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3-D Seismic Velocity Structure beneath Southwest Japan Revealed by Geotomography

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Three-dimensional Earth structure beneath Southwest Japan has been investigated by applying an inversion method which is called Geotomography or Seismic Wave Tomography. This Geotomography uses seismic waves from earthquakes to image the Earth structure, while the medical CT scanner uses X-rays to image the human body.

Our analysis clearly reveals the complicated three-dimensional structure of the Philippine Sea and Pacific plates subducting beneath Southwest Japan, which have higher seismic P-wave velocities than the surrounding upper mantle. The upper mantle earthquakes take place within these inclined high velocity plates.

INTRODUCTION

Recently, in geophysics, a number of seismologists have investigated three-dimensional Earth structures in the world instead of classical one-dimensional structures by applying a new method developed by Aki and his colleagues (Aki & Lee,1976, Aki et al.,1977). This method, which is based on an inversion theory, may be called Geotomography or Seismic Wave Tomography. The medical profession's computerized tomography (CT) scanner uses X-rays to image the human body (e.g. Herman,1980). Likewise, our Geotomography uses seismic waves from earthquakes to image the Earth structure.

We have many earthquakes around the Japan Islands. It is generally accepted that these earthquakes are mainly caused by two plates subducting beneath this region. Several studies revealed that these plates have very complicated configurations and structures (Ustu,1971). Most of these studies assumed, however, the location, shape and thickness of the descending plates on the basis of the distribution of intermediate and deep earthquakes. By using Geotomograpy, without such assumptions, we have revealed the complicated three-dimensional structures beneath the Japan Islands (e.g. Hirahara,1977).

In this paper, we will show the principle of the method in brief and review one of our recent results on 3-D seismic velocity structure beneath Southwest Japan (Hirahara,1981).

PRINCIPLE OF THE METHOD

First, we will briefly describe the principle of the method. Initially, we assume a classical one-dimensional layered velocity model, which is only depth-dependent. Further, we divide the modeling space beneath seismic stations into several 3-D blocks as shown in Fig.1.

Suppose the hatched blocks have lower seismic velocities than the initial assumed ones. Then, only seismic rays crossing these low velocity blocks give later arrivals than the calculated ones for the initial velocity model. Such time differences between the observed arrival times of seismic waves and the calculated ones are called travel time residuals. Using these travel time residuals for a variety of well distributed stations from earthquakes, we can determine the velocity anomaly in each block k, as well as the refined location and origine time for each earthquake j, in a least-squares sense, simultaneously. Here, we solved the observational equations by the damped least-squares method with resolution analysis (see the details in Aki and Lee,1976).

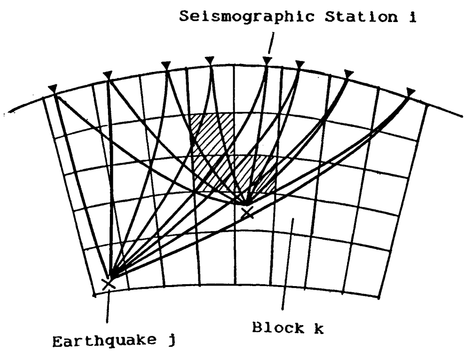

Fig.1 Schematic view of seismic rays from earthquakes j to seismic stations i in subdivided blocks k. The hatched blocks are supposed to have lower velocities than the initial assumed seismic velocity model.

SOUTHWEST JAPAN

Beneath the Japan Islands, the Pacific plate is subducting from the east along the Japan trench, and from the south the Philippine Sea plate is subducting along the Nankai trough (see the locations of the Japan trench and Nankai trough in Fig.2). We will investigate the three-dimensional structure of these plates beneath Southwest Japan from the Kanto, Shikoku, Kyushu to Okinawa regions in Fig.2.

Fig.2 also shows geophysical observations such as the depths of the upper mantle earthquakes (contour lines) and the location of volcanoes (open and closed circles) in this region. In relation to the descending Pacific plate, the depths of the earthquakes increase westwards from the Japan trench to 500 km. On the other hand, for the Philippine Sea plate, the earthquakes take place from the Nankai trough to a depth of only 60 km from the Tokai to Shikoku regions and 200 km in the Kyushu and Okinawa regions.

DATA AND MODEL PARAMETRS

From the Bulletins of International Seismological Centre (ISC), we selected 42 earthquakes occuring around Southwest Japan at depths between 39 km and 557 km during the period from 1964 to 1977. We used 2947 P-wave arrival time data observed at 118 Japanese seismic stations from these earthquakes.

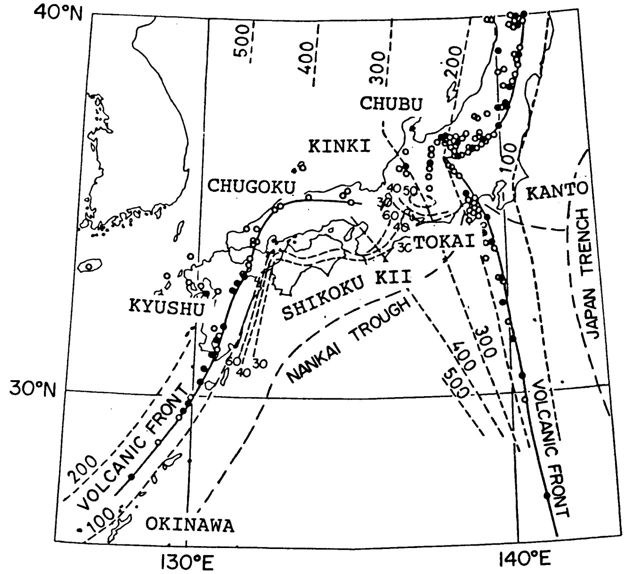

Fig.2. Index map around Southwest Japan and geophysical observations. Coarse-dashed lines indicate the trench axes. The contours of deep and intermediate earthquake depths are shown by fine-dashed lines. Closed and open circles represent active and other Quaternary volcanoes (modified after Hirahara,1981).

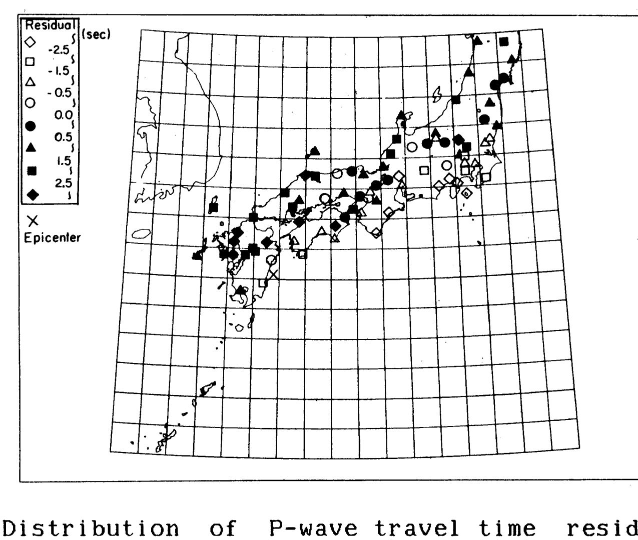

Fig.3. Distribution of P-wave travel time residuals from an earthquake with its depth of 47 km. Cross indicates the location of the epicenter (after Hirahara,1981).

In Fig.3, is shown the distribution of the P-wave travel time residuals for an earthquake with the depth of 47 km, whose epicenter is indicated by cross. The open and closed symbols represent early and late arrivals. The early arrivals appear along the coast from the Tokai to Shikoku regions, suggesting the existence of high P-wave velocity regions here.

Our upper modeling space down to a depth of 200 km consists of five layers with a thickness of 33 km to 50 km, each of which has 16 x 14 blocks with a block size of 1 deg x 1 deg. And the lower space from 200 km to 600 km has four layers with a thickness of 100 km and 8 x 7 blocks, their sizes being 2 deg x 2 deg.

Finally, we solved 2947 observational equations for 726 unknown parameters including 558 observed velocity anomalies and 42 x 4 earthquake parameters.

RESULTS AND DISCUSSIONS

Fig.4 shows the obtained slowness perturbations (negative values indicate high velocity anomalies and vice versa) for Layer-2 with the depth ranging from 33 km to 66 km, and the distribution of earthquakes occuring within this layer. The high velocity of the Philippine Sea plate appears from the Tokai to Shikoku and Kyushu regions, well correspondiong to the seismic activities in this layer. The high velocity of the Pacific plate can be also recognized along the eastern region around the Kanto and well corresponds to the seismic activities there.

In the lower layers, from the Tokai to Shikoku regions, the high velocity of the Philippine Sea plate disappears, corresponding to no earthquakes there, except for a small high velocity region in Layer-4 with the depth ranging from 100 km to 150 km beneath the Kinki region. Beneath the Kyushu and Okinawa regions, the high velocity anomalies continue down to Layer-4 or 5, a depth of 150 km or 200 km, corresponding to the seismic activities. For the Pacific plate, the high velocity anomalies can be traced down to Layer-7 or 8, a depth of 400 km or 500 km, also corresponding to the westwards inclined seismic activities.

These features can be more clearly seen from the cross sections along the profiles in Fig.5. Among these cross sections, we will show only the selected sections A, C and E in Fig.6.

Cross section A running from the Kanto to the Chubu regions indicates that the high velocity Pacific plate is descending to a depth of 400 km with a dip of 35 degrees, and that the earthquakes take place within this descending plate. The low velocity anomalies exist above this plate beneath the regions west of the volcanic front. These low velocities are related to volcanism.

In section C, an interesting feature appears. Beneath the Kii peninsula, the high velocities of the Philippine Sea plate can be seen down to Layer-2 with seismic activities, and disappear in Layer-3, corresponding to no seismic activities. However, small high velocities appear again in Layer-4, which seem to be an extension from Layer-2 with interruptions in Layer-3, although the seismic activities can not be found there. These high velocities might indicate some remnants of the past subduction of the Philippine Sea plate. Section E indicates the high velocity Philippine Sea plate subducts beneath the Kyushu

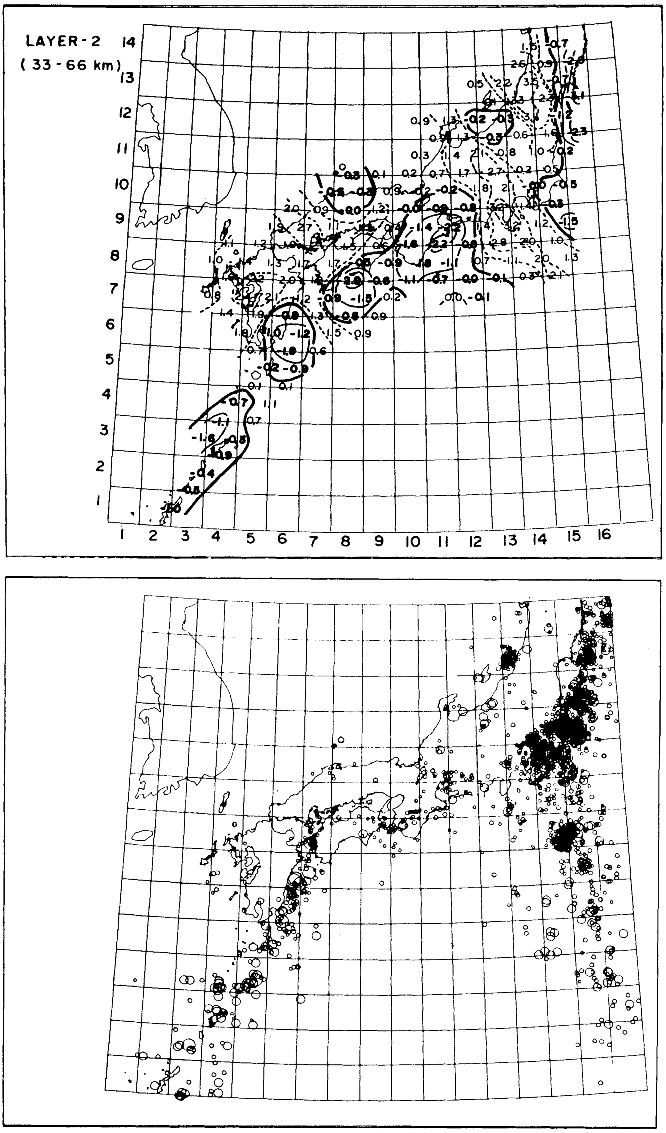

Fig.4. The slowness perturbations (negative values mean high velocity anomalies and vice versa) in percent for Layer-2 (upper) and the distribution of earthquakes located in this layer by ISC (lower). Contours are drawn at every 1 % interval where thick and broken lines indicate high and low velocity anomalies, respectively (after Hirahara,1981).

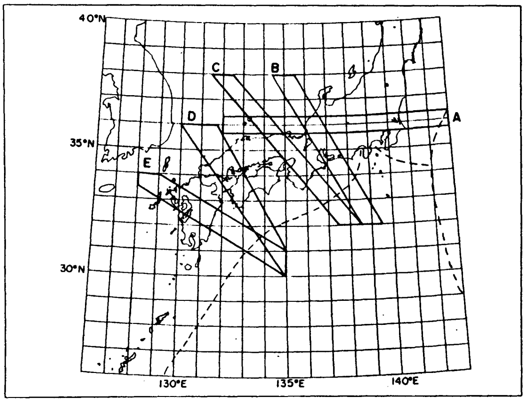

Fig.5. Locations of profiles A-E. Trench axes are also indicated by broken lines (after Hirahara,1981). Only the cross sections A, C and E are shown in Fig.7.

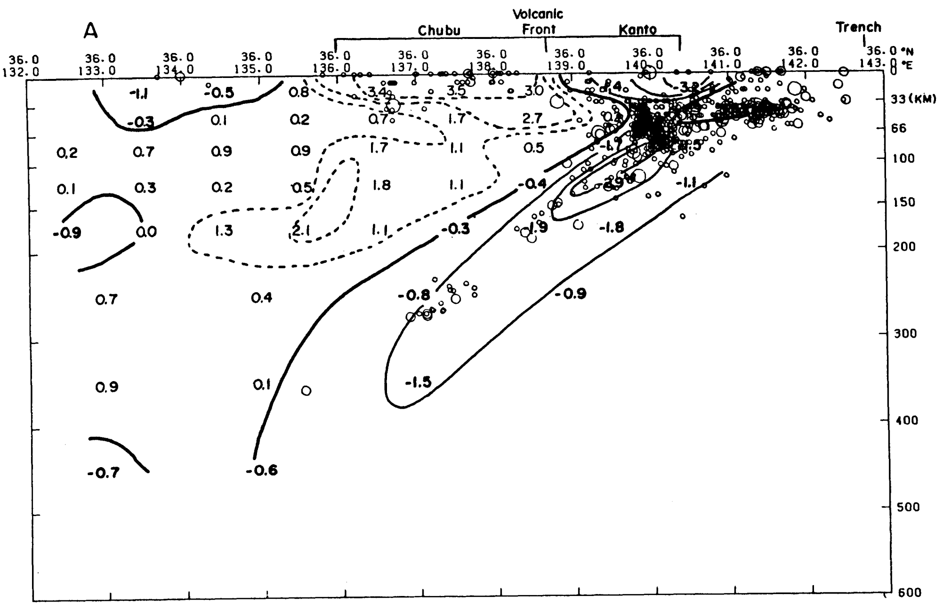

Fig.6. The obtained slowness perturbations and the distribution of earthquakes projected onto the vertical cross-sections along the profiles A, C and E indicated in Fig.6. There are no vertical exaggerations (after Hirahara,1981).

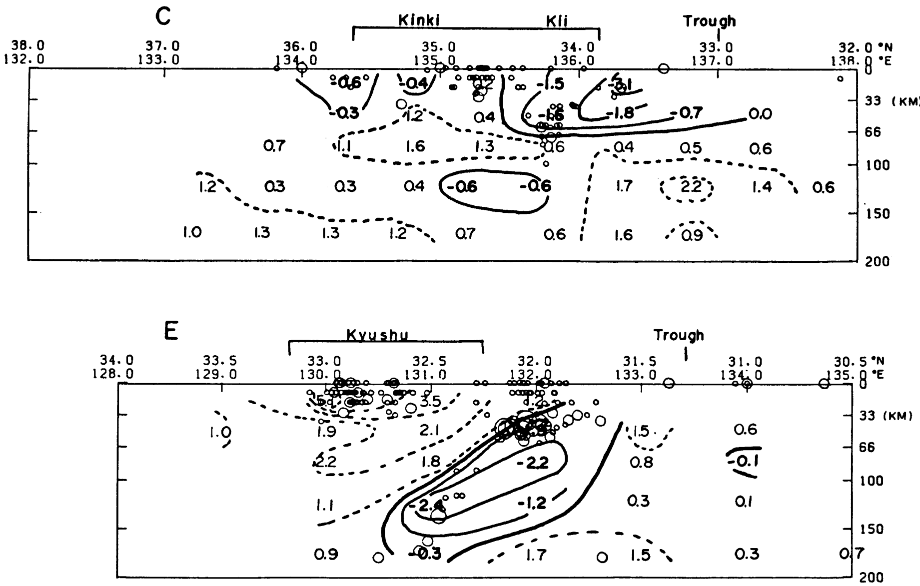

Fig.6 (continued).

region to a depth of 200 km with a rather steep dip of 40 degrees. We can see also the well-developed low velocity anomalies under this region where several large active volcanoes exist.

In general, the seismic velocities increase with the decrease of the temperature, and the materials with high velocities are rigid. This means that the high velocity regions revealed in this study have lower temperature and higher strength than the surrounding upper mantle. Therefore, within these regions, most of deep earthquakes can take place as brittle fractures. We have so far called these high velocity regions with the inclined seismic zones as plates. As explained in the theory of plate tectonics, these plates are created in the mid-oceanic ridges and become cool and thick during the travel over the oceans. After the travel, they go down beneath the subduction regions and thermally assimilate to the surrounding upper mantle, since the hot surrounding mantle warms the subducting cold plates. Thus, we could see a part of mantle convection in our subduction region.

In this paper, we presented one of our analyses as an example of the studies using Geotomography. These analyses by Geotomography have revealed the three-dimensional Earth structures from the regional scales (several km) to the global scales (whole mantle) and are now under way using several types of seismic waves (e.g. Aki,1982, Nakanishi,1985). Further, some improvements on Geotomography such as the inclusion of the effect of velocity anisotropy (e.g. Hirahara and Ishikawa,1984) and the total wave form inversion using high-quality digital seismic wave form data will provide us with more detailed and new images of dynamical Earth structure (e.g. Nakanishi,1985).

CONCLUSION

In this paper, we presented the principle of Geotomography and reviewed one of our recent results on three-dimensional seismic structure beneath Southwest Japan revealed by this method. Geotomography enabled us directly to see the complicated three-dimensional structures of the Plilippine Sea and Pacific plates subducting beneath Southwest Japan, which have higher seismic velocities than the surrounding upper mantle and are accompanied by deep and intermediate earthquakes.

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6-2

Q: What is the cause of the higher or lower seismic velocity? The temperature of the material? (S. C. Cowin)

A: Yes. In general, the seismic velocity of the material depends on the constitution of mineral assembly, its surrounding temperature and pressure. The classical seismology studied the depth distribution of seismic velocity, as the temperature and pressure are increasing with depth and the constitution of mineral assembly changes.

In my talk, the obtained velocity anomalies are perturbation from the initial depth-dependent velocity model, and we can compare only relative perturbations in the same depth level. The thermal conductivity of the crust and upper mantle is small and the geotherm has large lateral variations. So the temperature difference in some depth mainly causes lateral velocity variation. Of course, some other factors effect the velocity variations. For example, there are partial meltings in low velocity regions above the inclined high velocity zone, because the temperature is high in the low velocity regions.

Q: Is the earth velocity the main cause of the earthquake? It seems to me that the velocity gradient rather than the velocity itself is more important. (R. Takaki)

A: Earthquakes are thought to be brittle fractures in the Earth's interior. In general, as the seismic velocity is increasing, the material is considered to be colder and more brittle. In this respect, earthquakes are expected to occur in high velocity and cold regions of deep interior beneath subduction zones such as Japan Islands.