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Travel Time Analysis of Relatively Deep Earthquakes in Southwest Japan with Special Reference to the Underthrusting of the Philippine Sea Plate*

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(With 1 Table and 16 Figures)

Contents

1. Introduction

Near Southwest Japan, the oceanic Philippine Sea plate moves northwestwards relative to the continental China plate at a rate of about 8 cm/year (FITCH & SHOLZ, 1971; KANAMORI, 1972). The manner of plate convergence in Southwest Japan somewhat differs from the case of other typical island arc-trench systems. Although the Ryukyu arc connecting Taiwan and Kyushu islands is identified as one of typical island arc systems because of deep seismic zone (the Benioff zone), well developed trench and volcanic activity, some typical features that characterize the island arc system are absent along Southwest Japan which may be considered to be a NE continuation of the Ryukyu arc. As we can see in Figs. 1 and 14, there are apparently no activity of deep and intermediate earthquakes and no active volcanos.

On the other hands, historical large earthquakes have occurred periodically along the Nankai trough. Focal mechanisms of recent large earthquakes, the 1944 Tonankai and the 1946 Nankaido earthquakes, suggest a low dip angle thrust fault (KANAMORI, 1972). According to precise studies on micro-earthquakes, relatively deep earthquakes occur below

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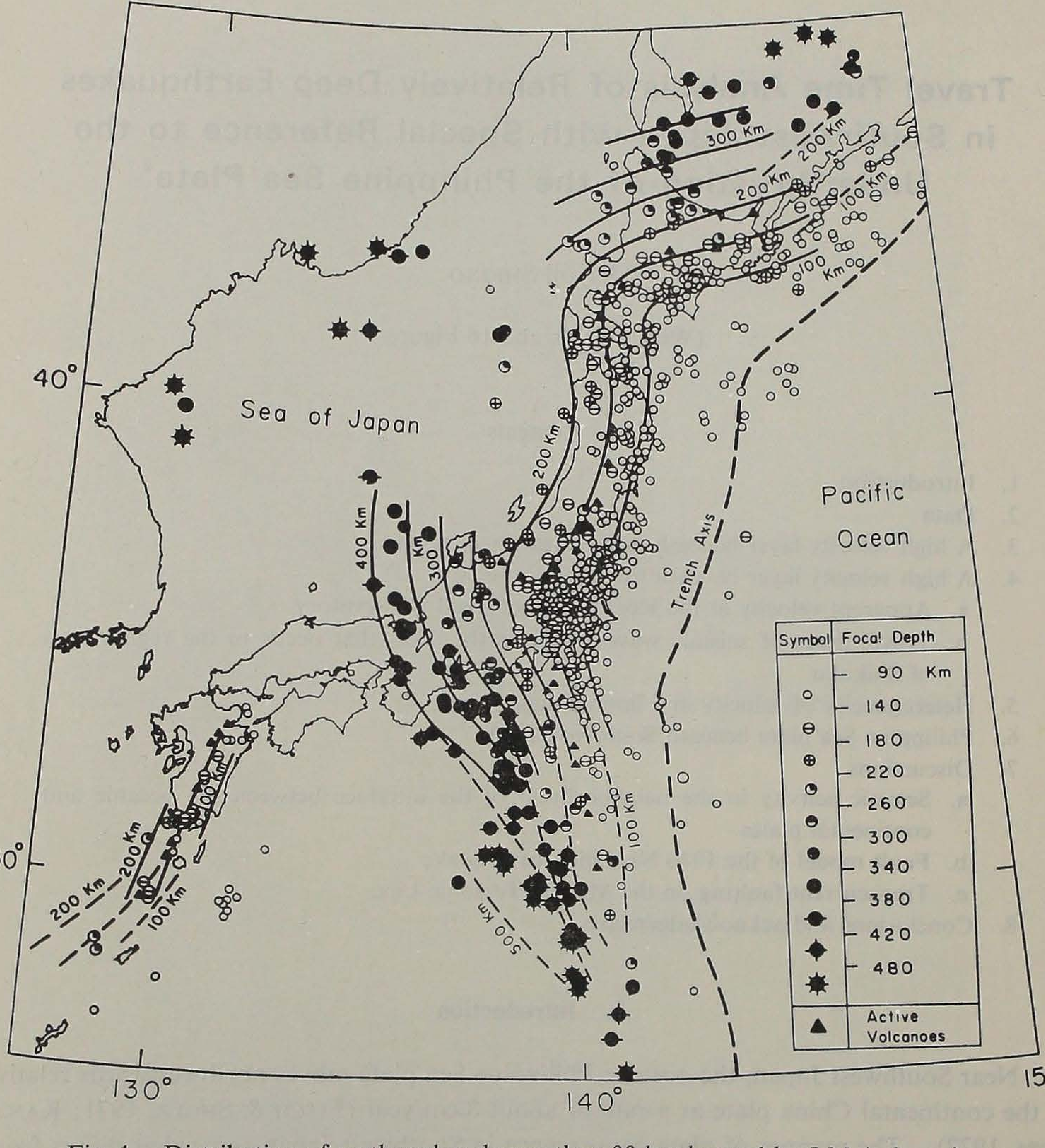

Fig. 1. Distribution of earthquakes deeper than 90 km located by J.M.A. by using Japanese data only, reproduced from UTSU (1971).

the Moho discontinuity along the Outer Zone of Southwest Japan and form an inclined seismic belt of a small scale, though these foci are shallower than 80 km (SAWAMURA & KIMURA, 1971; KANAMORI & TSUMURA, 1971; YAMADA et al, 1972). Focal mechanisms of these earthquakes (the N-S compression) differ from those of shallow earthquakes in the crust of the same region (the E-W compression) and are consistent with the underthrusting of the Philippine Sea plate (SAWAMURA & KIMURA, 1971; SHIONO, 1973; OOIDA & ITO, 1972; NISHIDA, 1973). In order to understand tectonics in the Kii peninsula region, KANAMORI (1972) proposed an interesting model that the Philippine Sea plate underthrusts with a low dip angle along the Nankai trough beneath the Kii peninsula and the leading edge of the plate still remains in the continental lithosphere. This model means that the relationship between two plates may be in the initial stage of plate convergence.

If a cool oceanic plate lies in the upper most mantle, anomalous early arrivals or other characteristic phases may be observed in seismic waves traveling through the uppermost mantle. This paper concerns with the travel times of initial waves and later phases from earthquakes which occur in the area west of Shikoku and in the southwestern Chubu region at depths greater than 30 km, and discusses the heterogeneity of velocity structure in the uppermost mantle beneath Southwest Japan. Moreover, the spatial extent of the Philippine Sea plate beneath the region is determined on the basis of the results obtained from the travel time analysis and seismic activity below the Moho discontinuity.

The results not only suggest that KANAMORI's model is applicable to the whole area of Southwest Japan. Moreover, the presumed shape of the underthrusting plate is not only similar to the presented fault model of the 1946 Nankaido earthquake but also harmonizes with the recent transcurrent movements on the Median Tectonic Line.

2. Data

Seismicity of relatively deep earthquakes suggests that the cool oceanic plate may lie beneath Southwest Japan within the depths ranging from about 40 km to atmost 100 km. However, there have been few studies on seismic velocity structure in the depth range, although various authors have discussed the corresponding structure in the crust. P_n phase bottoming at the Moho discontinuity is generally not so clear on the record from a short period instrument. This usually makes difficult to trace the phase over a long distance. It may be therefore much more difficult to identify the waves refracted deep into a high velocity layer far below the Moho discontinuity, even though the layer really exists. This may be the main reason why this field of research is difficult.

Fortunately, as mentioned in the previous section, relatively deep earthquakes frequently occur within the depth range from 40 to 100 km below the region west of Shikoku and below the southwestern Chubu. Arrival times of the initial waves and later phases can be usually observed at micro-earthquake observation stations within an accuracy of 0.2 to 0.5 sec. We can therefore use travel times of the earthquakes in order to reveal the heterogeneity of seismic velocity in the uppermost mantle. However micro-earthquake observation stations have not yet established around the focal regions and therefore we cannot obtain precise locations of the hypocenters and the origin times. In spite of this weak point, the advantage that we can obtain the clear initial motions of the waves traveling through the uppermost mantle enables us to confirm the existence of the high velocity layer through careful examinations of the travel times, at least qualitatively.

In this paper, travel times of waves traveling through the uppermost mantle beneath the Outer Zone of Southwest Japan are discussed, on the basis of data from the Kochi Seismological Observatory operated by the Kochi University and from the Wakayama Micro-earthquake Observatory operated by the Earthquake Research Institute, University of Tokyo. Coordinates of the hypocenters are taken from the Monthly Seismological Bulletin published by the Japan Meteorological Agency (J.M.A.). Probable error of the epicentral location varies from 1 to 3 minutes. Fig. 2 gives the distribution of epicenters and the location of observation stations. Table 1 shows the origin times and the location of hypocenters togethor with other information.

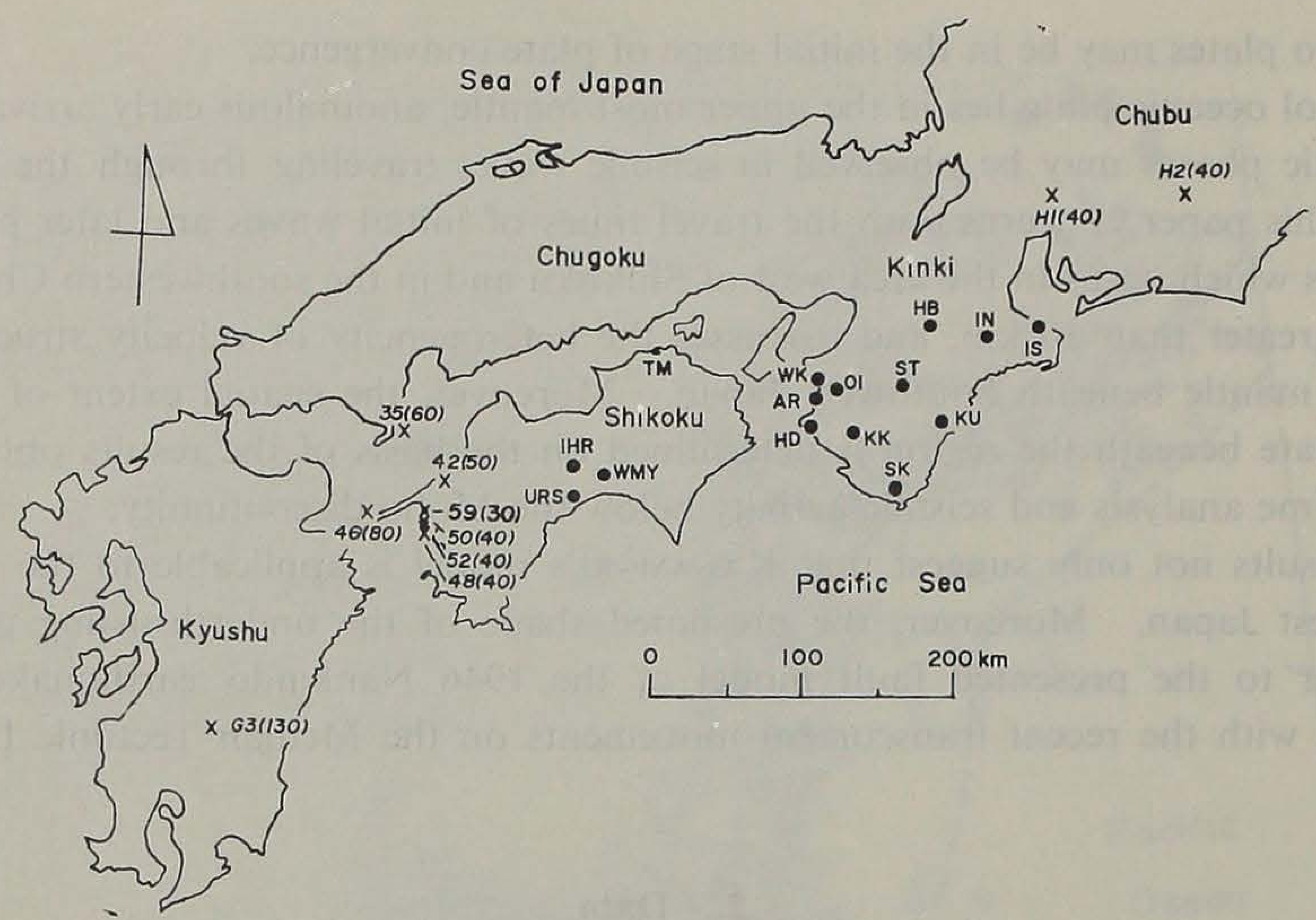

Fig. 2. Distribution of the earthquakes of which travel times are analyzed (cross mark) and location of seismological observation stations with high sensitive instruments (closed circles). Numerals near epicenters give the identification numbers in the annexed Table and numerals shown in parentheses give focal depths.
TM; Takamatsu.

Table 1. Source parameters of earthquakes, taken from the Monthly Seismological Bulletin published by the Japan Meteorological Agency (J.M.A.). Origin times are given in terms of the Japan Standard Time (J.S.T.). Numerals following symbol ± show probable errors in determination of source parameters. Column M gives magnitude and column Ref. indicates the figure in which data from the shocks are illustrated.

Shock	Date (J.S.T.)	Origin Time h	m	s	±	Origin Long.		±	Lat.		±	Depth	M	Ref.
H-1	Nov. 14, 1966	23	05	22.1	± 0.1	136°	52	± 1	35°	14	± 1	40 km	4.3	Fig. 4
H-2	Jan. 14, 1968	23	15	13.5	0.2	137	49	1	35	14	1	40	4.3	Fig. 3
N-42	Aug. 12, 1968	11	58	35.1	0.2	132	30	1	33	30	1	50	4.8	Fig. 10
N-48	Aug. 6, 1968	01	17	6.0	0.2	132	23	1	33	18	1	40	6.6	Figs. 8, 9
N-50	Aug. 6, 1968	05	51	20.7	0.3	132	24	1	33	22	1	40	4.8	Figs. 8, 9
N-52	Aug. 6, 1968	11	34	37.0	0.3	132	24	2	33	20	2	40	4.9	Fig. 7
N-59	Aug. 8, 1968	20	28	11.4	0.4	132	21	3	33	26	3	30	4.3	Fig. 7
N-35	Jul. 13, 1965	13	50	56.7	0.2	132	16	2	33	54	1	60	4.5	Fig. 12
G-3	Nov. 28, 1967	11	36	54.7	0.2	130	57	1	32	05	1	130		Fig. 13
N-46	May 12, 1968	17	14	38.4	0.1	130	59	1	33	23	2	80		Fig. 13

We treat only the data from the stations distributed in central Shikoku and the Kii peninsula regions, partly because it is expected that the leading edge of the Philippine Sea plate lies beneath the Outer Zone of Southwest Japan and partly because it is difficult to discuss the azimuthal variations of the travel time curves because of less accuracy in the epicentral location.

3. A high velocity layer beneath the Kii peninsula region

KANAMORI & TSUMURA (1971) showed that the local travel times in the Kii peninsula region can be fitted, in general, in terms of a uniform crustal structure within an error of 0.2 sec. However, at a station IN, a negative travel time residuals as large as -1.5 sec is consistently observed for all earthquakes along the western coast of the Kii peninsula south of a station HD. The fact that early arrivals are observed only at IN but not at stations at shorter distances or at different azimuths suggests that a region of the high seismic velocity exists at depths probably below 20 km.

Travel times of P-waves emitted from relatively deep earthquakes in the western Chubu region, which is a reverse profile of those studied by KANAMORI & TSUMURA (1971), also support the existence of a high velocity layer beneath the region. Fig. 3 shows the travel times of P-waves emitted from a shock H-2. The apparent velocity in the southern stations (8.4 km/sec) is higher by 5% than that in the northern stations (8.0 km/sec). The similar feature is also seen in the case of another shock H-1 (Fig. 4).

On the basis of arrival times of teleseismic waves, MIZOUE (1974a) determined the orientation of the maximum inclination of the Moho discontinuity (N10°W–N10°E) and the dip angle (6°–10°). MIZOUE (1974b) also showed that P-waves arriving from the NE direction has an apparent velocity of 7.8–8.0 km/sec in most cases, which is identified as the velocity just below the Moho discontinuity. From the above high apparent velocity together with his results, it may be concluded that the high velocity of 8.4 km/sec is due to a high velocity layer in the uppermost mantle. The spatial distribution of the stations, at which waves arrive with the high apparent velocity suggests that the high velocity layer lies only south of the line connecting two stations HD and HB.

ISHIBASHI (1974) showed that the apparent velocity of P-waves emitted from the earth-

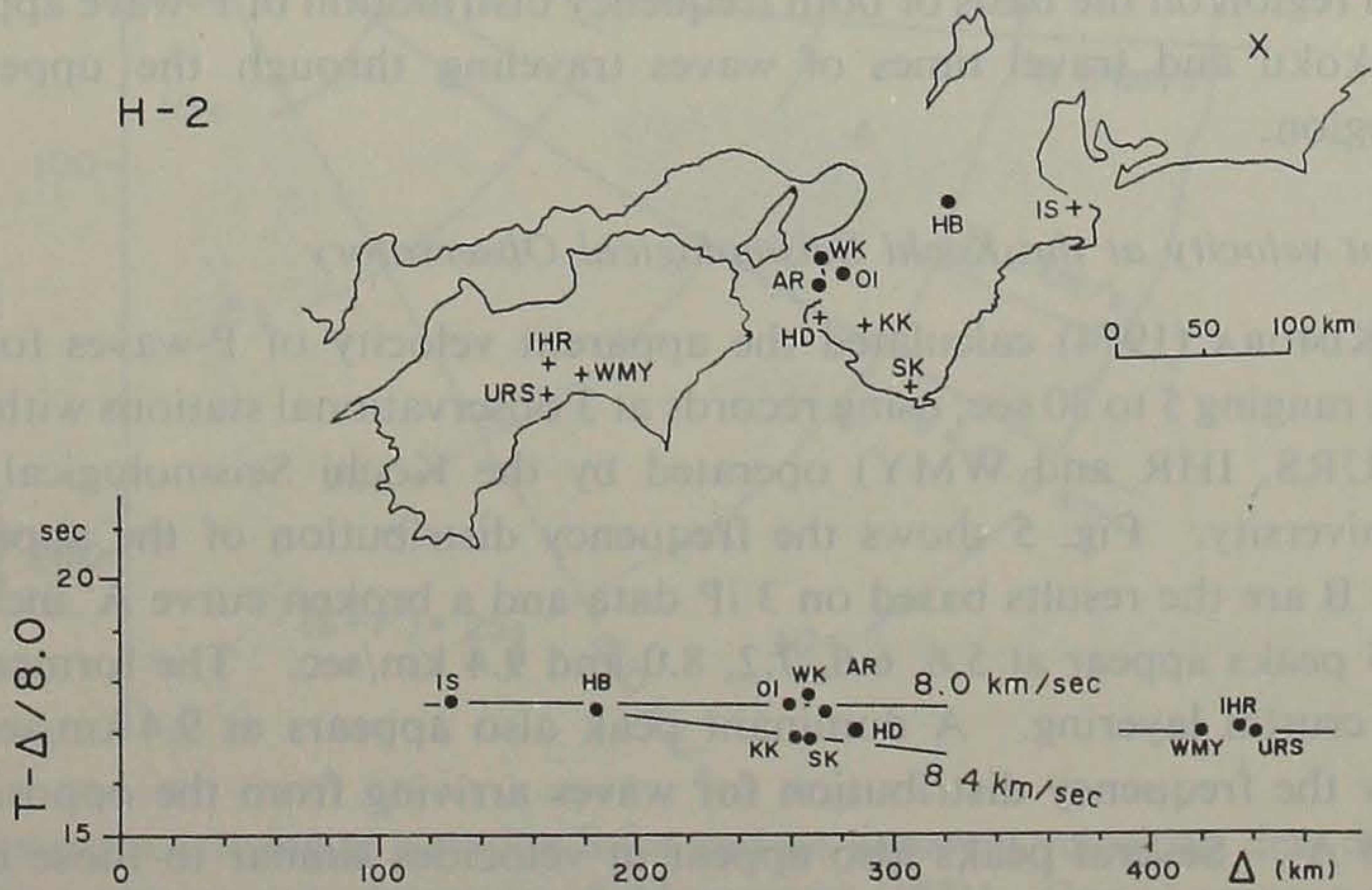

Fig. 3. Plots of reduced arrival times at stations in the central Shikoku and Kii peninsula region versus epicentral distances for a shock H-2. Arrival times are reduced by $\Delta/8.0$ km/sec. Note the distribution of stations showing the high apparent velocity of 8.4 km/sec. Arrival times in central Shikoku are fitted neither on the travel time curve with the apparent velocity of 8.0 km/sec nor on that of 8.4 km/sec.

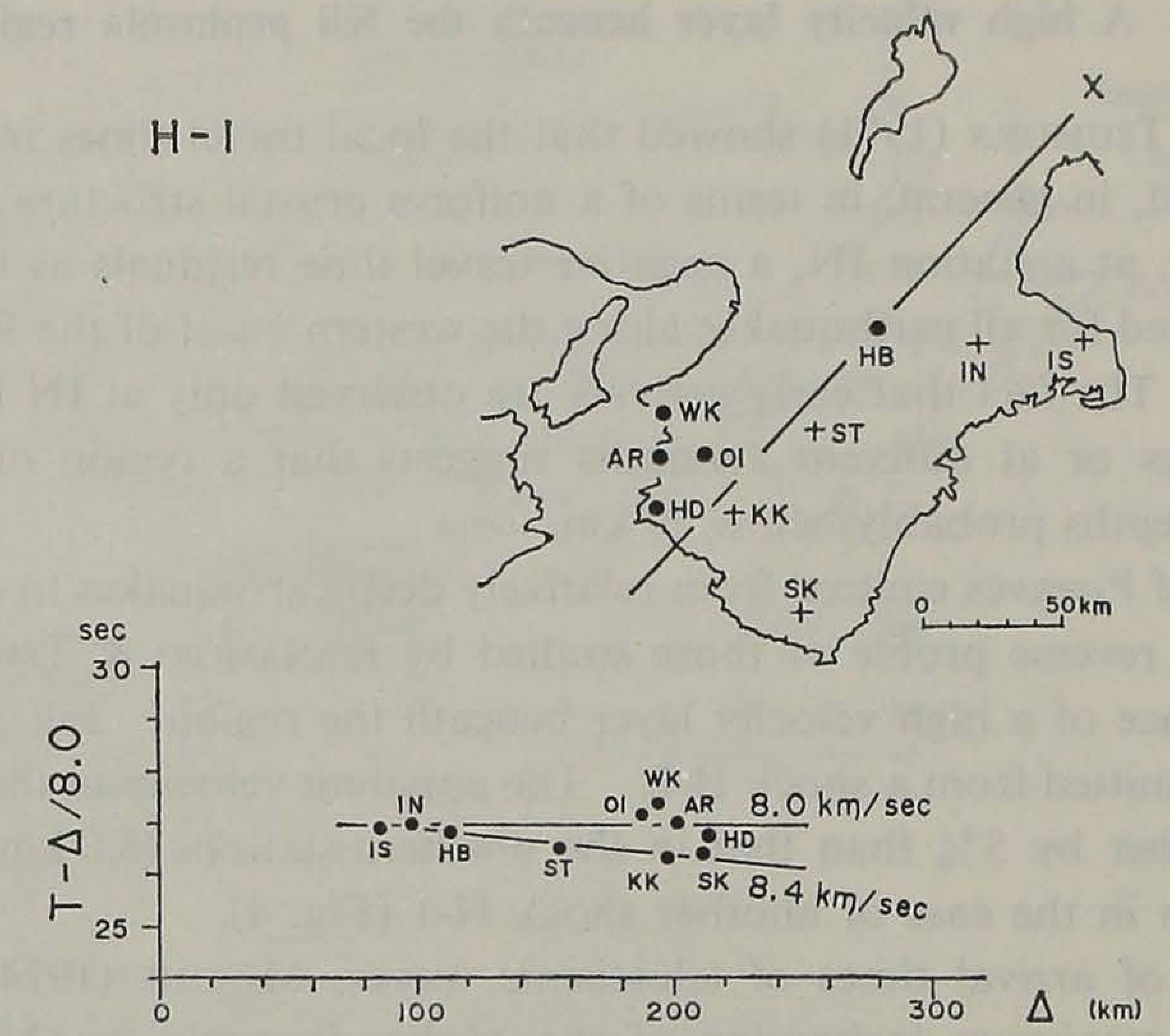

Fig. 4. Plots of reduced arrival times vs. epicentral distances for a shock H-1. The expressions are as same as in the case of Fig. 3.

quake which occurred in the Bay of Suruga in 1972 at a depth of 28 km was 8.6 km/sec in the Kii peninsula region. This also supports the existence of the high velocity layer.

4. A high velocity layer beneath the Shikoku region

The existence of a high velocity layer far below the Moho discontinuity is confirmed in the Shikoku region on the basis of both frequency distribution of P-wave apparent velocity in central Shikoku and travel times of waves traveling through the uppermost mantle beneath the region.

a. Apparent velocity at the Kochi Seismological Observatory

OIKE & KIMURA (1974) calculated the apparent velocity of P-waves for earthquakes with S-P times ranging 5 to 30 sec, using records at 3 observational stations with high sensitive instruments (URS, IHR and WMY) operated by the Kochi Seismological Observatory, the Kochi University. Fig. 5 shows the frequency distribution of the apparent velocity. Curves A and B are the results based on 3 iP data and a broken curve A′ includes eP data. In curve A′, 5 peaks appear at 5.6, 6.6, 7.2, 8.0 and 9.4 km/sec. The former 4 peaks may be related to crustal layering. A dominant peak also appears at 9.4 km/sec in curve A. Curve B show the frequency distribution for waves arriving from the opposite side to the case of A and A′. Several peaks also appear at velocities similar to those of A′, such as 5.6, 6.6 and 7.8 km/sec.

A high apparent velocity of 9.4 km/sec is suggestive of the following 3 cases; 1. at least one of velocity boundaries in the crust including the Moho discontinuity inclines west- or northwestwards, 2. earthquakes occur densely in some limited area below far the Moho discontinuity and 3. a high velocity layer exists far below the Moho discontinuity.

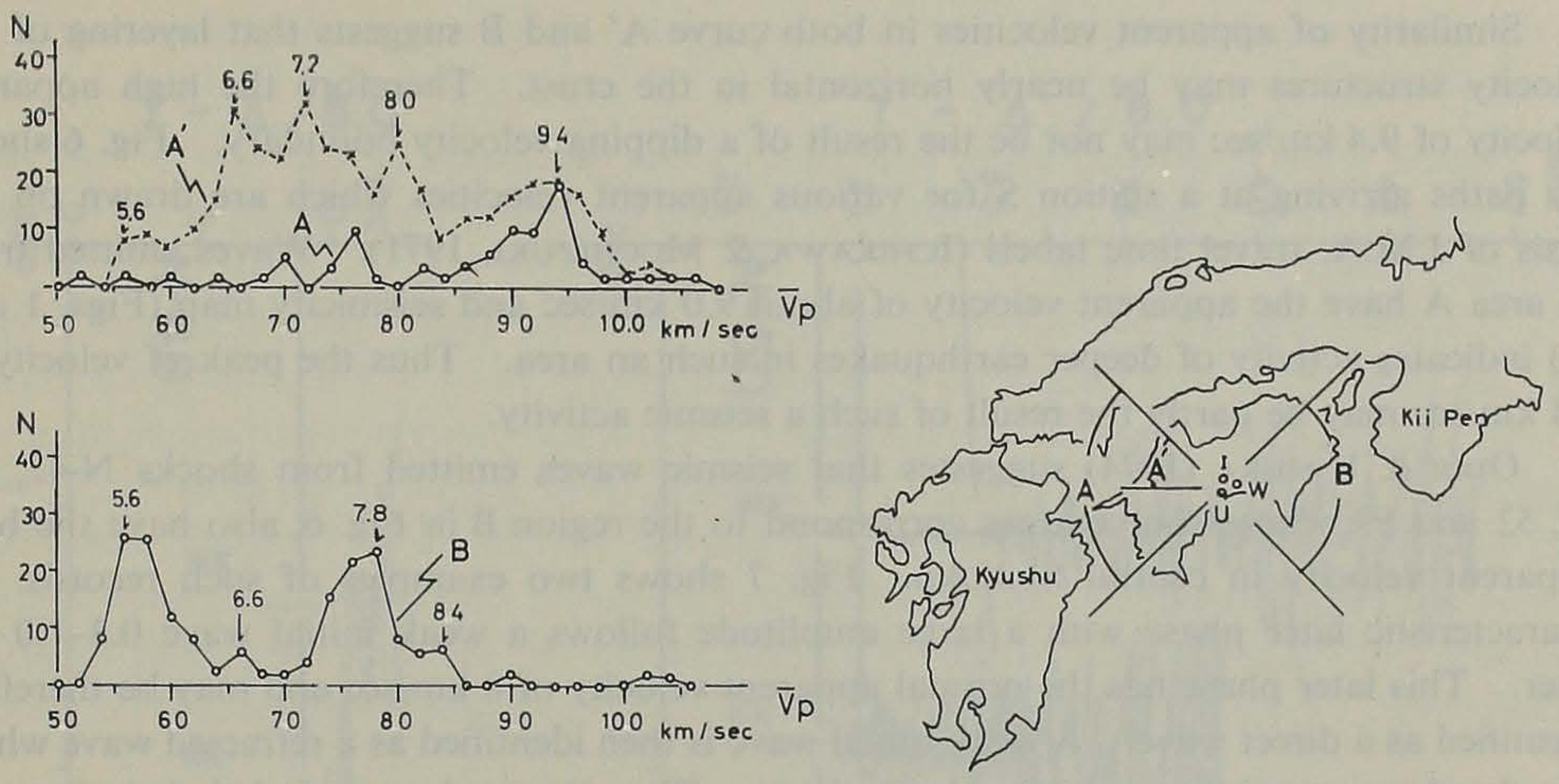

Fig. 5. Frequency distribution of apparent velocities of P-waves observed at three stations in central Shikoku (I; IHR, U; URS and W; WMY) for shocks occurring in each azimuthal range (A; N45°W-N135°W, B; N45°E-N135°E and A′; N45°W-N90°W) within a distance range of $5 < \text{S-P time} < 30$ sec. Two curves A and B give the results based on readings of records ranked as iP and a curve A′ gives the result based on both readings of iP- and eP-ranked P-waves.

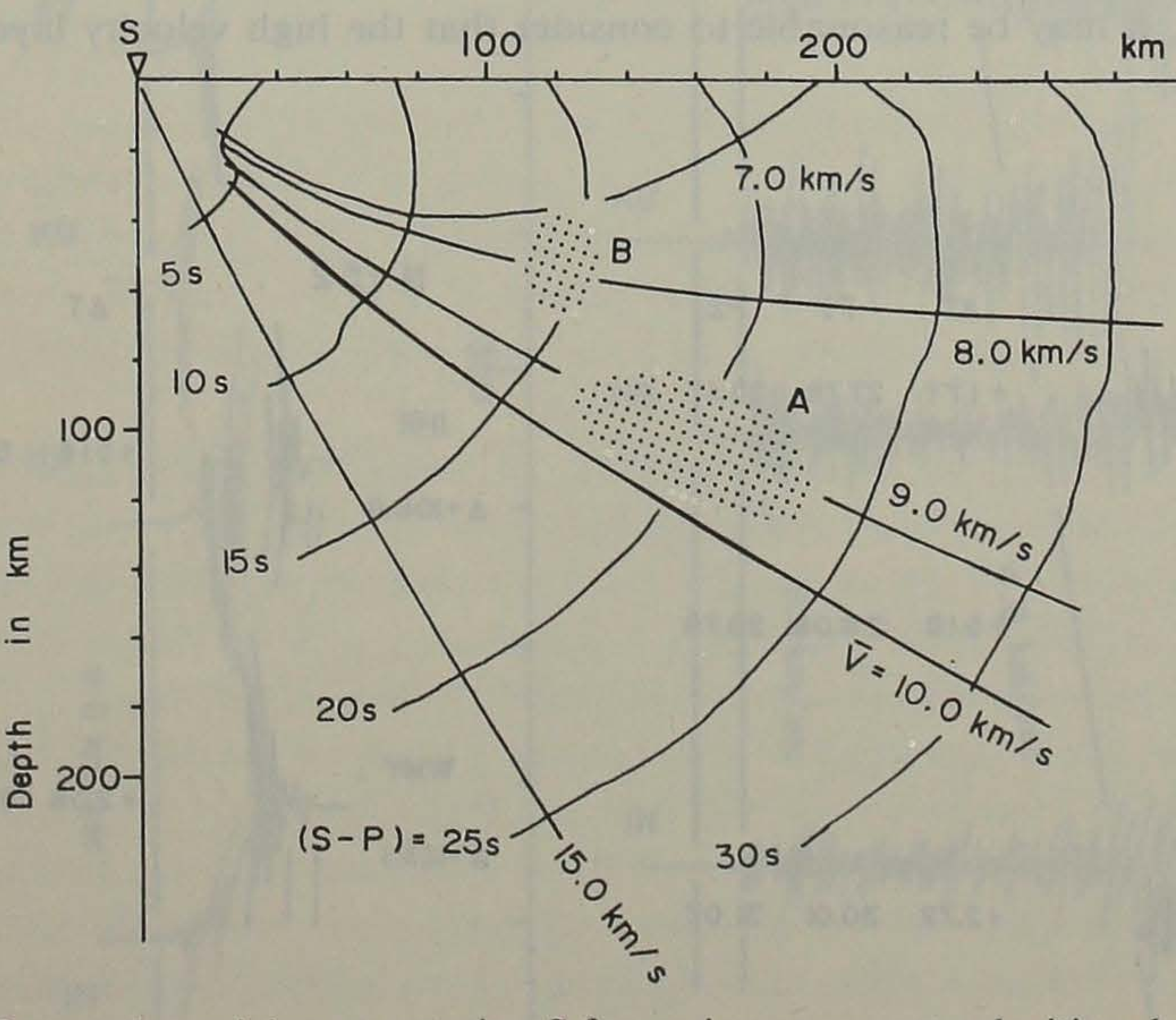

Fig. 6. Ray paths arriving at a station S for various apparent velocities, drawn from travel time tables given by Ichikawa & Mochizuki (1971). Curves crossing ray paths at right angles indicate S-P times. Consider a station S, zones A and B as observation station in central Shikoku, active zone beneath Kyushu and aftershock zone of earthquake which occurred in 1968 near Uwajima City, western Shikoku. P-waves from A and B have the apparent velocity of about 9 and 8 km/sec at a station S, respectively.

Similarity of apparent velocities in both curve A′ and B suggests that layering of the velocity structures may be nearly horizontal in the crust. Therefore the high apparent velocity of 9.4 km/sec may not be the result of a dipping velocity boundary. Fig. 6 shows ray paths arriving at a station S for various apparent velocities which are drawn on the basis of J.M.A. travel time tabels (ICHIKAWA & MOCHIZUKI, 1971). Waves emitted from an area A have the apparent velocity of about 9.0 km/sec and seismicity map (Figs. 1 and 14) indicates activity of deeper earthquakes in such an area. Thus the peak of velocity at 9.4 km/sec may be partly the result of such a seismic activity.

OIKE & KIMURA (1974) suggestes that seismic wave's emitted from shocks N-42, 48, 50, 52 and 59, whose source areas correspond to the region B in Fig. 6, also have the high apparent velocity in central Shikoku. Fig. 7 shows two examples of such records. A characteristic later phase with a large amplitude follows a weak initial wave 0.3–1.0 sec later. This later phase has the normal apparent velocity of 8 km/sec and may be therefore identified as a direct wave. A weak initial wave is then identified as a refracted wave which has the deepest point at a high velocity layer. Thus it may be concluded that the peak of the apparent velocity at 9.4 km/sec is partly due to the activity of deeper earthquakes and also partly due to the high velocity layer far below the Moho discontinuity.

In curve B, no peak can be seen at velocities greater than 8.0 km/sec, although relatively deep earthquakes occur at depthes ranging from 40 to 80 km in the eastern Shikoku-Kii peninsula regions (Fig. 14). This suggsests that the high velocity layer may not exist in the region east of Shikoku.

Because the velocity of 9.4 km/sec is too high to be accepted as a real velocity in the uppermost mantle, it may be reasonable to consider that the high velocity layer dips west- or northwestwards.

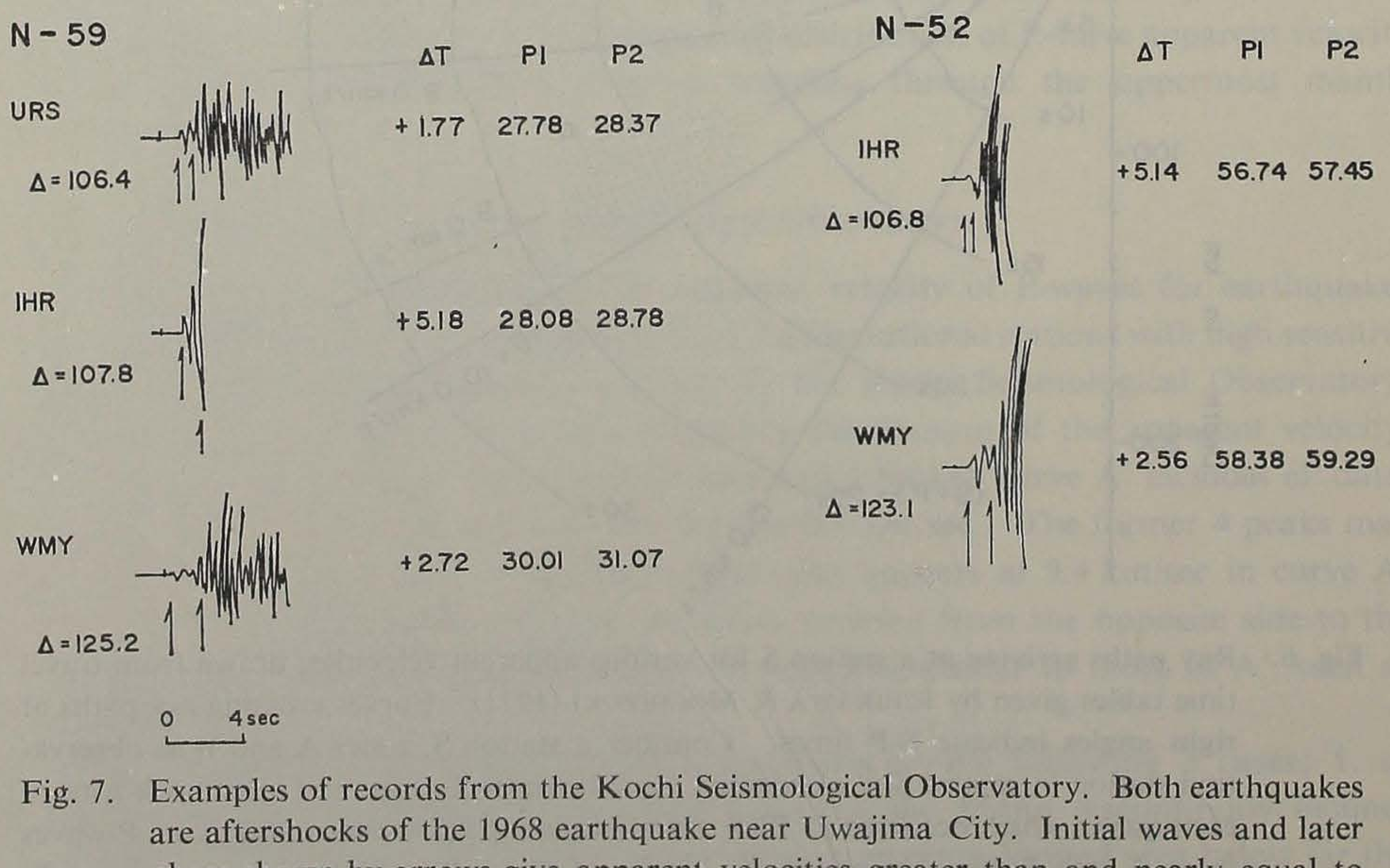

Fig. 7. Examples of records from the Kochi Seismological Observatory. Both earthquakes are aftershocks of the 1968 earthquake near Uwajima City. Initial waves and later phase shown by arrows give apparent velocities greater than and nearly equal to 8.0 km/sec, respectively.

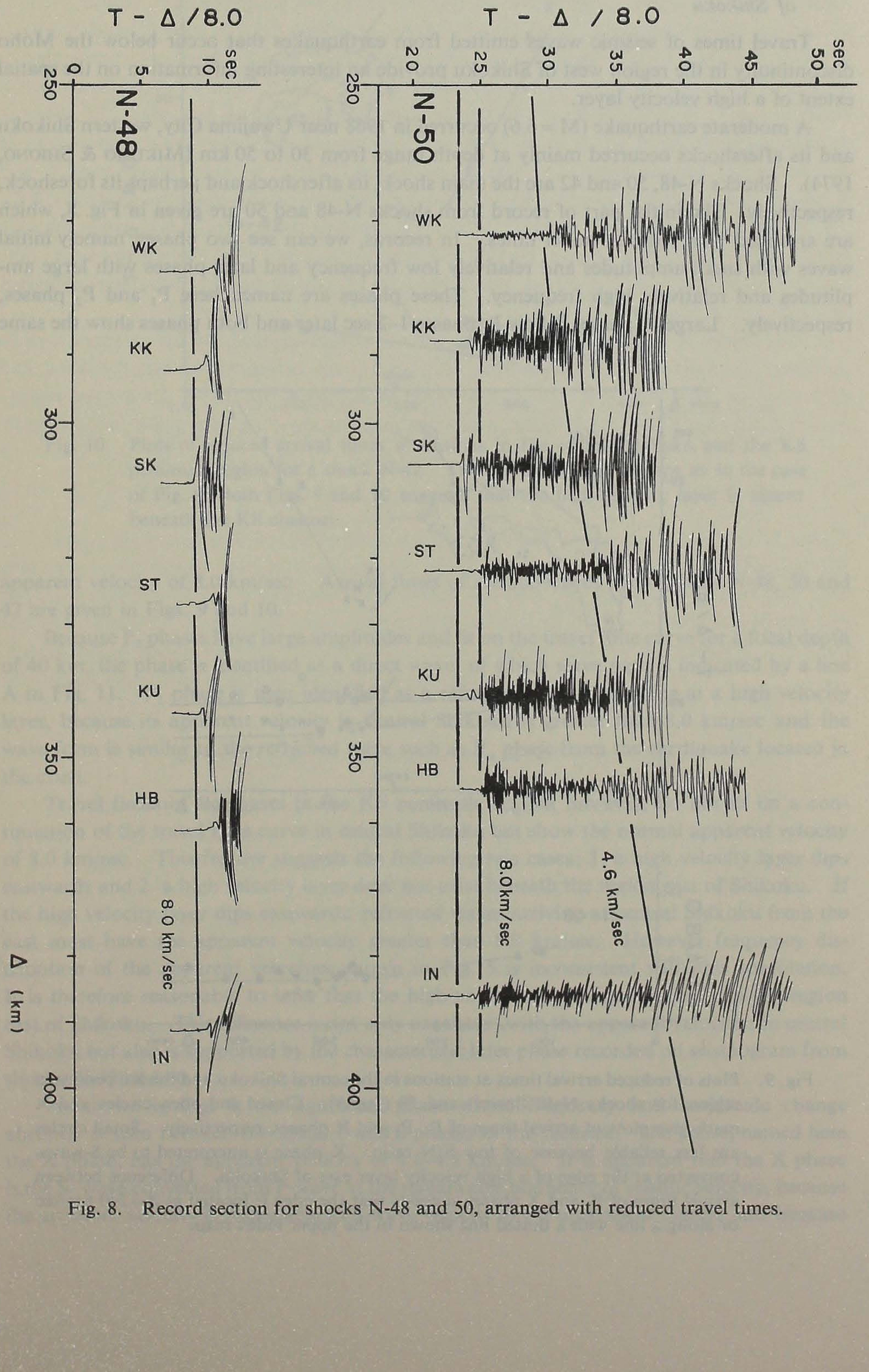

Fig. 8. Record section for shocks N-48 and 50, arranged with reduced travel times.

b. Travel times of seismic waves from earthquakes that occur in the region west of Shikoku

Travel times of seismic waves emitted from earthquakes that occur below the Moho discontinuity in the region west of Shikoku provide an interesting information on the spatial extent of a high velocity layer.

A moderate earthquake (M=6.6) occurred in 1968 near Uwajima City, western Shikoku and its aftershocks occurred mainly at depth range from 30 to 50 km (MIKUMO & SHIONO, 1974). Shocks N-48, 50 and 42 are the main shock, its aftershock and perhaps its foreshock, respectively. The initial part of record from shocks N-48 and 50 are given in Fig. 8, which are arranged with reduced travel times. In records, we can see two phases, namely initial waves with small amplitudes and relatively low frequency and later phases with large amplitudes and relatively high frequency. These phases are named here P_1 and P_2 phases, respectively. Large P_2 phases follow P_1 phases 1–2 sec later and both phases show the same

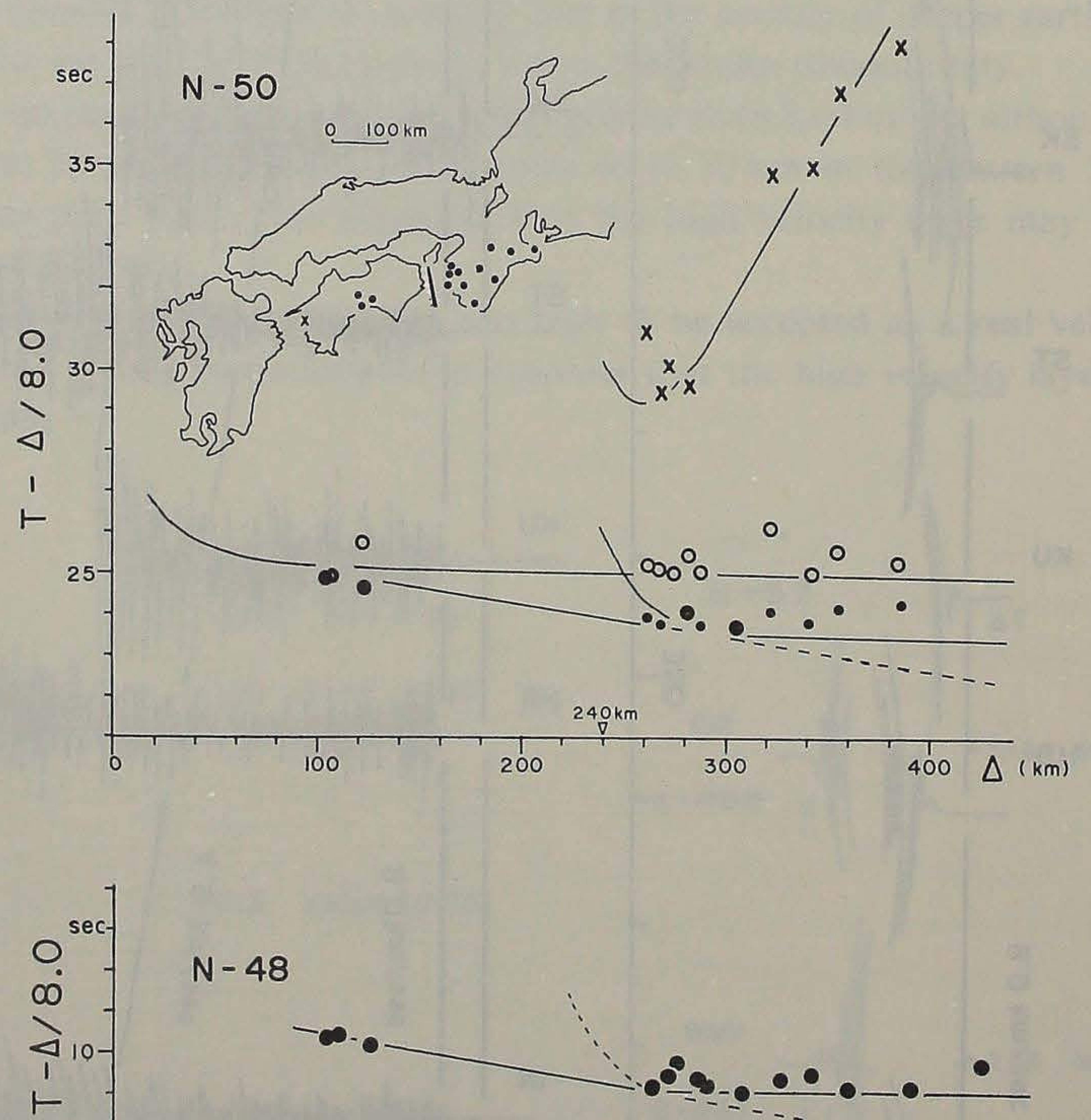

Fig. 9. Plots of reduced arrival times at stations in the central Shikoku and the Kii peninsula region for shocks N-48 (lower) and 50 (upper). Closed and open circles and X mark give plots of arrival times of P_1, P_2 and X phases, respectively. Small circles are less reliable because of low S/N ratio. X phase is interpreted to be S-waves converted at the edge of a high velocity layer east of Shikoku. Difference between arrival times of P_1 and X phases suggests that the edge is located at Δ=240 km/sec or along a line with a dotted line shown in the upper index map.

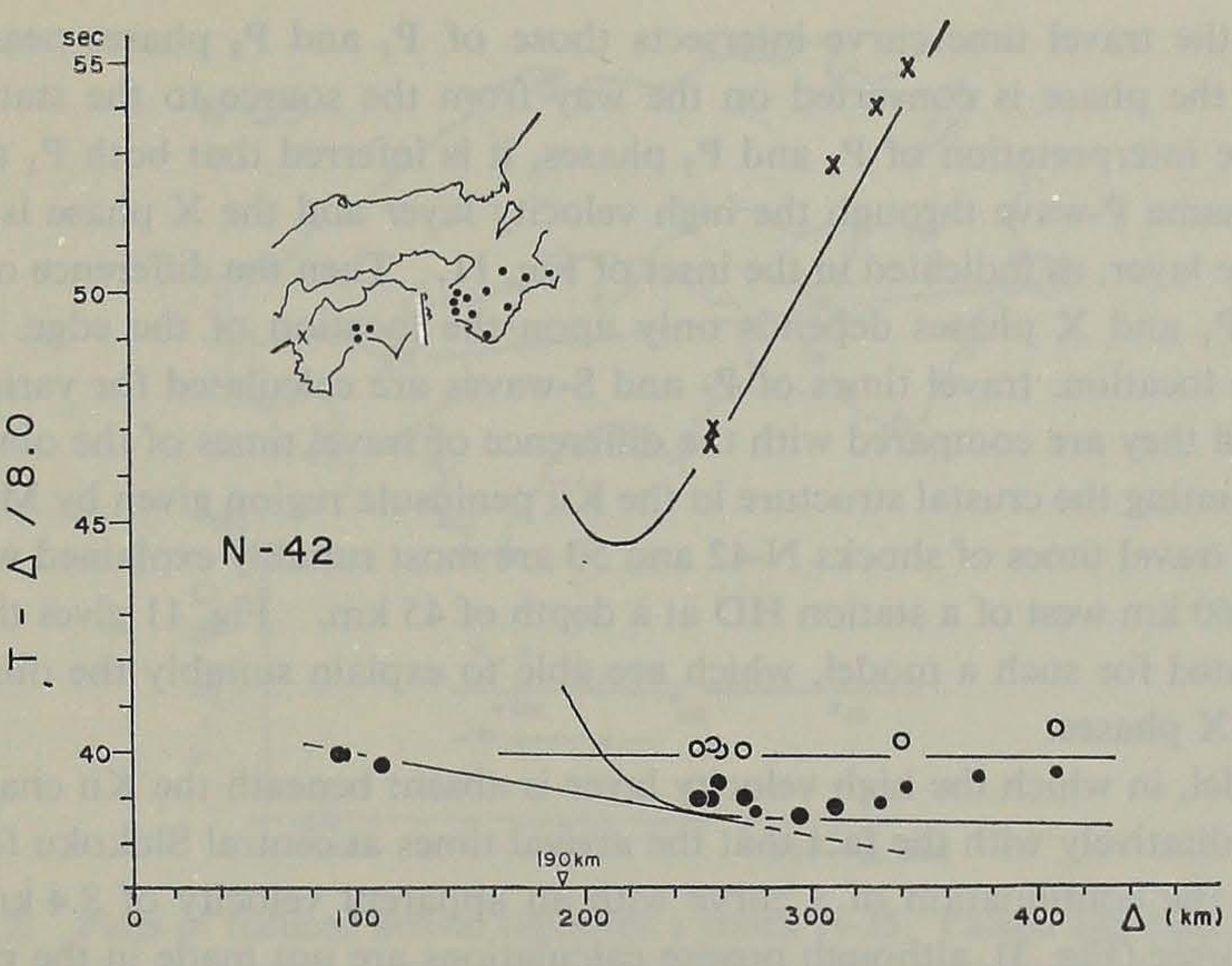

Fig. 10. Plots of reduced arrival times at stations in the central Shikoku and the Kii peninsula region for a shock N-42. The expressions are as same as in the case of Fig. 9. Both Figs. 9 and 10 suggests that the high velocity layer is absent beneath the Kii channel.

apparent velocity of 8.0 km/sec. Arrival times of seismic waves from shocks N-48, 50 and 42 are given in Figs. 9 and 10.

Because P_2 phases have large amplitudes and fit on the travel time curve for a focal depth of 40 km, the phase is identified as a direct wave, of which wave path is indicated by a line A in Fig. 11. P_1 phase is then identified as a refracted wave bottoming at a high velocity layer, because its apparent velocity in central Shikoku is greater than 8.0 km/sec and the wave form is similar to the refracted wave such as P_n phase from the earthquake located in the crust.

Travel times of P_1 phases in the Kii peninsula region, however, do not fit on a continuation of the travel time curve in central Shikoku but show the normal apparent velocity of 8.0 km/sec. This feature suggests the following two cases; 1. a high velocity layer dips eastwards and 2. a high velocity layer does not exist beneath the region east of Shikoku. If the high velocity layer dips eastwards, refracted waves arriving at central Shikoku from the east must have the apparent velocity greater than 8.0 km/sec. However frequency distribution of the apparent velocities shown in Fig. 5 is inconsistent with this speculation. It is therefore reasonable to infer that the high velocity layer does not exist in the region east of Shikoku. This inference is not only consistent with the apparent velocities in central Shikoku but also is supported by the characteristic later phase recorded on seismogram from shocks N-42 and 50.

As shown in Fig. 8, the significant phase whose frequency and amplitude change abruptly is seen between the initial P and S phases in the records. The phase, named here the X phase, has the apparent velocity of 4.6–4.8 km/sec. It is apparent that the X phase is the S- wave converted from P-wave at the remarkable boundary of seismic velocity, because the apparent velocity is reasonable as S-wave velocity in the uppermost mantle and because the fact that the travel time curve intersects those of P_1 and P_2 phases near $\Delta = 200$ km suggests that the phase is converted on the way from the source to the station. Taking account of the interpretation of P_1 and P_2 phases, it is inferred that both P_1 and X phases travel as the same P-wave through the high velocity layer and the X phase is converted at the edge of the layer, as indicated in the inset of Fig. 11. Then the difference of travel times between the P_1 and X phases depends only upon the location of the edge. In order to determine the location, travel times of P- and S-waves are calculated for various values of the depths and they are compared with the difference of travel times of the observed P_1 and X phases, assuming the crustal structure in the Kii peninsula region given by MIZOUE (1971). The observed travel times of shocks N-42 and 50 are most suitably explained when the edge is located 30–60 km west of a station HD at a depth of 45 km. Fig. 11 gives the travel time curves calculated for such a model, which are able to explain suitably the observed curves of P_2, P_1 and X phases.

This model, in which the high velocity layer is absent beneath the Kii channel, may be consistent qualitatively with the fact that the arrival times at central Shikoku for shock H-2 fit neither on the continuation of a curve with an apparent velocity of 8.4 km/sec nor on that of 8.0 km/sec (Fig. 3), although precise calculations are not made in the present study.

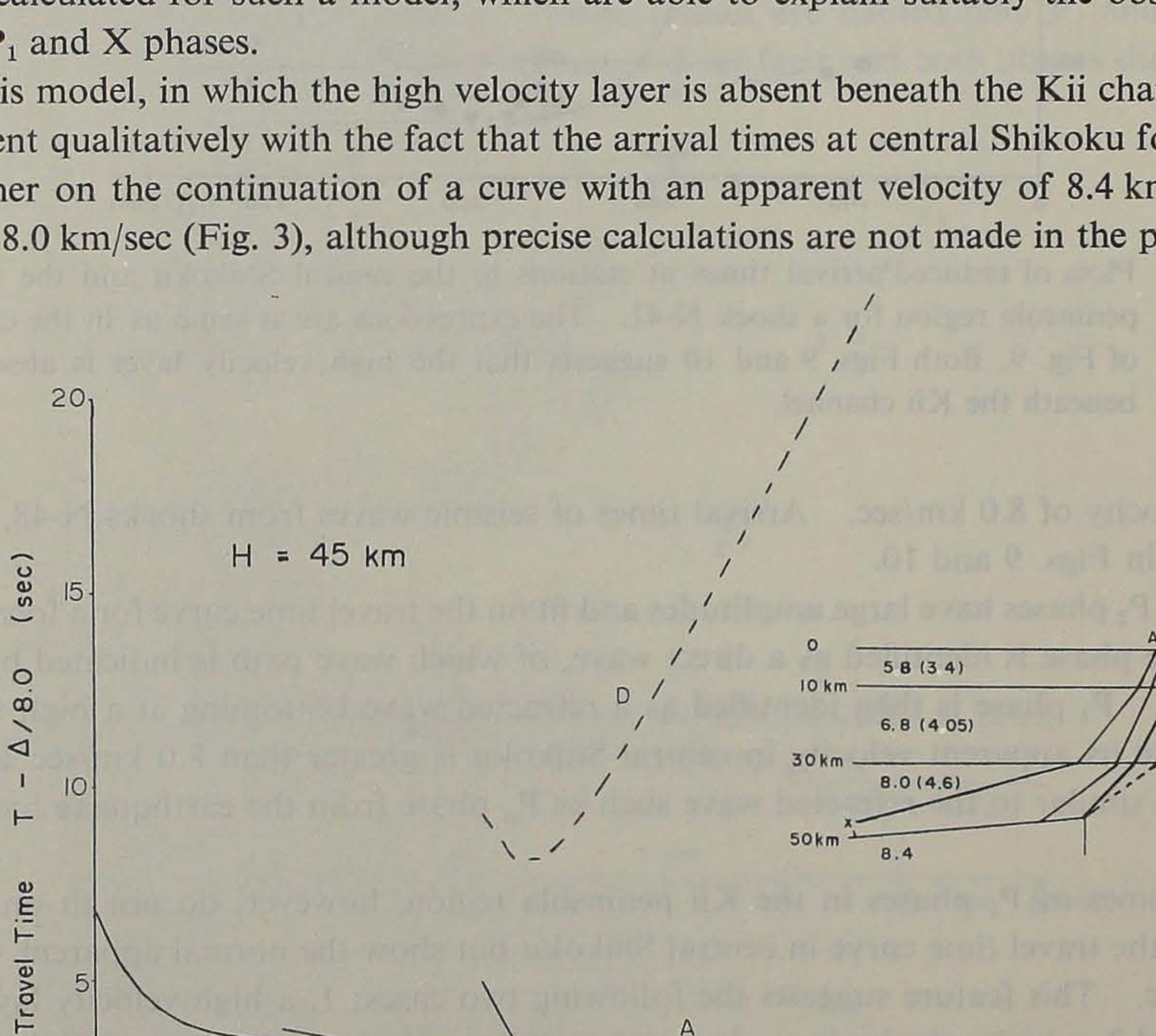

Fig. 11. Calculated travel times of P_1, P_2 and X phases, assuming crustal structure determined by MIZOUE (1971), $V_P = 8.0$ km/sec and $V_S = 4.6$ km/sec beneath the Moho discontinuity, $V_P = 8.4$ km/sec in a high velocity layer, a dip angle of the high velocity layer $= 5°$ the distance where the high velocity layer disappears $= 200$ km. Travel time curves A, B, C and D are calculated for ray paths shown by labels A, B, C and D in the inset. Ray paths of P_1, P_2 and X phases are consisdered as ray paths B and C, A and D, respectively. Fact that relation between travel times of P_1, P_2 and X phases is similar to the observed one supports the present interpretation.

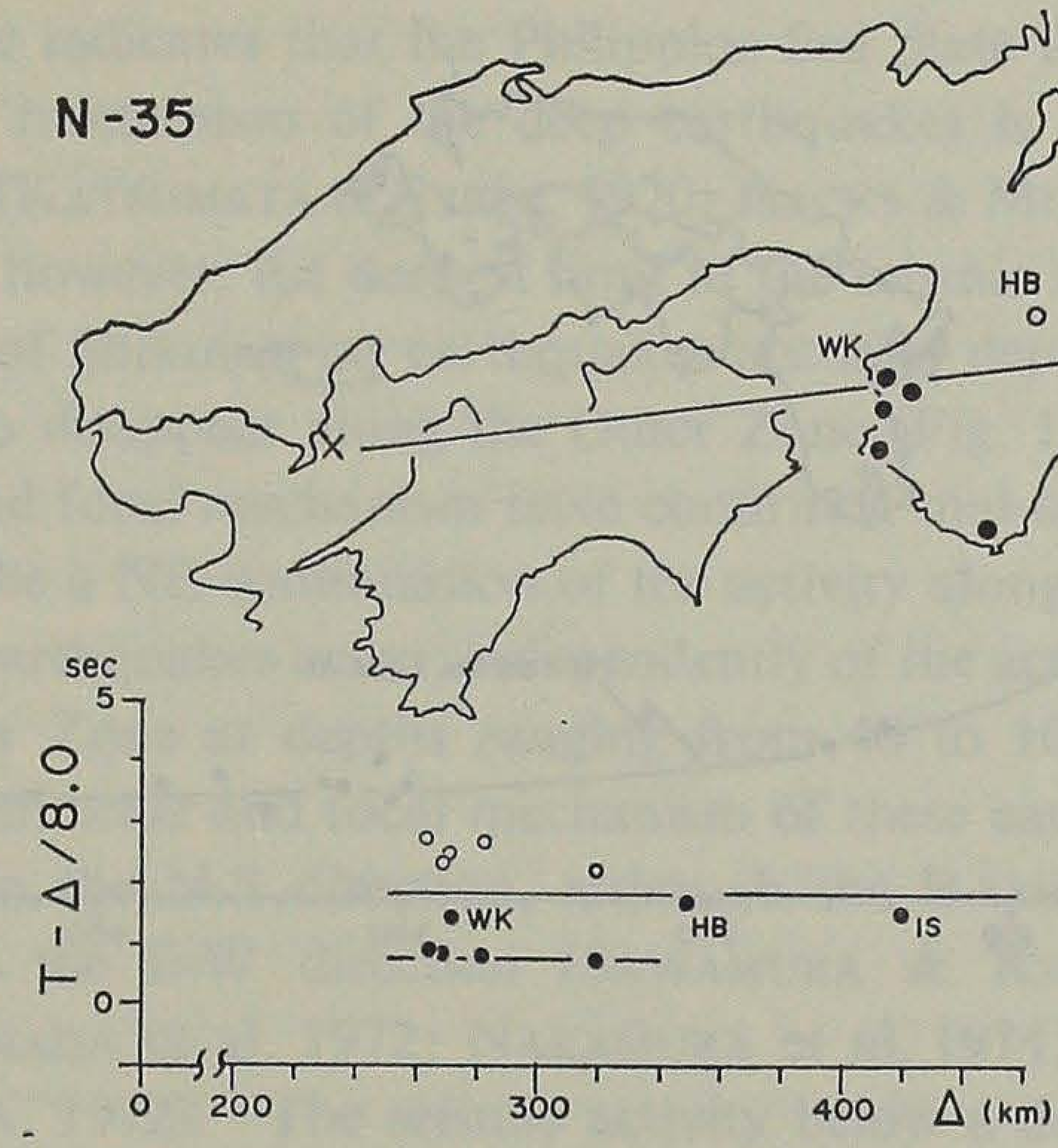

Fig. 12. Plots of reduced arrival times for a shock N-35. Closed and open circles give the initial and later phases. Note that northern stations do not observe P_1 phase as a first arrival.

Shock N-35 occurred in Iyo-nada at a depth of 60 km. As shown in Fig. 12, which gives the travel times from the earthquake, initial motions at stations WK, HB and IN, northern stations of the Wakayama observation network, arrive about 1.0 sec later than at other stations. Seismogram recorded at HB shows that P_1 phase does not arrive and that P_2 phase is observed as a first arrival. This suggests that the high velocity layer lies only south of the line connecting the origin and a station HB.

5. Heterogeneity of velocity in a limited depth range

Fig. 13 shows travel times with a reduction of 8.0 km/sec for shocks N-43 and G-3 which occurred in Kyushu at depths of 80 and 130 km, respectively. The horizontal projection of wave path cuts the velocity boundary east of Shikoku but there seems to appear no remarkable later phase that is attributable to an abrupt change of seismic velocity such as X phase as appeared in the records of shocks N-42 and 50. Arrival times fit on the J.M.A. travel time curves for focal depths of 80 and 130 km respectively. These evidences are suggestive of the normal upper mantle structure. Therefore the heterogeneity of velocity in the uppermost mantle may be restricted to a limited depth range from 40 to at least 80 km. Hamada (1973) and Aoki & Tada (1973) calculated travel time anomalies of teleseismic waves from the nulear explosion and suggested that the velocity in the upper mantle below the Outer Zone of Southwest Japan might be relatively lower than that below the Inner Zone. This evidence seems to be inconsistent with the existence of the high velocity layer beneath the Outer Zone. However because the result may be regarded as suggesting that the low velocity zone just below the high velocity layer extends more deeply than the case of the Inner Zone since the teleseimic waves penetrate the deeper portion of the upper mantle, the result is not necessarily inconsistent with the present result.

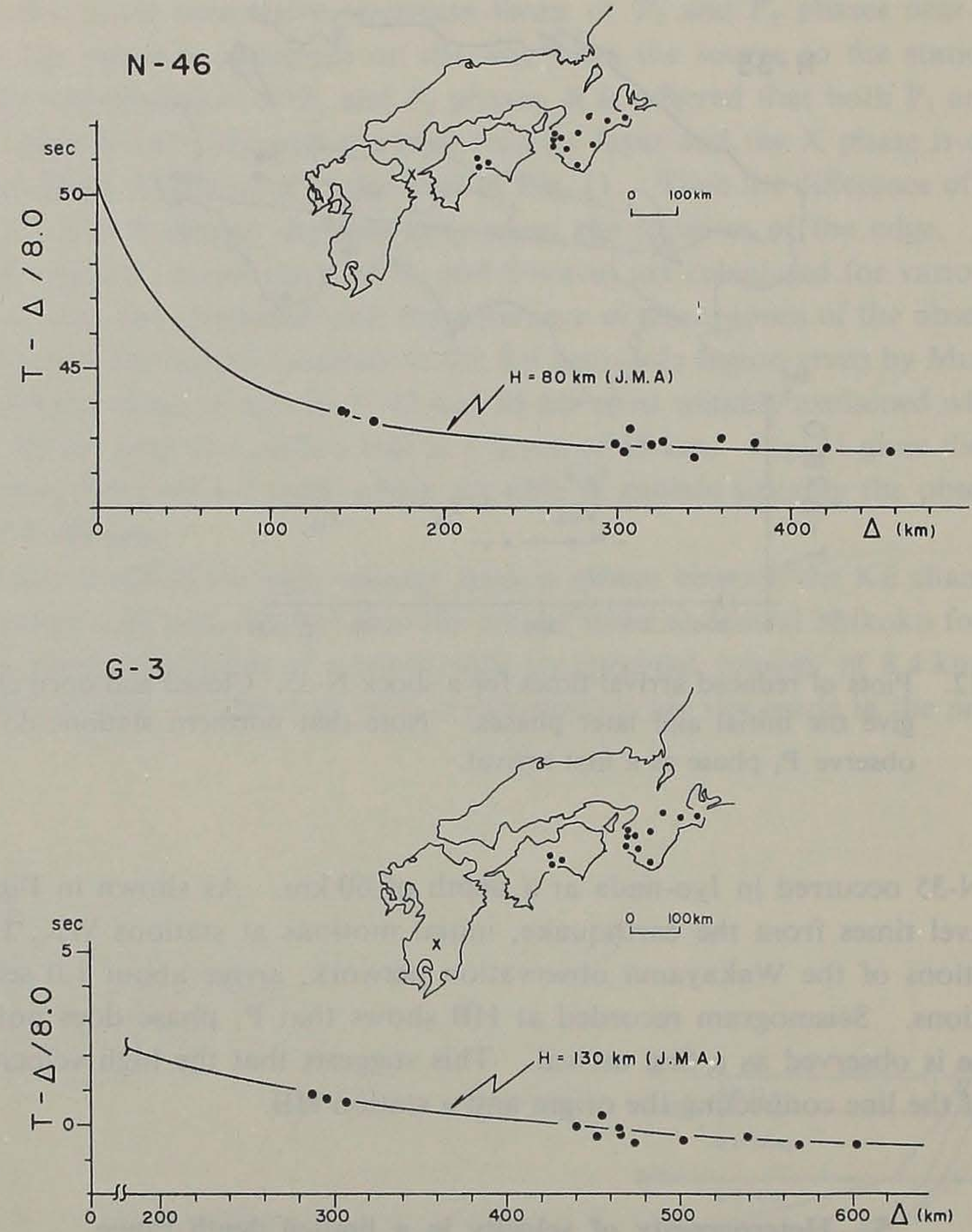

Fig. 13. Plots of reduced arrival times for shocks N-46 and G-3. Fact that arrival times are fitted on travel time curves for focal depths of 80 and 130 km, respectively, suggests a normal upper mantle structure.

6. Philippine Sea plate beneath Southwest Japan

From the travel time analysis and the activity of relatively deep earthquakes, the spatial extent of the underthrusting Philippine Sea plate beneath Southwest Japan is discussed in this section.

Existence of a high velocity layer beneath the Outer Zone of Southwest Japan verifies directly that a cool oceanic plate lies far below the Moho discontinuity in the area and its northern boundary suggests that the leading edge of the oceanic plate has reached only about 150–200 km inland from the Nanaki trough.

The shape of a descending oceanic plate is generally indicated most apparently by an active zone of deep and intermediate earthquakes (the Benioff zone). The leading edge of the plate is approximated by the deepest side of the active zone. A deep seismic zone along the Ryukyu arc indicates that the Philippine Sea plate descends to a depth of about 200–300 km. Focal mechanism of the deep earthquakes is also consistent with the descending of the plate (KATSUMATA & SYKES, 1970; ISACKS & MOLNER, 1971; OIKE, 1971a, b). Near Kyushu island, however, the deepest limit of the seismic zone becomes shallower. In Iyo-nada, northwest of Shikoku, no earthquakes occur at depths over 100 km. The deep seismic zone seems to disappear along the Outer Zone (Fig. 1). However, precise studies on seismic activity and focal mechanism have confirmed that seismic activity in the regions is also considered to be a NE continuation of the activity along the Ryukyu arc.

Relatively deep earthquakes occur, independently of the activity in the crust, in a narrow zone along the Outer Zone at depths ranging from 40 to 100 km and form an inclined seismic zone of a small scale and focal mechanism of these earthquakes generally indicates the P-axis oriented in the N-S direction, although the P-axis of a crustal earthquake is generally oriented in the E-W direction (SAWAMURA & KIMURA, 1971; KANAMORI & TSUMURA, 1971; YAMADA et al, 1972; NAKAMURA et al, 1974; SHIONO, 1970, 1973; OOIDA & ITO, 1972; NISHIDA, 1972). The seismic activity below a depth of 40 km is represented approximately in Fig. 14 on the basis of the Regional Catalogue of Earthquakes in and near Japan (1961–1970) published by the J.M.A.. These evidence suggests that the earthquakes represent the interaction between the continental and oceanic plates. Because the leading edge of the underthrusting oceanic plate may be considered to extend to the neighborhood of the active area of the relatively deep earthquakes, it may be possible to infer the location of the leading edge independently of the travel time analysis, on the basis of seismic activity, mainly of Fig. 14 and additionaly of the results of studies on micro-earthquakes.

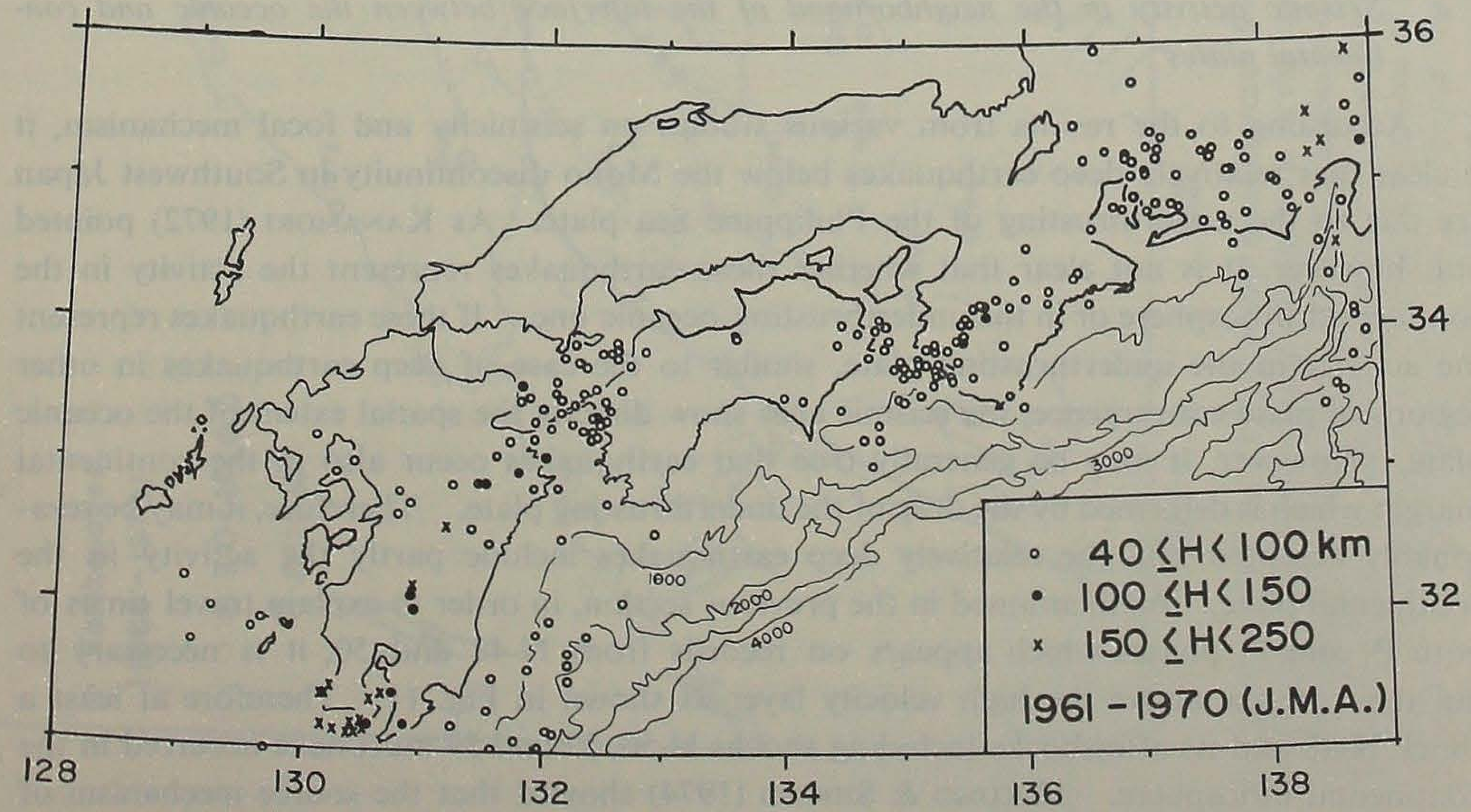

Fig. 14. Distribution of earthquakes deeper than 40 km, drawn on the basis of theRegional Catalogue of Earthquakes in and near Japan (1961–1970) published by J.M.A.. Contour lines show a bathymetry in meters.

As far as the regions from Shikoku to the Kii peninsula are concerned, the spatial extent of the underthrusting plate inferred from the travel time analysis resembles to the active area of relatively deep earthquakes (Figs. 14 and 15). This supports the reality of the plate in the irregular (convex) form in the Shikoku-Kii peninsula region.

Existence of the high velocity layer in the Chubu region has not yet been confirmed by any travel time analysis. Relatively deep earthquakes also occur in southern Chubu at depths ranging from 40 to 60 km. These earthquakes have focal mechanisms with the P-axes oriented generally in the N-S direction (YAMADA et al, 1972; OOIDA & ITO, 1972). These facts support the underthrusting of the Philippine Sea plate. Therefore the active area represents approximately where the plate extends. SUGIMURA (1971) discussed the plate boundary around Japanese islands and proposed a boundary between the continental plate and the oceanic Philippine Sea one. The boundary which is traced eastwards along the Nankai trough impinges the Hunshu in the west part of the Izu peninsula and passes through the area north of the peninsula to continue to the Sagami trough on the east side. From SUGIMURA's proposal and both or either of the travel time analysis and the seismic activity, it is concluded that the leading edge of the Philippine Sea plate crosses obliquely the Kii peninsula and reaches north part of the Izu peninsula through the southern Chubu region (Fig. 15).

The high velocity layer beneath Kyushu also has not discussed from any travel time analysis. However the location of the leading edge will be easily inferred only from seismic activity in the area, considering the seismic activity along the Ryukyu arc. The results are summarized in Fig. 15.

7. Discussions

a. Seismic activity in the neighborhood of the interface between the oceanic and continental plates

According to the results from various studies on seismicity and focal mechanism, it is clear that relatively deep earthquakes below the Moho discontinuity in Southwest Japan are due to the underthrusting of the Philippine Sea plate. As KANAMORI (1972) pointed out, however, it is not clear that whether these earthquakes represent the activity in the continental lithosphere or in the underthrusting oceanic one. If these earthquakes represent the activity in the underthrusting plate, similar to the case of deep earthquakes in other regions of plate convergence, the seismic area show directly the spatial extent of the oceanic plate. However, it may be generally true that earthquakes occur also in the continental margin which is deformed by the drag of the underthrusting plate. Therefore, it may be rezasonably accepted that the relatively deep earthquakes include partly the activity in the continental plate. As mentioned in the previous section, in order to explain travel times of both P_1 and P_2 phases which appears on records from N-48 and 50, it is necessary to put their origins above the high velocity layer as shown in Fig. 11. Therefore at least a shock N-48 and its aftershocks including shocks N-50, 52 and 59 must have occurred in the continental lithosphere. MIKUMO & SHIONO (1974) showed that the source mechanism of this earthquake could be interpreted in terms of internal deformation in the margin of the continental lithosphere.

Then, the active area of relatively deep earthquakes may be regarded as showing ap-

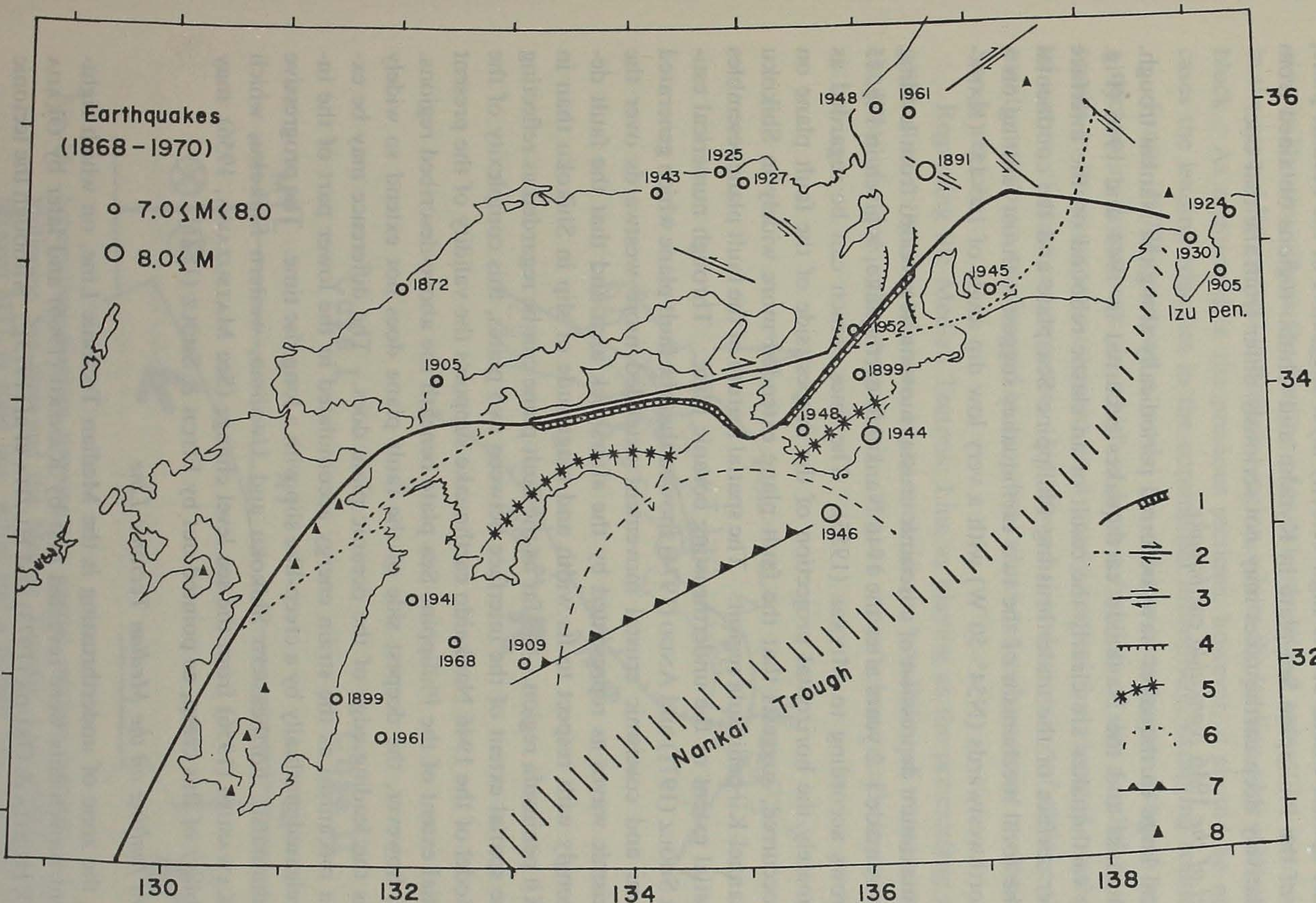

Fig. 15. Spatial extent of the Philippine Sea plate beneath Southwest Japan. The Philippine Sea plate underthrusts northwestwards along the Nankai trough and its leading edge extends to the zone shown by a line 1. 1; the location of the leading edge of the underthrusting plate. 2; the Median Tectonic Line (a solid line; active and a broken line; inactive). 3; major active transcurrent fault. 4; major active thrust fault. 5; a line of maximum depression of coseismic crustal movements at the time of the 1946 Nankaido earthquake drawn from MIYABE (1955). 6; a source area of Tsunami at the time of the 1946 Nankaido earthquake presented by HATORI (1970). 7; the Nankai Thrust proposed by SAWAMURA (1953), who attributed first the 1946 Nankaido earthquakes to thrusting along the Nankai Thrust. 8; active volcanoes. Epicenters and dates of recent major earthquakes are also drawn.

proximately the spatial extent of the Philippine Sea plate but, strictly speaking, should be regarded as showing only the strongly stressed area due to the underthrusting of the Philippine Sea plate. As the seismic area around the Kii channel shows a fairly good agreement with the spatial extent of the high velocity layer suggestive of the oceanic plate, the leading edge of the Philippine Sea plate in Kyushu and Chubu regions obtained from the activity of relatively deep earthquakes may not seriously differ from the real one.

b. Fault model of the 1946 *Nankaido earthquake*

Many histrical large earthquakes have occurred periodically along the Nankai trough. Recently the Tonanaki and the Nankaido earthquakes occurred in 1944 and 1946 (Fig. 15). These large earthquakes are clearly the result of an elastic rebound on the interface between the upper surface of the underthrusting Philippine Sea plate and the continental plate. In fact, the focal mechanism of the two earthquakes suggest a thrust faulting on a plane inclining northwestwards (N54°–50°W) with a very low dip angle of 10°–15° (KANAMORI, 1972).

The lines of maximum depression of coseismic crustal movement revealed from leveling resurvey, which was made 1–2 years after the 1946 Nankaido earthquake, is given in Fig. 15 by lines with arrows according to MIYABE (1955). The lines, which can be regarded as showing approximately the horizontal projection of the deepest side of the fault plane on which thrusting occurred, suggests that the fault plane extended more widely in Shikoku than in the Kii channel-Kii peninsula region. The spatial feature of the fault plane resembles to that of the spatial extent of the underthrusting oceanic plate. Through numerical estimations, FITCH & SHOLZ (1971) and ANDO (1974) showed that the fault plane which generated effectively Tsunami and coseismic crustal movement extended more westwards over the source area of seismic waves as represented by the aftershock area and that the fault developed more strongly with respect to its width and magnitude of slip in Shikoku than in the Kii channel-Kii peninsula region. As far as the fault plane can be regarded as reflecting approximately the spatial extent of the interface between two plates, this complexity of the presented fault model of the 1946 Nankaido earthquake supports the validity of the present result on the spatial extent of the Philippine Sea plate beneath the above-described regions. Strictly speaking, however, the deepest side of the fault plane does not extend so widely towards inland as the leading edge of the oceanic plate does. The difference may be explained by such a mecanism as the strain energy accumulated in the lower part of the interface has been released gradually by a creep-like slip with a long rise time. The progressive depression at Takamatsu, northeastern Shikoku and Uwajima, western Shikoku, which was inferred by KAWASUMI (1956) from the sea level change (See MATSUZAWA, 1956), may suggest the possibility of this creep, as pointed out by FITCH & SHOLZ (1971).

c. Transcurrent faulting on the Median Tectonic Line

Inland from the zone of underthrusting is the Median Tectonic Line, on which right-lateral transcurrent movements were revealed first by KANEKO (1966) and later by OKADA (1968, 1970, 1971), HUZITA & OKUDA (1973) and HUZITA et al (1973). Although the tectonic line extends for more than 800 km in Southwest Japan (Fig. 15), sharp and fresh topographic offsets are not distributed along the whole course of the tectonic line but are confined within the western half, about 250 km long from the middle part of the Kii peninsula as far as the Mt. Ishizuchi in the western part of Shikoku. Recent movements in central Shikoku yields an average rate of right-lateral slip of about 5 mm/year (OKADA, 1968, 1970).

Fig. 16 shows a spatial relationship between the activity of faulting on the Median Tectonic Line and the spatial extent of the Philippine Sea plate beneath Southwest Japan; the transcurrent movement is inactive in the central Kii peninsula-Chubu region, possibly also in Kyushu, where the leading edge extends inland across the tectonic line, and active in the central Kii peninsula-Shikoku region, where the leading edge still remains in the outer block. As mentioned in the previous sections, however, it should be noted that in both cases the leading edge lies in the continental lithsophere, excepting southern Kyushu.

FITCH (1972) proposed a model for oblique convergence between two plates, namely a decoupling hypothesis, in which at least a fraction of slip parallel to the plate margin results in transcurrent movement on a nearly vertical fault located on the continental side of a zone of plate convergence. He showed that decoupling of oblique slip in the manner mentioned above was favored in many real situations such as recent movements in the western Sunda region.

Regarding the Median Tectonic Line as playing as the pre-existeng zone of weakness conductive to horizontal shear, let us consider the possibility of transcurrent movements on the basis of a decoupling hypothesis. Fig. 16 shows schematically in cross sections the two

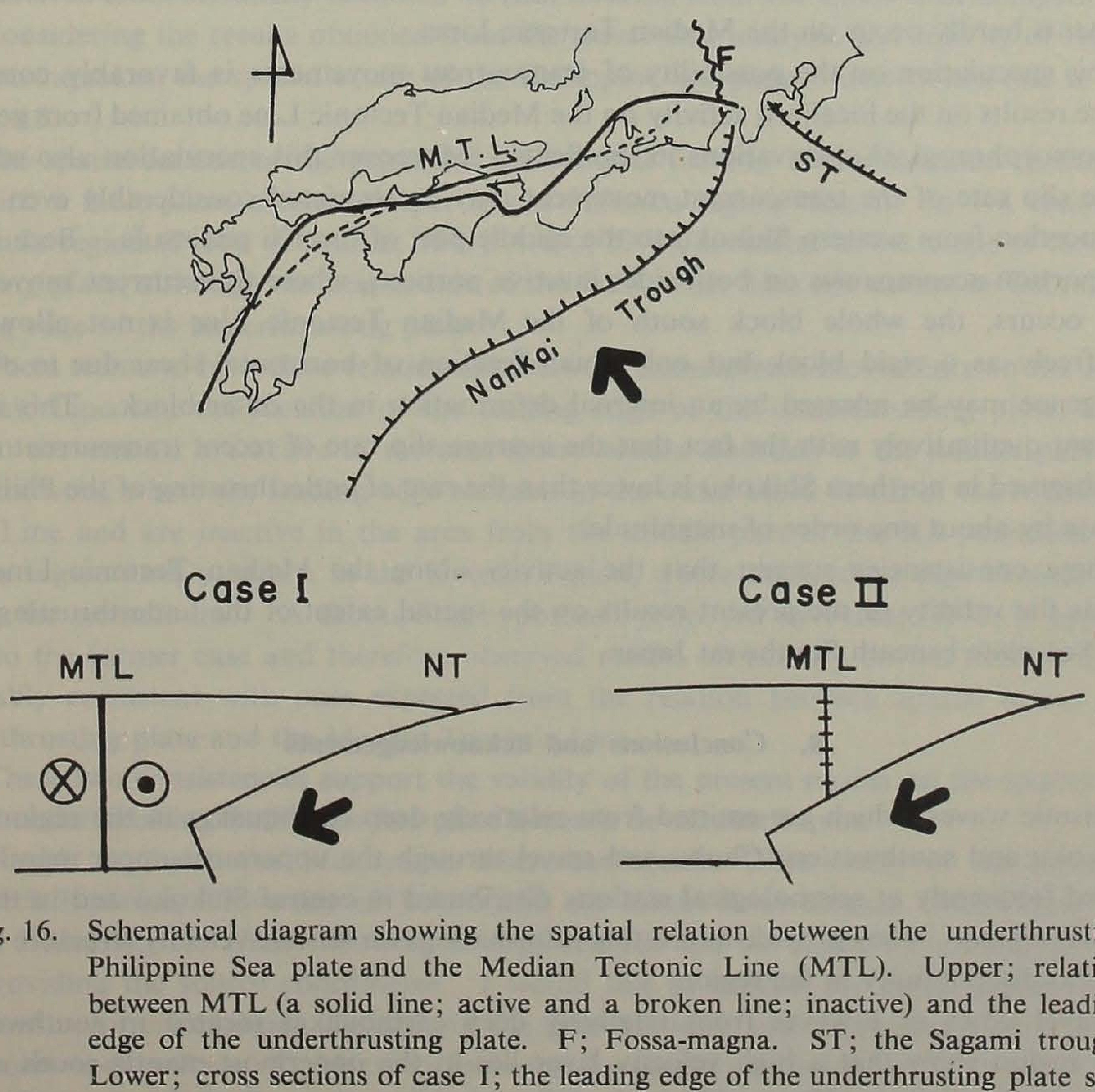

Fig. 16. Schematical diagram showing the spatial relation between the underthrusting Philippine Sea plate and the Median Tectonic Line (MTL). Upper; relation between MTL (a solid line; active and a broken line; inactive) and the leading edge of the underthrusting plate. F; Fossa-magna. ST; the Sagami trough. Lower; cross sections of case I; the leading edge of the underthrusting plate still remains in the outer block, and case II; the leading edge extends inland across MTL. Cases I and II correspond to the active and inactive area of MTL.

cases of the spatial relations between the Median Tectonic Line which is assumed to extend vertically throughout the continental plate.

In the case that the leading edge of the underthrusting plate does not reach the Median Tectonic Line (case I in Fig. 16), transcurrent movements occur in the right-lateral sense on the tectonic line. Because the oceanic plate underthrusts northwestwards along the Nankai trough, in other wards, oblique convergence occurs between the oceanic and continental plates, horizontal shear stress is generated in the continental margin. A vertical fault concentrates horizontal shear stress more effectively than the inclined interface between two plates does. Therefore the outer block of the continental plate moves westwards, decoupling the underthrusting plate. Thus a fraction of slip parallel to the plate margin results in transcurrent movements on the Median Tectonic Line. The remaining stress results in thrusting on the inclined interface, namely a large earthquake such as the 1946 Nankaido earthquake.

On the other hands, the decoupling hypothesis is not applicable to the case that the leading edge extends inland across the Median Tectonic Line (case II in Fig. 16), because the underthrusting oceanic plate is in contact with both the outer and inner blocks. The hypothesis is not also applicable to Kyushu, where the tectonic line is nearly normal to the direction of a relative motion between two plate. Therefore in this case transcurrent movements hardly occur on the Median Tectonic Line.

This speculation on the possibility of transcurrent movements is favorably consistent with the results on the localized activity on the Median Tectonic Line obtained from geologic and geomorphorogical observations in the fields. Moreover this speculation also suggests that the slip rate of the transcurrent movement may be restricted considerably even in the active portion from western Shikoku to the middle part of the Kii peninsula. Because the active portion accompanies on both sides inactive portions, where transcurrent movements hardly occurs, the whole block south of the Median Tectonic Line is not allowed to move freely as a rigid block but only small fraction of horizontal shear due to oblique convergence may be released by an internal deformation in the outer block. This is also consistent qualitatively with the fact that the average slip rate of recent transcurrent movement observed in northern Shikoku is lower than the rate of underthrusting of the Philippine Sea plate by about one order of magnitude.

These consistencies suggest that the activity along the Median Tectonic Line also supports the validity of the present results on the spatial extent of the underthrusting Philippine Sea plate beneath Southwest Japan.

8. Conclusions and acknowledgements

Seismic waves, which are emitted from relatively deep earthquakes in the region west of Shikoku and southwestern Chubu and travel through the uppermost upper mantle, are observed frequently at seismological stations distributed in central Shikoku and in the Kii peninsula region. They provide interesting informations on seismic velocity structure below the Moho discontinuity in the region.

Travel times of P-waves from relatively deep earthquakes located in southwestern Chubu region show that a high velocity layer lies in the uppermost mantle south of the line connecting stations HD and HB in the Kii peninsula region. Both frequency distribution of apparent velocities in central Shikoku given by OIKE & KIMURA (1974) and travel times of seismic waves from earthquakes in the region west of Shikoku show that a high velocity layer lies below the Shikoku region and is absent in the Kii channel.

Travel times of waves from earthquakes which occur at depths of 80 and 130 km in Kyushu and travel time anomalies of teleseismic waves from a nuclear explosion calculated by HAMADA (1973) and AOKI & TADA (1973) suggest the possibility that heterogeneity of seismic velocity in the uppermost mantle may be limited only within a depth range from 40 to at most 80 km.

The presented high velocity layer verifies directly that a cool oceanic plate lies beneath the Moho discontinuity and suggests that the leading edge of the underthrusting plate reaches only 150–200 km inland from the Nankai trough and still remains in the continental lithosphere. This suggests that KANAMORI's model is applicable to the whole area of Southwest Japan.

Because relatively deep earthquakes forms an inclined seismic belt of a small scale along the Outer Zone of Southwest Japan and can be considered to represent the interaction between the continental and oceanic plates, the spatial extent of the oceanic plate beneath the regions may be inferred from epicentral distribution of these earthquakes, independently of the travel time analysis. In the Shikoku-Kii peninsula region, the leading edge inferred from seismicity is similar to that inferred from the travel time analysis.

Considering the results obtained from the travel time analysis and activity of relatively deep earthquakes, the spatial extent of the Philippine Sea plate is determined and is shown in Fig. 15.

The spatial feature of the presented fault model for the 1946 Nankaido earthquakes, in which a fault plane extends deeper in the Shikoku region than in the Kii channel-Kii peninsula region (FITCH & SHOLZ, 1971; ANDO, 1974), is similar to the shape of the underthrusting plate, although the deeper side of the fault plane does not extend so inalnd as the leading edge of the underthrusting plate.

There seems to be a close relationship between transcurrent movements on the Median Tectonic Line and the location of the leading edge of the underthrusting plate. Transcurrent movements are active in the area from western Shikoku to the middle part of the Kii peninsula, where the leading edge remains in the outer block south of the Median Tectonic Line and are inactive in the area from the middle part of the Kii peninsula to the Chubu region and, possibly, in the Kyushu region, where the leading edge extends inland across the tectonic line. A decoupling hypothesis proposed by FITCH (1972) is applicable only to the former case and therefore observed results on activity on the tectonic line are favorably consistent with ones expected from the relation between spatial extent of the underthrusting plate and the Meidan Tectonic Line.

These two consistencies support the validity of the present results on the spatial extent of the underthrusting Philippine Sea plate beneath Southwest Japan.

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