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P-traveltime Anomalies and Upper Mantle Structures Beneath Japan —Review of Japanese Seismological Investigations—*

By

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Abstract

A brief review of the studies on large-scale lateral inhomogeneity in the upper mantle beneath Japan will be presented. A considerable amount of seismological evidences suggesting an anomalous structure in the upper mantle have been accumulated without definite explanations since about 50 years ago. Recent investigations of the upper mantle beneath Japan have revealed a remarkably anomalous structure and gave a reasonable explanation as to the cause of the anomalous observational data in the past. Such works are represented by Utsu's papers including critical reviews of Japanese papers up to 1970.

The anomalous structure under consideration seems to be completed by Utsu to a first approximation. For further development of such an investigation, however, quantitatively precise treatment is essential. That is, precise calculations of the path and traveltime of the seismic wave propagating through a heterogeneous medium are necessary, especially for complicated areas like Japan. Yamamizu and Hamada advanced their studies independently along this direction by means of three-dimensional-seismic-wave-ray tracing. Using the traveltime to the Japanese stations for the nuclear explosion Cannikin in the Central Aleutian islands in 1971, Hamada constructed the upper mantle model based on the work by Utsu and showed the theoretically expected traveltime anomalies for the model, comparing those with the actually observed anomalies for that nuclear explosion.

1. Introduction

The existence of anomalous upper mantle structure beneath Japan has been established by the recent seismological investigation, especially by a series of Utsu's works (*Katsumata*, 1960; *Hisamoto*, 1965; *Utsu*, 1966, 1967, 1971a, b, c; *Utsu and Okada*, 1968; *Kanamori*, 1968). That is, the existence of high-Q, high-velocity zone dipping from the vicinity of the trench beneath the arc, with a thickness of about 50–100 km, and two low-Q, low-velocity zones surrounding this dipping zone. And most of deep and intermediate earthquakes are confined to this inclined zone. Such a discovery is one of the biggest contributions to the development of the new global tectonics.

In the light of the present knowledge, we find a large body of data suggesting lateral inhomogeneity in the upper mantle in the Japanes seismological litera-

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ture during the last 50 years or so. Detailed summaries and reviews of such papers up to 1970 have been presented by *Utsu* (1971b, 1971c). At the present stage, furthermore, quantitatively precise investigations of the structure, such as accurate velocity and Q distributions and their regional differences, absolute and/or relative locations of hypocenters and the lithospheric plate, definite situation on deformation of the plate beneath the arc, especially at the junction of two arcs, and related physical parameters in the mantle, are requested and now in progress in part (*Ishida*, 1970; *Tada*, 1972; *Aoki and Tada*, 1973; *Shimamura*, 1973; *Yamamizu*, 1973; *Hamada*, 1973).

In this paper, the auther will show a brief review of papers on lateral inhomogeneity in the upper mantle in the Japanese region, emphasizing the author's study by means of three-dimensional-seismic-ray tracing recently developed by *Jacob* (1970).

Investigations of anomalous upper mantle structures associated with island arcs in other regions in the world have been started since *Oliver and Isacks* (1967, 1968). Such studies, however, are omitted in the present review (e.g., *Mitronovas and Isacks*, 1971; *Barazangi and Isacks*, 1971; *Jacob*, 1970, 1972).

2. Traveltime anomalies

A large-scale anomalous upper mantle structure reflects upon traveltime

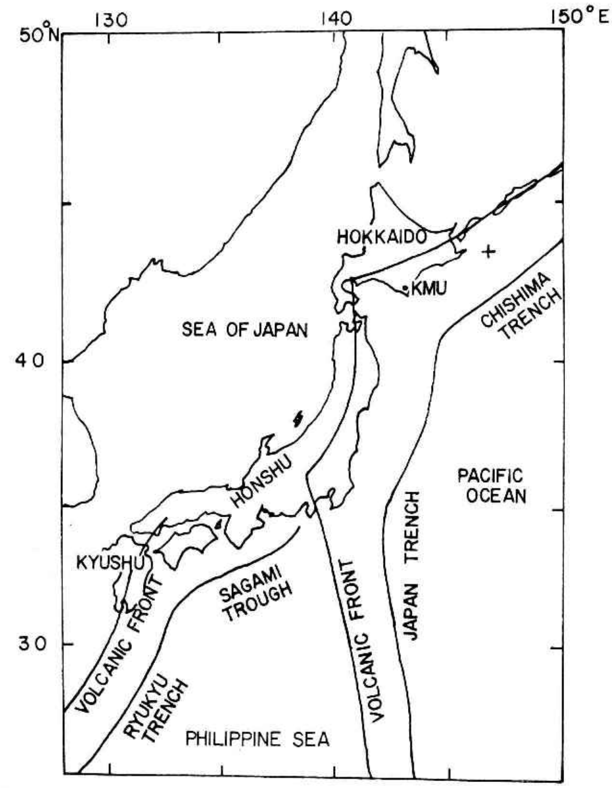


Fig. 1. Geographical map of Japan and its vicinity.

anomalies, seismic intensity distributions, and wave forms of seismograms. At first, we see a typical example of traveltimes of *P* and *S* waves. Figure 2 is the reduced traveltimes by *Utsu* (1971a) for a shallow earthquake east off Hokkaido located by International Seismological Centre (ISC) (see "+" in Fig. 1). Traveltimes are late in Hokkaido (Δ<500 km) and early in northern Honshu (500<Δ<1,100 km) for both *P* and *S* waves, comparing with the Jeffrey-Bullen (J-B) standard. The figure suggests the presence of contrasting two zones, a high-velocity zone in the upper mantle on the Pacific sides of Hokkaido and northeast Honshu, and a low-velocity zone beneath Hokkaido. These velocities are higher and lower by a few percent than the J-B standard. For a distance greater than 1,000 km, fluctuations of the traveltimes are so large, particularly for *S* waves, that interpretation of the traveltimes is difficult with respect to the distance alone. Generally, for the case of lateral inhomogeneity, characteristics of traveltimes are not dependent on the distance only, but also on the both locations of hypocenters and observational stations. There are many studies of geographical distributions of traveltime residuals (e.g., *Wadati*, 1931, 1932; *Honda*, 1932). The Japan Meteorological Agency (JMA) reported *P* and *S* traveltime residuals in Japan as shown in Fig. 3, where geographical distributions of the residual are separately illustrated by the epicentral area of earthquakes (*Seismological Section, JMA*, 1967). Dependency of geographical distribution of traveltime residuals upon the epicentral zone is clearly seen in

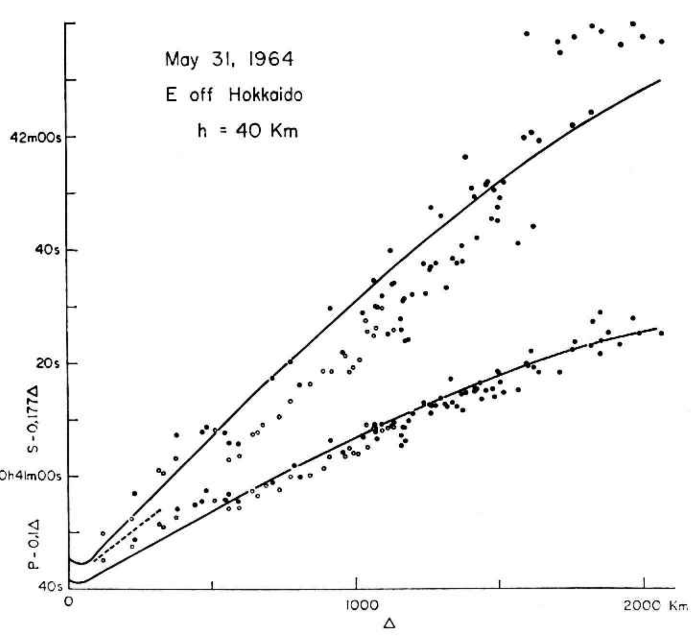


Fig. 2. Reduced traveltime curves for a shallow earthquake east off Hokkaido based on the ISC epicenter. Solid curves are the Jeffrey-Bullen's curves for *P* and *S* waves. Open circles indicate the stations on the oceanic side of the volcanic front (after *Utsu*, 1971a).

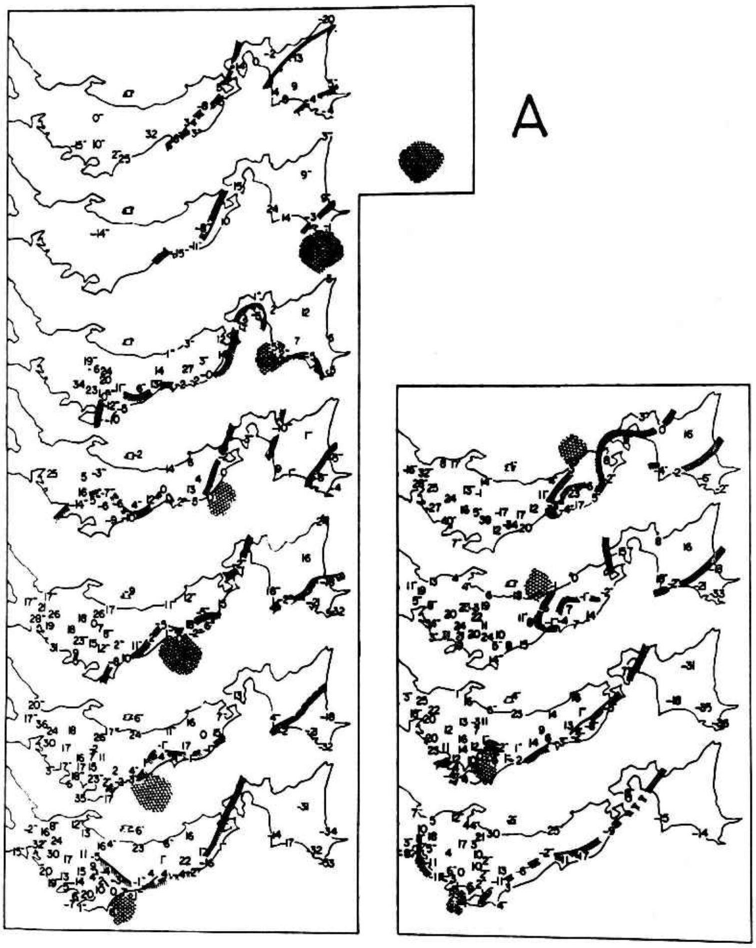


Fig. 3-a. Geographical distribution of mean P traveltime residuals in 1/10 sec for earthquakes in various zones (*Seismological Section, JMA*, 1967). Hatched areas show epicentral zones.

Fig. 3. Characteristics of distributions of P and S waves are similar to each other. As a general tendency, early arrivals appear in Hokkaido and on the Pacific Ocean side of Honshu, suggesting the presence of relatively high-velocity zone on the Pacific Ocean sides of Hokkaido and northern Honshu. An interesting narrow zone of negative anomaly in Central Japan is in the figure on the left-hand side at the bottom for both P and S waves. Such an anomaly is not seen in any of other figures, that is, this local anomaly depends strongly on epicentral zones. This phenomenon might be related to the complicated situation of deformation of the down-going slab in Central Japan as will be discussed later by *Aoki and Tada* (1973).

3. Anomalous distribution of seismic intensities

There are many investigations by Japanese seismologists concerning anoma-

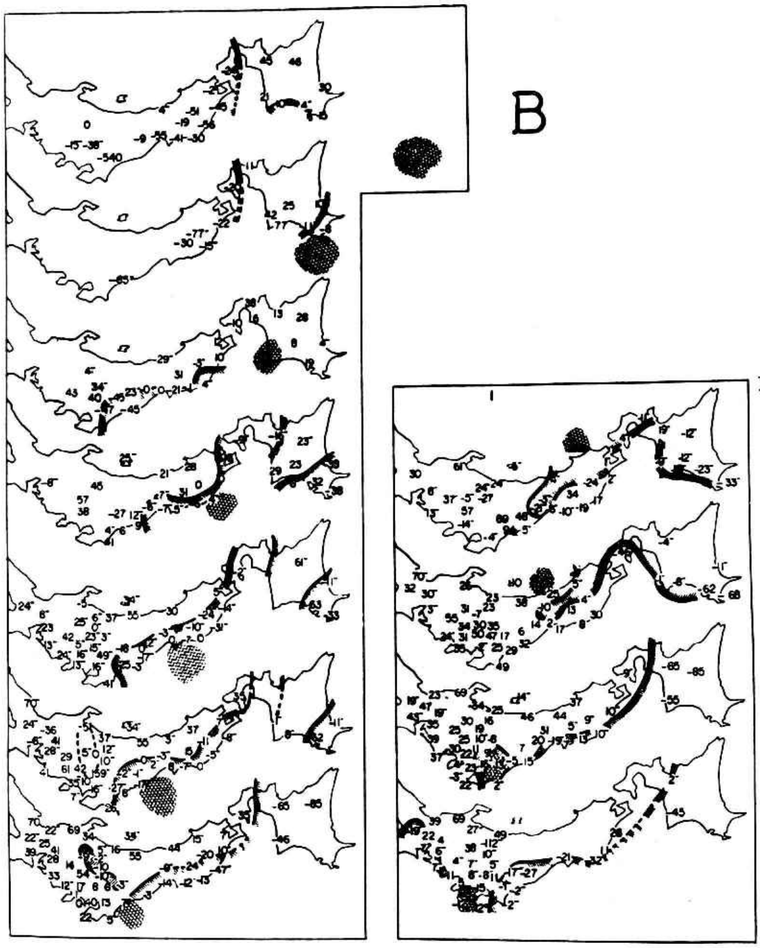


Fig. 3-b. Geographical distribution of mean S traveltime residuals in 1/10 sec for earthquakes in various zones (*Seismological Section, JMA*, 1967). Hatched areas show epicentral zones.

lous distributions of seismic intensities since *Hasegawa's* (1918) report, in which a shock that occurred in the middle of the Sea of Japan was reported to be felt on the Pacific coast of east Japan only. A systematic investigation of intensity distribution in Japan was done by *Utsu* (1966). More than 60 isoseismal maps were prepared by him for earthquakes during about 40 years up to 1965. He emphasized that the inclined deep and intermediate earthquake zone is an efficient transmitter of high-frequency seismic waves, particularly of S waves, and that the attenuating zone is almost aseismic. Figure 4 illustrates typical isoseismal maps of which originals are taken from *Utsu* (1971a). Furthermore, *Utsu* (1971a) checked several simplified models which have a low-Q zone in the upper mantle on the continental side of the inclined seismic zone, comparing with the observed patterns of isoseismals. It has been concluded that the three models as shown in Fig. 5 are consistent with the observations and there are tenfold differences in Q values.

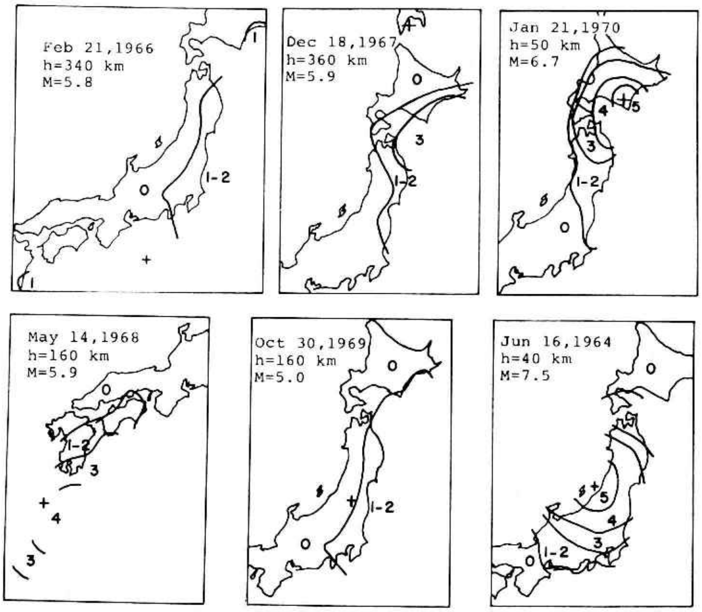


Fig. 4. Isoseismal maps compiled from *Utsu* (1971a). "+" shows an epicenter located by USNOAA. Numerals indicate intensities on JMA scale. 0 means unfelt and 4 corresponds to 5 or 6 on the modified Mercalli scale.

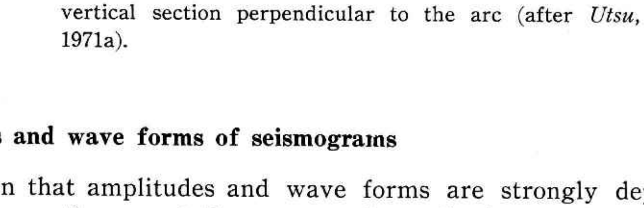


Fig. 5. Models of the low-Q zone in the upper mantle in a vertical section perpendicular to the arc (after *Utsu*, 1971a).

4. Amplitudes and wave forms of seismograms

It is known that amplitudes and wave forms are strongly dependent upon the propagation path even at the same station. Good examples are taken from *Utsu* (1971a) also and are shown in Fig. 6. The record for the Central Japan earthquake has relatively low-frequency, identification of S waves is difficult because of the lack of the pronounced S phase, and amplitude is small in comparison with the other for the Kurile Islands earthquake although the magnitude is larger by 1.6. On the contrary, high frequency is pronounced on the record for the Kurile Islands earthquake and S waves have large amplitudes. The earthquake of Central Japan has been propagated through low-Q zone primarily,

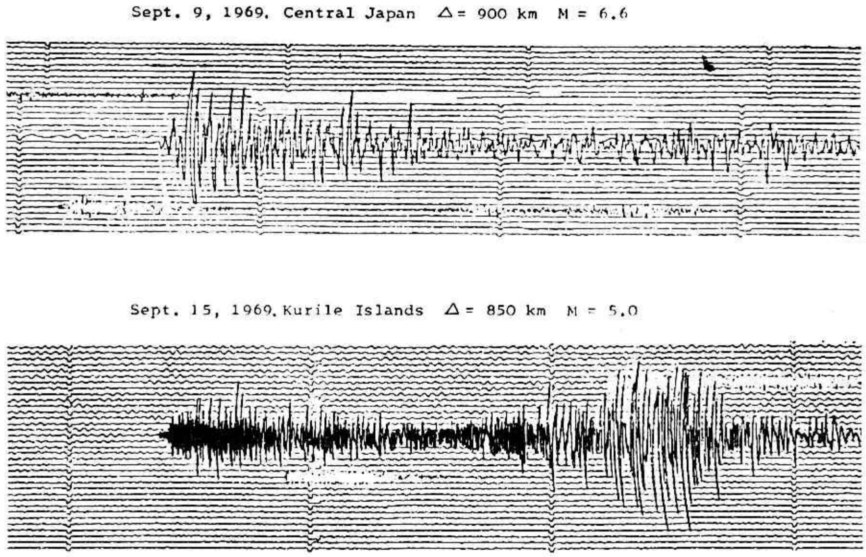


Fig. 6. Comparison of seismograms recorded by a short-period vertical seismograph at KMU (see Fig. 1) in southern Hokkaido (after *Utsu*, 1971a).

and the other one of Kurile Islands has been propagated through high-Q zone. *Utsu and Okada* (1968) examined some earthquakes by spectral analysis and estimated Q value of the low-Q zone at less than 50–100.

5. Various upper mantle models beneath Japan

The upper mantle model finally proposed by *Utsu* (1971a) is illustrated in Fig. 7. There are tenfold differences in Q-values and several percent differences in seismic wave velocities for both P and S waves between the two zones. The oceanic side low-Q, low-velocity zone seems to be less prominent than that on the continental side, although the data is not sufficient.

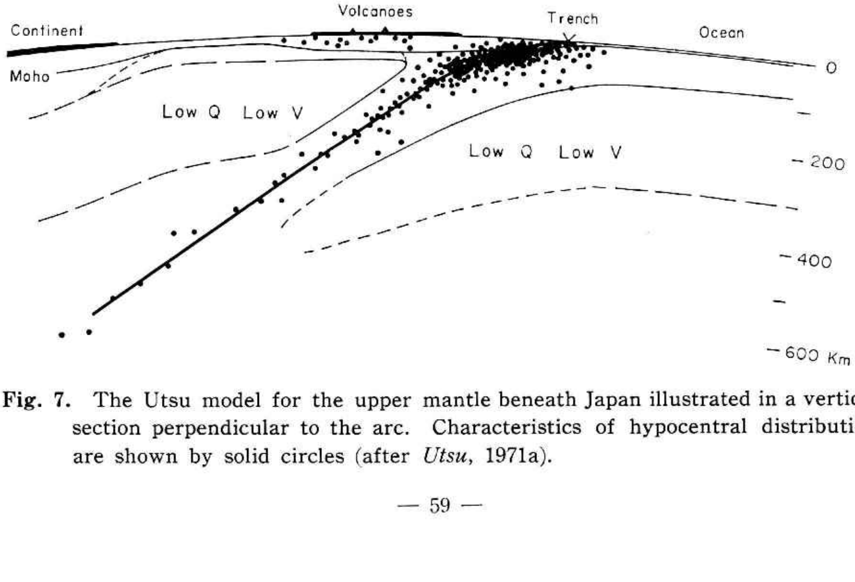


Fig. 7. The Utsu model for the upper mantle beneath Japan illustrated in a vertical section perpendicular to the arc. Characteristics of hypocentral distribution are shown by solid circles (after *Utsu*, 1971a).

Traveltimes to Japanese stations from the nuclear explosion Longshot of 1965 were studied by *Kanamori* (1968). A systematic variation of traveltime residuals was found and interpreted in terms of lateral inhomogeneity in the upper mantle associated with the dipping seismic plane beneath the arc. Figure 8 shows the inclined seismic plane by the depth contours, locations of the stations used in his study, and propagation paths to the stations from the shot point in the Aleutian Islands. Figure 9 illustrates the vertical sections along the seismic ray paths, where L is defined as the path length in the upper mantle above the deep seismic plane. The systematic variation of traveltime residuals against the path

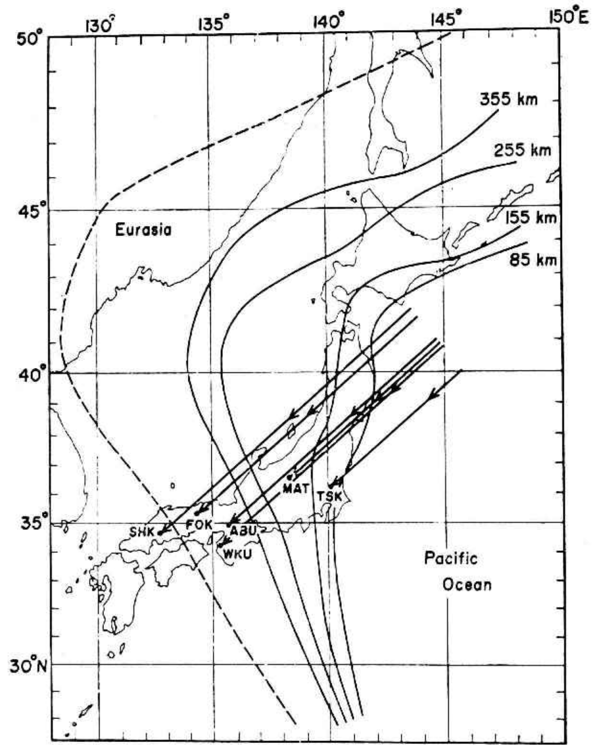


Fig. 8. Location of stations, contour lines of dipping seismic plane after *Sugimura and Uyeda* (1968), and wave paths to the stations from the shot point in the Aleutian Islands. The dashed line defines the western limit of the deep seismic zone (after *Kanamori*, 1968).

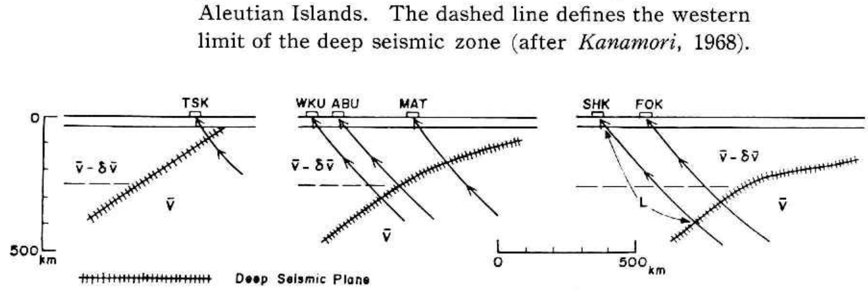


Fig. 9. Cross sections of the structure along the seismic ray (after *Kanamori*, 1968).

length L is shown in Fig. 10. Kanamori concluded that the P-wave velocity in the uppermost 250 km in the mantle on the continental side of the deep seismic plane is reduced by 0.4 km/sec as compared with the velocity on the ocean side of the deep seismic plane. The average Q was estimated at 80 in the low-velocity

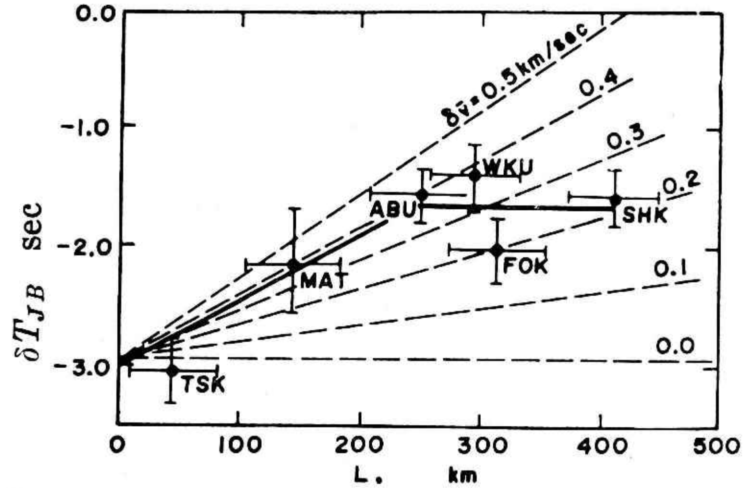


Fig. 10. J-B residuals of P-waves against the path length above the deep seismic plane. The dashed line gives the slope for various velocity contrast $\delta\bar{V}$ in Fig. 9. The solid line gives the relation when the "$\bar{V}-\delta\bar{V}$" region is bounded at the depth of 250 km as shown in Fig. 9 (after *Kanamori*, 1968).

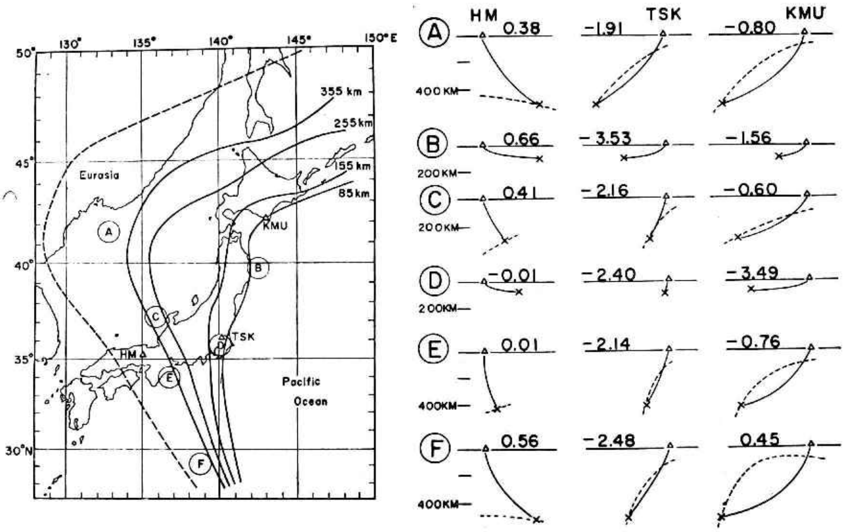


Fig. 11. Average P-wave traveltime residuals $\Delta t/t$ in percent and the ray paths. Epicenters of earthquakes and stations used for analysis are shown on the left. Vertical sections of the structure and the ray paths to the stations are shown on the right. The vertical exaggeration is about 2 : 1. The solid lines indicate the ray paths, and the dotted lines the seismic planes (after *Ishida*, 1970).

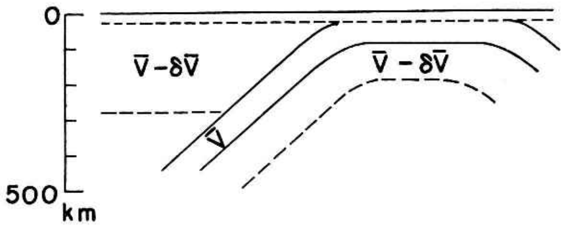


Fig. 12. An upper mantle model by Ishida (after *Ishida*, 1970).

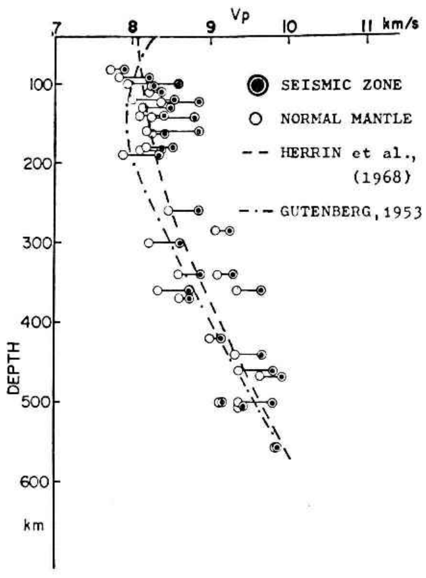


Fig. 13. *P*-wave velocity distribution in the upper mantle beneath Japan. Double and open circles denote the velocity in the deep seismic zone and the surrounding mantle, respectively (after *Tada*, 1972). Two values connected with the horizontal bar are obtained from the same earthquake.

zone stated above, from the amplitude ratio of *PcP* and *P* phases. Such low-*Q* and low-velocity were explained by a temperature excess of about 500°C coupled with a partial melting of about 2%. It is noticed that Kanamori did not introduced the high-*Q*, high-velocity lithospheric plate dividing the low-*Q*, low-velocity zone, differently from Utsu.

Ishida (1970) relocated about 410 earthquakes in and around Japan which occurred during 1967. Besides, she investigated traveltime anomalies using three stations and six groups of relocated earthquakes as shown in Fig. 11. When determining the residuals, 3, 7, 4, 9, 10, and 10 earthquakes were used for the regions *A*, *B*, *C*, *D*, *E* and *F*, respectively. To explain the observed traveltime anomalies, she proposed an upper mantle model in Fig. 12. Characteristics of her model are the presence of low-velocity zone on the oceanic side delimited to a region parallel to the seismic plane and the smaller velocity contrast of 2–3%, about a half of that by previous investigators.

Tada (1972) applied *Kaila's* (1969) method to determine the velocity in the high-velocity slab beneath Japan, using 31 natural earthquakes which occurred in northern Honshu and the Izu-Mariana regions. The analyzed results are shown in Fig. 13. His conclusions are: 1) Resultant velocity differences between the high-velocity slab and the surrounding mantle are 5, 3.5, and 2.5% at depths of 200, 400 and 600 km, respectively. 2) The velocity in the surrounding mantle is consistent with that of *Herrin et al.* (1968). 3) Low-velocity layers may start just beneath the *M*-discontinuity in the surrounding mantle beneath Japan. Velocity contrast of 5% (=0.4 km/sec) at a 200-km depth corresponds to temperature difference of 1,000°C, assuming dV/dT for olivine by *Anderson et al.* (1968). To ascertain his second conclusion, however, resolution of absolute value of the velocity should be taken into account.

Aoki and Tada (1973) discussed on deformation of the sinking plate beneath Japan. They pointed out a possibility of complicated situation, like overlapping of the plate, at the junction of the two arcs, the Kurile and Honshu arcs, the Honshu and Izu-Mariana arcs, if the plate is rigid and its area is not changed when going down. They tried to explain the reason of the early arrivals from the nuclear explosion Cannikin of the Aleutian Islands that appeared at a narrow band in the central part of Japan to the west along the latitude of 35.5°N by overlapping of the plates at the junction of the Honshu and Izu-Mariana arcs. A narrow band of early arrivals similar to it is seen in the figure on the left at the bottom in Fig. 3 for both *P* and *S* waves. However, to obtain the conclusion, detailed and accurate investigations of the structure must be waited for.

6. Upper mantle models by three-dimensional-seismic-ray tracing

For the development of our knowledge of plate tectonics, more detailed structure of the upper mantle, particularly beneath the arc, is requested. One of the important subjects is a three-dimensional treatment of the seismic ray that enables us to determine definite traveltimes on the basis of the definite wave path. *Yamamizu* (1973) and *Hamada* (1973) advanced the studies along this direction by means of three-dimensional-ray tracing recently developed by *Jacob* (1970). Yamamizu obtained the 6% *P*-wave velocity contrast between the high-velocity slab and the surrounding mantle, by using three natural earthquakes that occurred under Wakasa Bay (35°35′N, 135°30′E). Figure 14 shows comparison of observed traveltime residuals and calculated ones assuming the model in Fig. 15.

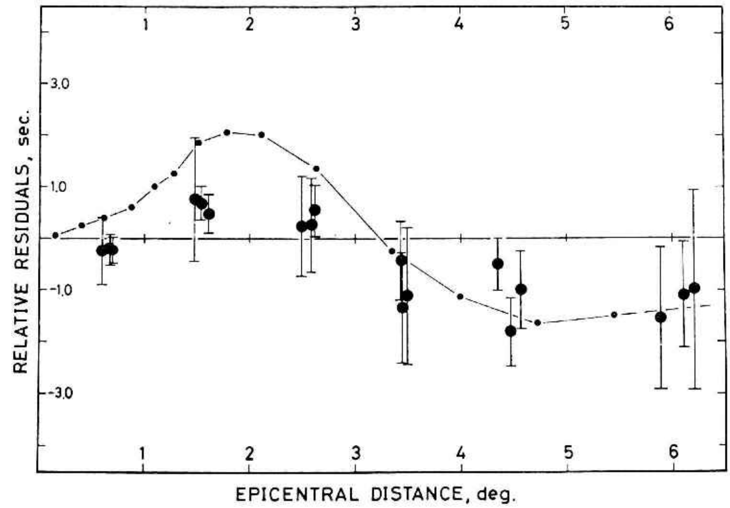


Fig. 14. Comparison of relative residuals between computed (small solid circles) and observed (large solid circles) ones. The vertical bars show the standard deviation. The epicentral distance is measured from the epicenter to the NE direction (after *Yamamizu*, 1973).

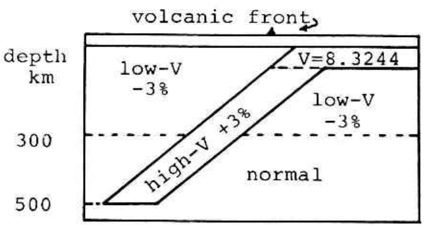


Fig. 15. Schematic representation of the upper mantle model by *Yamamizu* (1973).

Using about 150 observational data for the nuclear explosion Cannikin on Amchitka in the Central Aleutian Islands, *Hamada* (1973) constructed *P*-wave upper mantle model based on the work by Utsu. Figure 16 shows contour lines of *P*-wave traveltime residuals, and regional averages are shown in Fig. 17. General trends of the residuals are: The average is 0.4 sec in the whole Japan. Large negative anomaly is seen in northeast Japan, especially in Hokkaido, and large pasitive anomaly in southwest Japan, especially in Kyushu. Moreover, the Pacific side has earlier arrivals than the Japan Sea side in northeast Japan, while the Pacific side has later arrivals than the Japan Sea side in southwest Japan. Of special interest are positive anomalies whose average is 0.9 sec in the Outer Zone of southwest Japan and its extension in the Kanto district, Central Japan. Such positive anomalies in the Outer Zone of southwest Japan appear to be inconsistent with the high-velocity Philippine Sea plate thrusting there (*Ando*, 1972; *Kanamori*, 1972), unless we assume the existence of very low-velocity zone surpassing the high-velocity Philippine Sea plate covering that low-velocity zone. To explain the observed traveltime residuals, Hamada adopted an *A*-type model as is schematically shown in Fig. 18, and examined

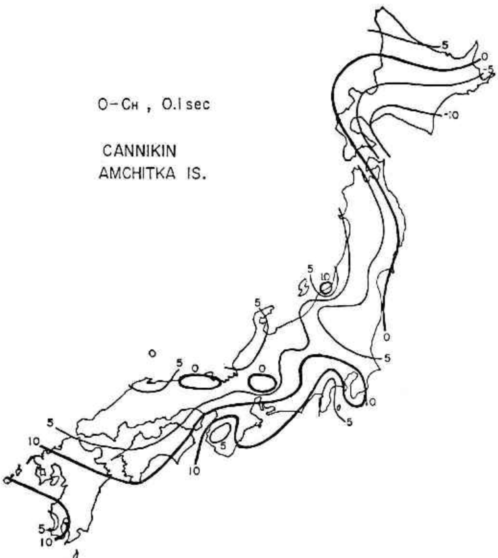


Fig. 16. Smoothed contours of *P*-wave traveltime residuals for the nuclear explosion Cannikin of 1971 on Amchitka, the Central Aleutian Islands. O and C_H denote the observed traveltime and the theoretical one by *Herrin et al.* (1968) (after *Hamada*, 1973).

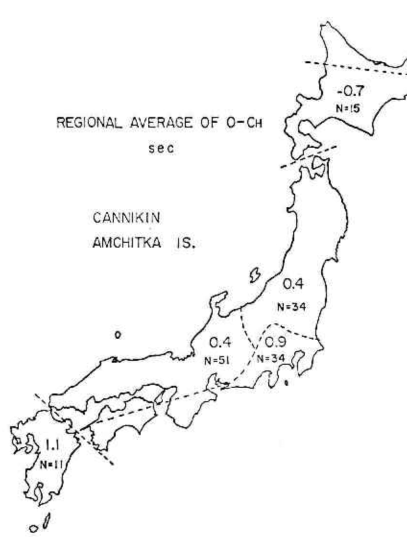


Fig. 17. Regional average of the traveltime residuals for the nuclear explosion Cannikin. Dotted lines are boundaries of the regions. N is the number of the observations used in averaging (after *Hamada*, 1973).

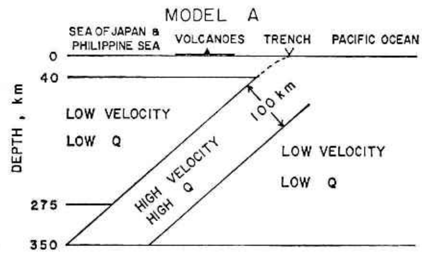


Fig. 18. The upper mantle model A made by simplifying the result of Utsu. Low or high velocity means lower or higher velocity at the same depth than that of the standard earth model $P68$. Actual locations of the high-velocity slab correspond to those of the deep and intermediate earthquake zone as shown in Fig. 19 by depth contours of its center position (after *Hamada*, 1973).

velocity contrast in the three zones without changing the boundaries of the zones. Actual locations of the high-velocity slab are given in Fig. 19 by contours of the center position, where the center of the slab is the center of concentration of deep and intermediate earthquakes. The best fitted model was finally chosen, and its theoretical traveltime residuals are shown in Fig. 20. Some theoretical seismic ray paths for this model are illustrated in Fig. 21. The model A-431 was made so that the general trend of the observed traveltime anomalies in the whole Japan could be explained regardless of local traveltime anomalies and fluctuations inherent in the observation. Consequently, the observed negative residual in Hokkaido, whose average is -0.7 sec, is consistent with the theoretical one whose average is also -0.7 sec. The observed positive residual

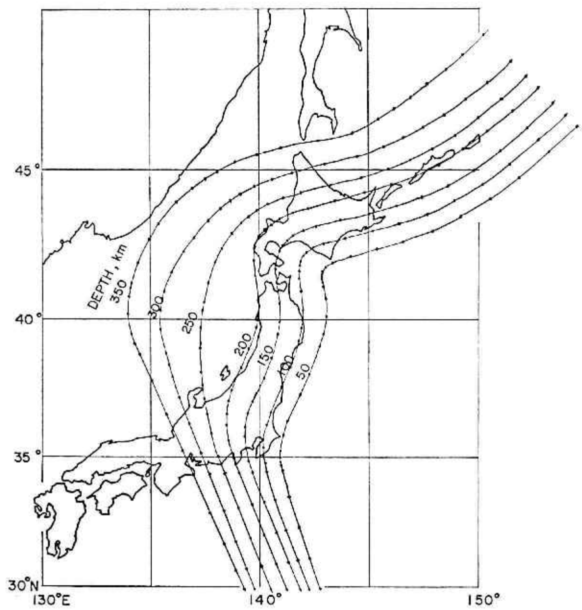


Fig. 19. Smoothed contours showing the deep and intermediate earthquake zone taken with slight modification from *Uyeda and Sugimura* (1970) and *Utsu* (1971a). The coordinates of the solid circles on the contour were used for locating the high-velocity slab (after *Hamada*, 1973).

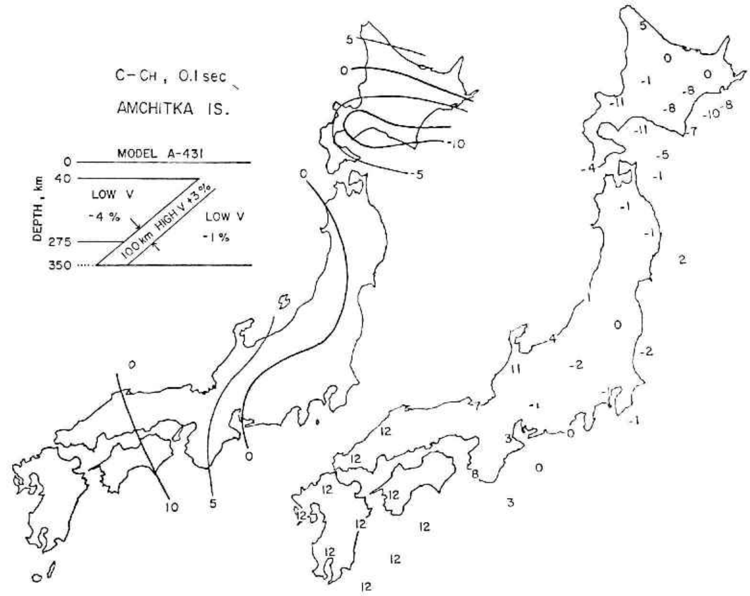


Fig. 20. Theoretical P-wave traveltime residuals and its smoothed contours for the best fitted model A-431 (after *Hamada*, 1973).

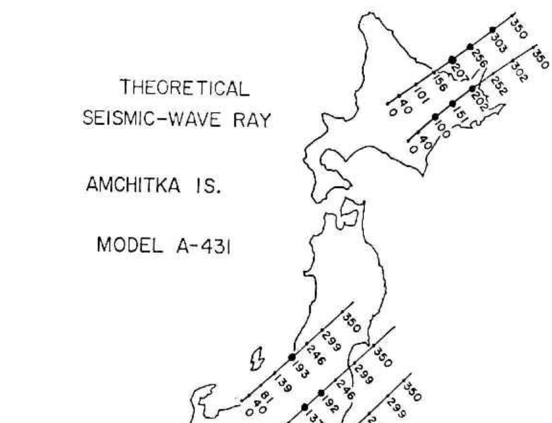
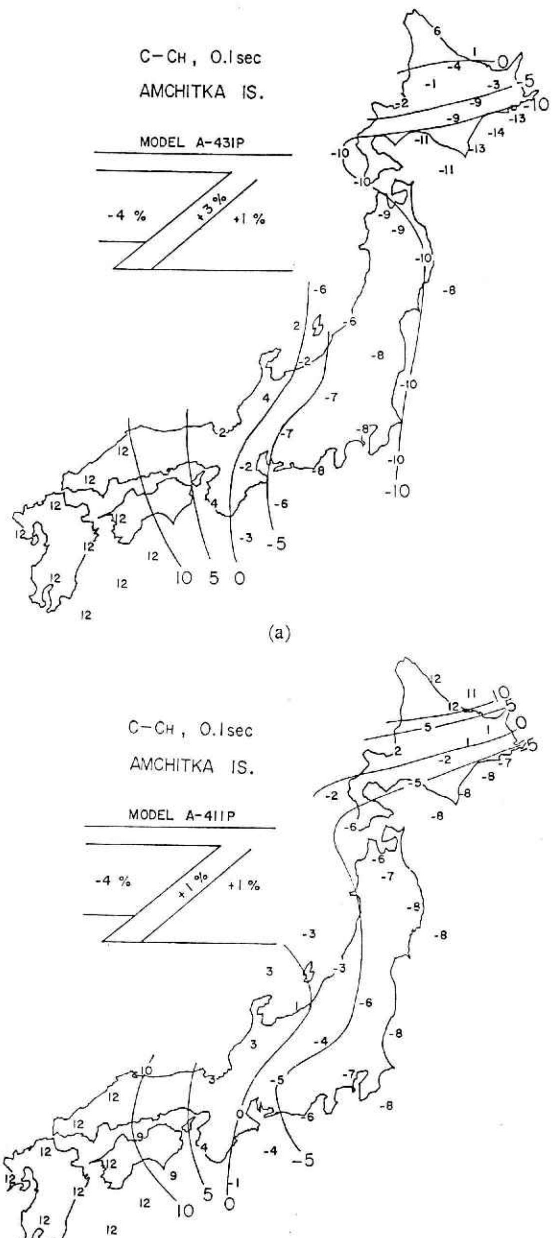


Fig. 21. Some theoretical seismic-ray paths for the model A-431. Numerals indicate the depth of that point on the ray. The point shown by large solid circles is located within the high-velocity slab (after *Hamada*, 1973).

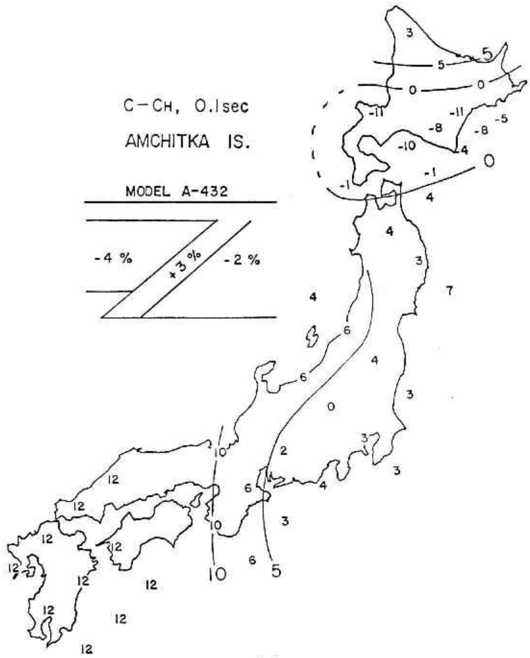
in Kyushu, whose average is 1.1 sec, is consistent with the theoretical one of 1.2-sec average. Fig. 22–a, b, and c illustrate theoretical traveltime residuals for the three variations of the best model *A*-431. These figures enable us to discuss



(a)

(b)

Fig. 22-a and b. Theoretical traveltime residuals for the three variations of the model *A*-431 (after *Hamada*, 1973).



(c)

Fig. 22-c. Theoretical traveltime residuals for the three variations of the model A-431 (after *Hamada*, 1973).

about uniqueness and resolution of the velocity contrasts of the selected model A-431. It seems difficult to change the velocity contrast of the model by 1% as far as the A-type model (Fig. 18) is adopted for the whole Japan.

As is stated above, the observations of early arrivals appear on the Pacific side compared with the Japan Sea side in northeast Japan, namely, it shows the tendency similar to that of the theoretical traveltimes. In southwest Japan, however, theoretical anomalies are different from the observed ones in detail reluctantly. That is, conversely, the observed later arrivals appear on the Pacific side compared with the Japan Sea side: While the theoretical later arrivals appear westwards and the earlier arrivals do on the Pacific side of Central Japan, the Kanto district. Such pattern of the theoretical contour of the traveltime residuals appeared in all cases of calculations as far as the velocity in the inclined slab is higher than the surrounding mantle. Therefore, to explain the traveltime anomalies in southwest Japan a model different from the present type is required. Apparent inconsistency between the observed later arrivals in the Outer Zone and the existence of the Philippine Sea plate underthrusting there should be resolved also.

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P 波走時の異常と日本の上部マントル構造

——日本における地震学的研究——

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日本の上部マントル中の大規模な異常構造についての研究を簡単なレビューとしてここに発表する. 日本の上部マントルの異常構造を暗示していたおびただしい数の観測データは確かな説明もなしにこの50年間に蓄積されてきた. しかし最近の上部マントル構造の研究は顕著な異常構造が在ることを明らかにし過去の異常な観測データを説明する根拠を与えた. 1970年までのこれらの仕事は宇津の一連の研究によって代表される. 今考えている異常構造は宇津の研究によって第1近似としては完成されたように見える. しかしこのような研究を更に発展させるためには定量的に正確な取扱いが必要である. つまり, 一様でない物質を通り抜ける地震波の正確な経路と伝搬時間の計算が必要である. 特に日本のように構造が複雑な所ではそうである. 山水, 浜田は三次元の波線追跡法によって, この方向に研究を進めた. 浜田は 1971 年のアリューシャン列島で行なわれた核実験のデータを使い宇津の仕事を基礎に上部マントルのモデルを作り理論上期待される *P* 波走時の異常を示した.