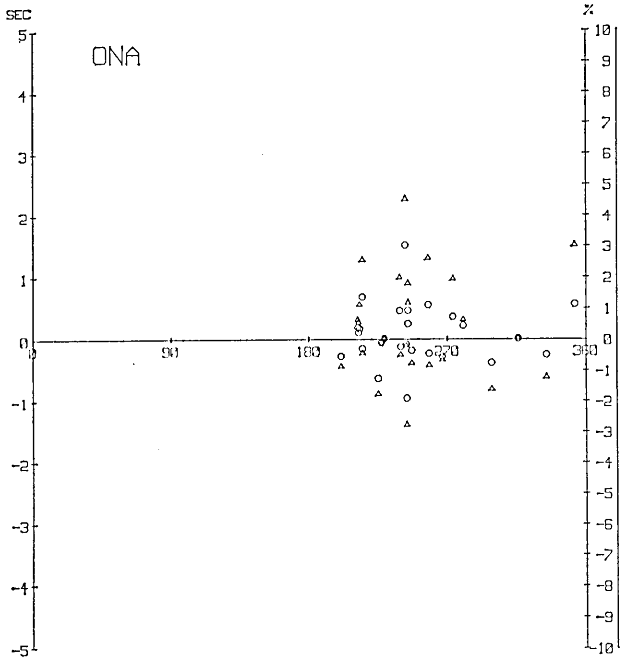

Fig. 13(a)

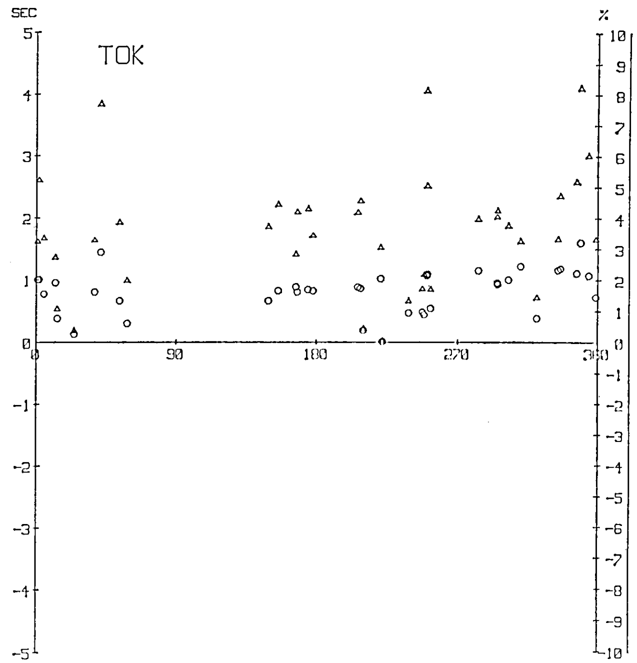

Fig. 13(b)

Fig. 13. Azimuthal variation of travel-time residuals (circles) and residual ratios (triangles) observed at several stations. (a) ONA (Onahama), (b) TOK (Tokyo), (c) MAT (Matsushiro), (d) KMG (Kumagaya), (e) KOF (Kofu) and (f) CHJ (Chichibu). Scales of abscissa are in seconds for residuals and in % for residual ratios, respectively.

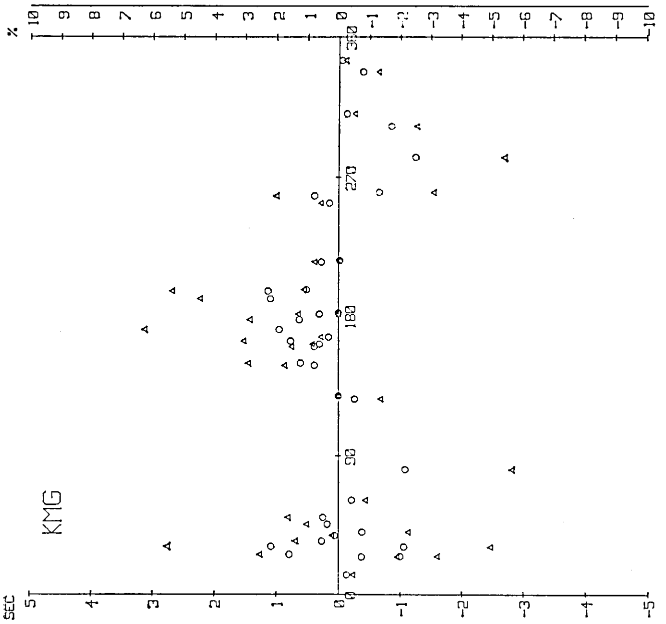

Fig. 13(d)

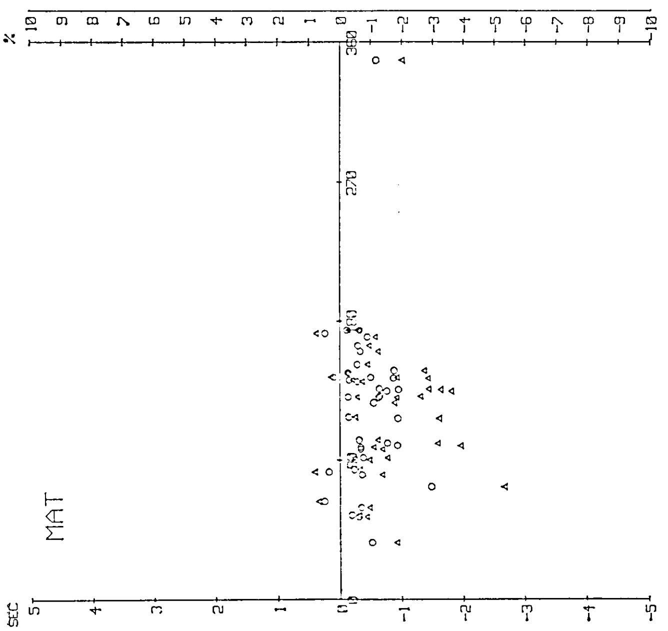

Fig 13(c)

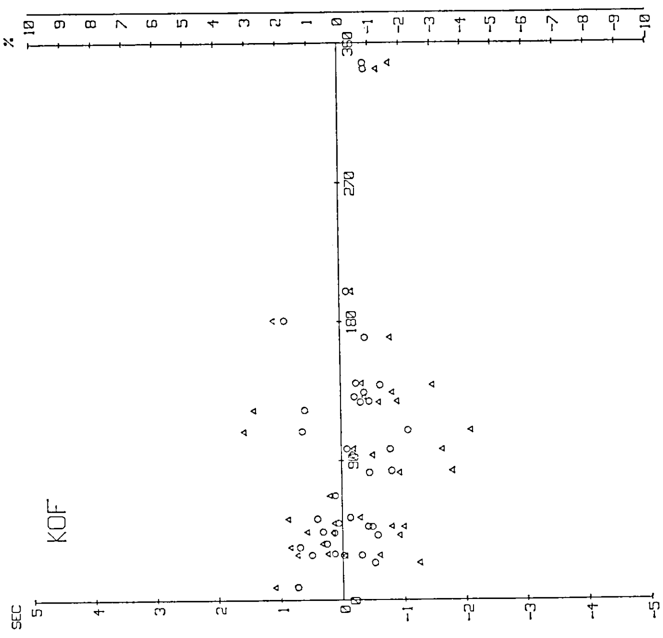

Fig. 13(f)

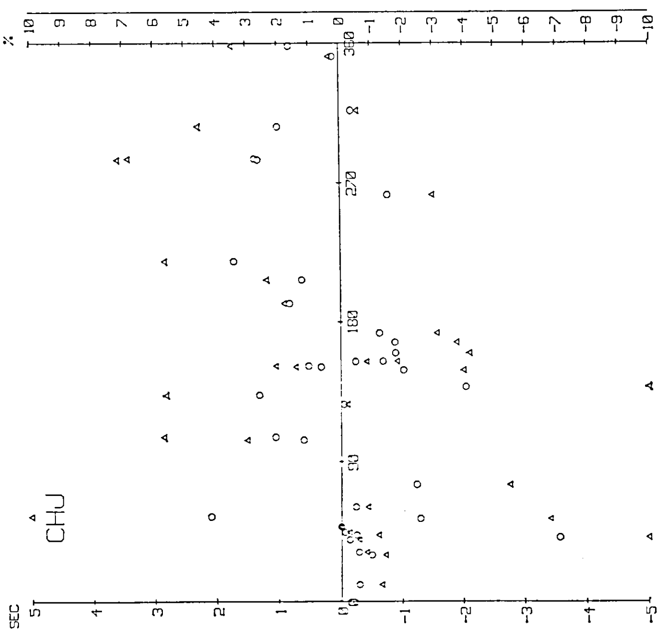

Fig. 13(e)

Table 5. Mean residuals of travel times at each station for intermediate-depth earthquakes in the Kanto region.

Station	Obs	Residual SEC	Res. Ratio %	Station	Obs	Residual SEC	Res. Ratio %
TSK	11	−0.96±0.73	−3.06±1.49	OFU	17	−0.46±0.63	−0.85±1.33
DDR	12	−0.23±0.33	−0.88±1.32	OKA	2	−0.38±0.02	−0.62±0.03
SRY	9	−0.33±0.55	−0.92±1.60	OMA	20	0.03±1.34	−0.18±4.75
KYS	11	−0.11±0.45	−0.10±1.50	ONA	26	0.07±0.47	0.42±1.65
OYM	3	−0.54±0.15	−2.03±0.34	OSH	34	−0.40±0.53	−1.59±2.26
AIK	17	−1.10±0.50	−3.31±2.03	OWA	10	−0.78±0.56	−1.49±0.94
AJI	39	−0.60±0.48	−2.21±2.03	SAK	10	1.44±0.88	3.61±1.96
AKI	9	0.73±0.35	1.56±0.76	SEN	23	−0.32±0.44	−0.76±1.13
CHJ	35	−0.05±1.09	−0.07±4.89	SHR	33	−0.12±0.43	−0.32±1.62
CHO	34	0.41±0.63	1.59±2.22	SHZ	29	0.15±0.60	0.50±2.23
FKS	30	0.31±0.55	0.95±1.67	SNH	4	0.73±0.21	1.89±0.69
FUK	9	0.38±0.40	0.87±0.87	TKD	23	−0.20±0.76	−0.83±2.16
FUN	26	−0.04±0.63	−0.22±2.57	TKY	9	0.42±0.79	1.13±2.16
GIF	22	0.12±0.70	0.35±1.82	TAT	24	0.41±1.11	1.25±2.92
HIK	17	0.13±0.67	0.26±1.53	TOK	39	0.81±0.35	3.57±1.89
HIM	2	0.10±0.07	0.17±0.11	TOY	15	0.11±0.86	0.42±2.08
HJJ	24	0.19±0.58	0.54±1.51	TSU	7	0.42±1.15	0.87±2.36
HMM	24	0.11±0.32	0.28±0.97	TSR	11	0.06±0.82	0.14±1.79
HJH	5	0.14±0.19	0.34±0.40	UTS	37	−0.37±0.58	−1.33±2.23
IID	32	0.19±0.53	0.65±1.60	WAJ	16	0.11±1.20	0.20±3.02
NGN	34	0.47±0.74	1.41±2.28	YAM	17	0.01±0.41	−0.00±1.10
NGT	2	−0.74±1.57	−4.79±7.11	YOK	33	0.49±0.69	1.91±2.60
ISN	21	−0.39±0.46	−0.85±1.03	INU	2	−0.41±0.03	−0.95±0.15
KAM	6	−0.02±0.72	−0.14±1.60	TMS	10	−0.04±0.50	−0.07±1.95
KAN	16	−0.01±0.96	−0.06±2.40	ABU	10	−0.33±0.24	−0.61±0.44
KRZ	38	0.43±0.62	1.49±2.35	KAK	21	−0.74±0.54	−3.09±2.55
KOF	36	−0.11±0.47	−0.56±1.79	KOB	4	1.09±0.29	1.90±0.53
KMG	38	0.07±0.61	0.35±2.76	KYO	13	−0.07±0.51	−0.08±1.01
MAE	32	−0.22±0.67	−1.19±2.36	SHJ	7	−0.09±0.77	−0.24±1.28
MAI	6	0.49±0.41	1.00±0.85	SUM	7	0.13±0.40	0.27±0.72
MTM	24	0.18±0.49	0.55±1.46	OSK	2	0.70±0.70	1.60±1.61
MAT	40	−0.41±0.35	−1.49±1.33	TYK	15	−0.12±0.78	−0.21±1.33
MIS	37	−0.18±1.00	−0.95±3.52	WKU	4	0.05±0.31	0.10±0.61
MIT	37	0.06±0.41	0.28±1.69	WKY	6	0.56±0.48	1.03±0.87
MIY	8	−0.83±0.56	−1.59±1.02	OSA	12	0.00±0.40	0.03±0.84
MIZ	15	0.52±0.85	1.19±1.78	OIC	5	−0.33±0.55	−0.49±0.90
MRK	14	−0.37±0.48	−0.63±0.93	OIS	4	−0.38±0.36	−0.71±0.68
NAG	31	−0.00±0.51	0.05±1.39	TOT	5	−0.08±0.38	−0.11±0.63
NAR	8	−0.10±0.41	−0.20±0.83	HAC	5	−1.19±0.52	−2.14±0.98
NII	13	0.87±0.99	3.05±3.22	AOM	3	0.58±0.19	0.92±0.28

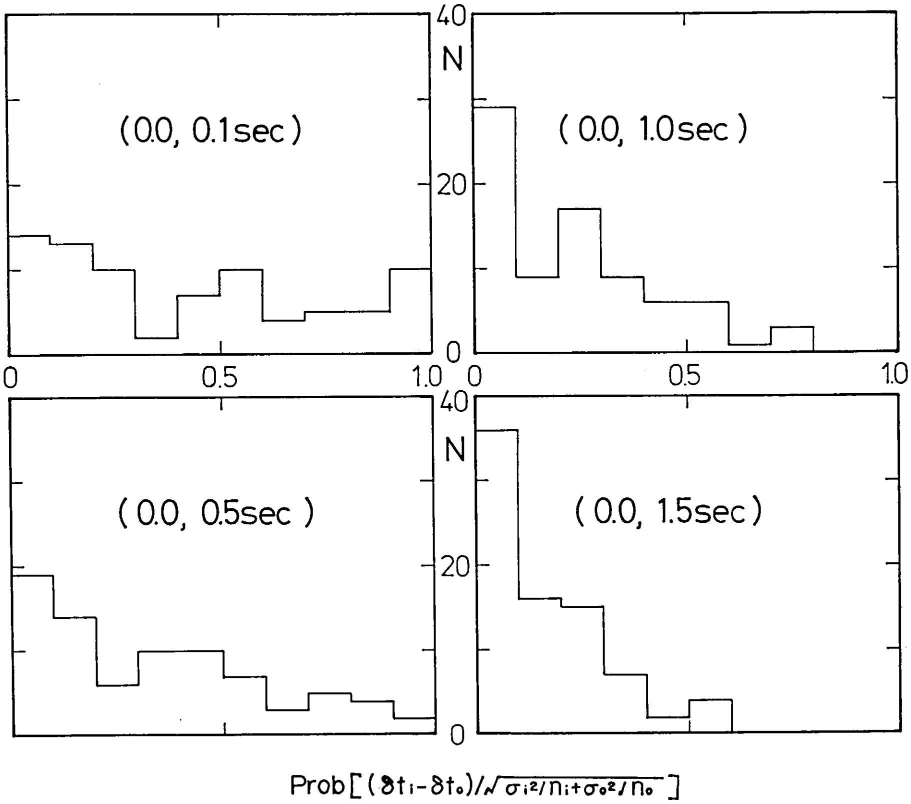

Fig. 14a. Frequency distribution of significance levels at which the mean residual at each station in Table 5 are statistically different from the mean residual of 0 sec and the standard deviations of 0.1, 0.5, 1.0 and 1.5 seconds.

is normally distributed with the zero mean and unit standard deviation.

At first significance levels at which the mean residual at each station is statistically different from other stations are discussed. Frequency distributions of these significance levels are shown in Fig. 14a for various standard deviations. It is concluded that the mean residuals at almost all stations may be identified as 0 sec. For the small standard deviation of 0.1 sec, there are many stations wihch are different from the zero mean residuals. Therefore the travel-time data observed at individual stations can be considered to be consistent with the travel-time table used here. Any differences from the zero mean are not observed for the residual ratios (Fig. 14b).

Differences of the mean residuals between stations are statistically tested. In Fig. 15 significance levels at which the mean residuals at each station are different from other stations are represented for some typical stations with earlier and later arrivals. Stations with negative mean

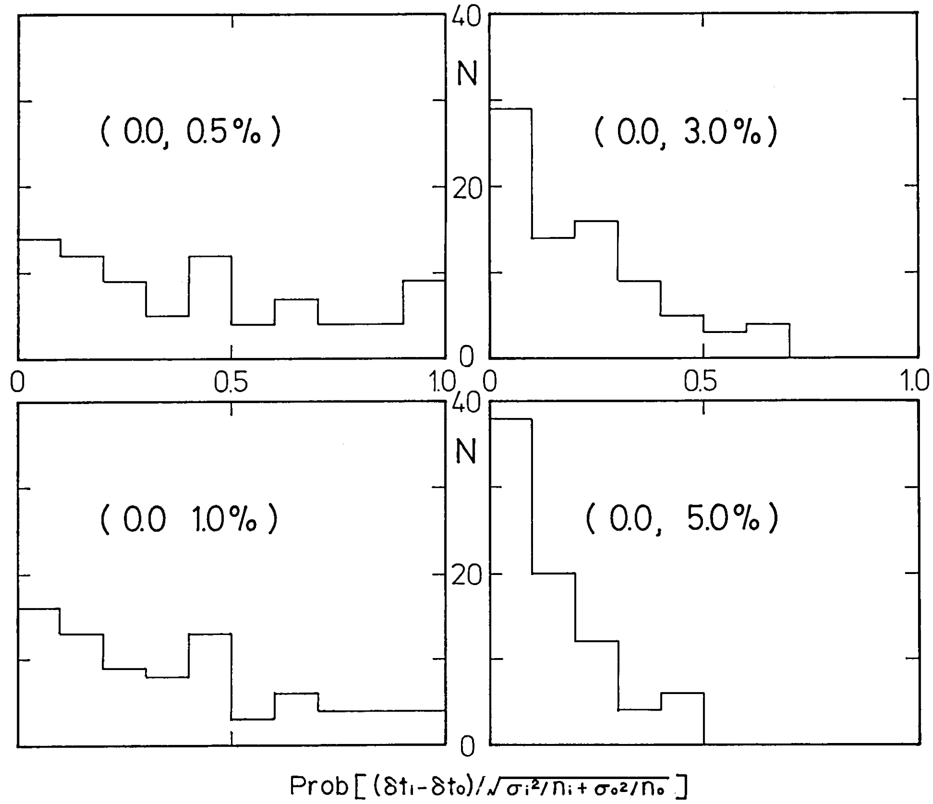

Fig. 14b. Frequency distribution of significance levels at which the mean residual ratios at each station are different from the mean of 0% and standard deviation of 0.5, 1.0, 3.0 and 5.0%.

residuals or earlier arrivals, for instance AIK (Aikawa) and KAK (Kakioka), are different from many other stations. On the other hand, stations with positive mean residuals or later arrivals, for instance TOK (Tokyo) and NII (Niigata) are different from other stations. In Fig. 16 same signifince levels are represented for typical stations with small and large standard deviations. Some stations with large standard deviations, for instance CHJ (Chichibu) and MIS (Mishima), can not be statistically distinguishable from almost all stations. Even stations with a small standard deviation, for instance HMM (Hamamatsu) and MAT (Matsushiro), are not significantly different from other stations. Solid lines are shown for the travel-time residuals and broken lines are shown for the residual ratios.

In this chapter the station biases of travel times were obtained for 40 intermediate-depth earthquakes beneath Central Japan. Earlier and later arrivals were systematically observed at some stations. Because of the standard deviation of one second or greater, the differences from the

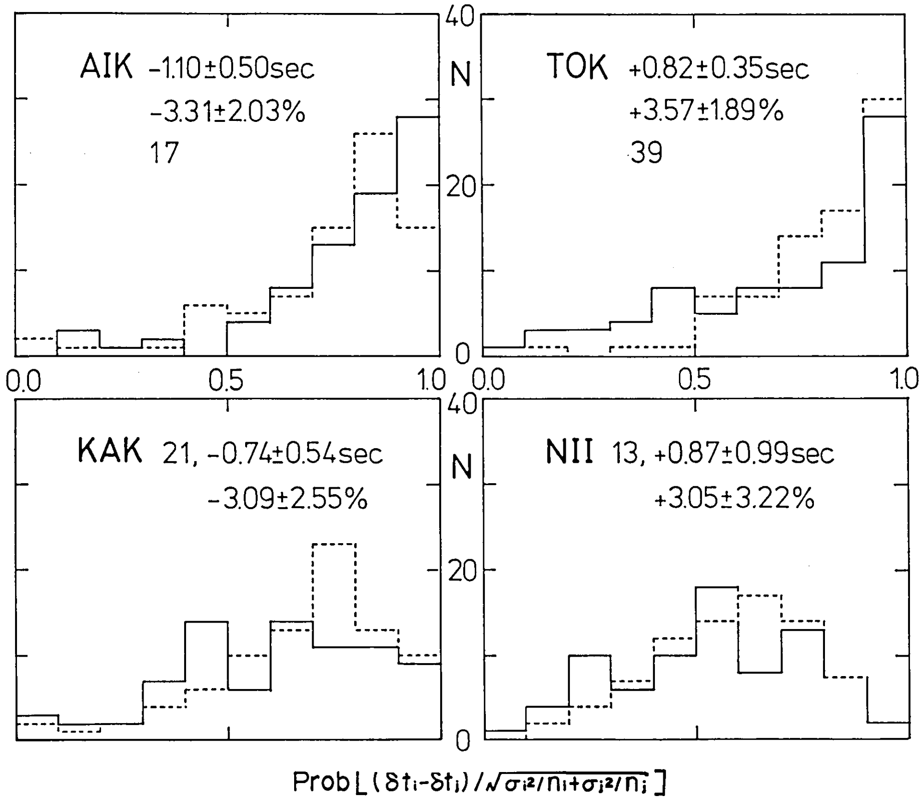

Fig. 15. Frequencies of signficance levels at which the mean residuals (solid lines) and residual ratios (broken lines) are statistically different from other stations with later and earlier arrivals.

zero mean are not statistically significant. However, the differences of the mean residuals could be statistically identified between some stations.

6. Conclusion

Effects of observational conditions (errors in travel times, number, and distance and azimuth coverage of stations) on hypocenter locations have been studied for an intermediate-depth earthquake which occurred at the depth of 190 km beneath Niigata Prefecture, Central Japan, on September 21, 1971. Travel times observed at Japanese stations are affected by the anomalous structure associated with the descending lithospheric plate. Then the station biases of travel times were derived from 40 intermediate-depth earthquakes beneath Central Japan.

The following conclusions have been obtained.

(1) Travel-time residuals observed at Japanese stations show an azi-

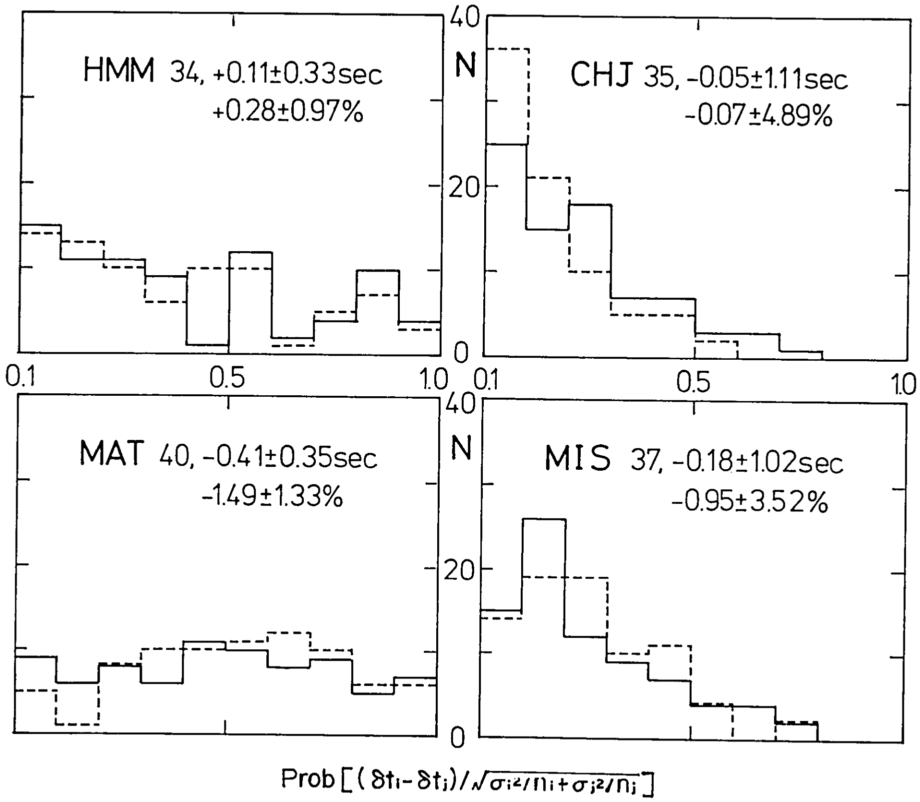

Fig. 16. Frequencies of signficance levels at which the mean residuals (solid lines) and residual ratios (broken lines) are different from other stations with typical standard deviations.

muthal dependence for the focal coordinates determined by ISC, NEIS and JMA, and a biased base line is observed for the focal coordinates by JMA. It is worth while to redetermine focal coordinates of earthquakes more precisely, and especially focal depths may be determined other than at the 10 or 20 km intervals as made by JMA.

(2) Effects of observational errors in travel times on hypocenter location were studied by determining focal coordinates with superposing normal random errors to the observed travel times at various numbers of stations. The shifts in focal coordinates are comparable to the differences between those of JMA, ISC and NEIS, and the probable errors obtained by these agencies. Larger effects on focal depths were observed, and number of sampled stations and standard deviations of random errors affects range of shifts.

(3) Effects of station numbers were studied by two methods of sampling certain numbers out of all stations. Focal coordinates determined

by a small number of sampled stations show great departures, especially in the focal depth. Cumulative effects of errors in observed travel times are predominant for data sets of more superposed stations. On the other hand, data sets of a small number of stations produce greater shifts to hypocenter location due to effects of errors at individual stations, although focal coordinates can be determined with less errors. As far as the abovementioned effects station number of 20 to 30 is suitable for stable locations of hypocenters.

(4) Distance effects on focal coordinates were systematically studied by sampling stations located within a certain range of distances. There was a tendency for only the near data ($\Delta<200$ km) to cause the westward shift, and for distant data ($200<\Delta<500$ km) to cause the eastward shifts and larger depths. Earthquakes directly below an observational network of a small number of stations may sometimes suffer a great shifts exceeding 50 km in focal depth. It is very dangerous to determine focal coordinates of intermediate-depth earthquakes by using only the nearest stations.

(5) Effects of azimuthal coverage on focal coordinates were studied by sampling stations located within certain ranges of azimuth. Station data within a narrow range of azimuth produce large shifts in focal coordinates. Particularly fatal departures are observed at station subsets with azimuthally dependent residuals.

(6) Station biases of travel-time data for intermediate-depth earthquakes which occurred beneath Central Japan were derived. Forty intermediate-depth earthquakes observed at more than 20 stations were selected. These earthquakes were located with the probable errors less than 5 km in epicentral location and 10 km in focal depth. The mean residuals of 1402 travel times for these earthquakes is -0.01 ± 0.77 second and the mean residual ratio is $+0.06\pm0.94\%$. Significant differences in the mean residuals were statistically found between some stations.

Acknowledgments

The author would like to express his sincere thanks to Prof. T. Utsu for his critical review of the manuscript and his useful comments.

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2. 震源決定における観測条件の影響（中部日本稍深発地震の場合）

東京大学地震研究所　牧　　正

震源座標は走時データの観測誤差の他，観測点数や観測網の影響（距離，方位範囲）をうけると考えられている．稍深発地震（1971年9月21日新潟県下深さ 190 km）の走時データを用いて，震源決定における観測条件の影響について調べた．

観測された走時データから，NEIS・ISC・JMA による震源に対する走時残差（市川，望月の走時表）を比較した．NEIS・ISC 震源に対する走時残差は方位性を示し，JMA 震源に対してはづれを示す．

観測条件の影響を調べるため，①観測走時に誤差を与え震源決定を行なう，②抽出した観測走時丈で震源決定を行なう．③震央距離・方位の範囲について抽出した観測走時を用いて震源決定を行なうことをくり返した．こうして得られる震源座標から次のような結果を得た．観測誤差よりも，観測網の距離・方位の範囲の影響が極めて大きい．特に方位や距離のせまい範囲に位置する走時データだけで求められた震源座標は大きなふらつきを示し，通常の震源誤差よりもはるかに大きい．小数の観測点だけで震源決定を行なうのは危険であり，特に深さ決定に不安定さがみられる．

日本中部の稍深発地震40個（1965～1976年）の震源決定を行ない，走時残差と残差比について観測点の差の統計的有意性が調べられた．いくつかの観測点間では平均走時残差の有意性が認められた．