Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), Vol. 10, No. 1, 31-52, 1996.

Crustal Structure in the Central Hokkaido, Japan, from a Seismic Refraction Experiment

Oguz Ozel, Takeo Moriya

Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Sapporo 060, Japan

Takaya Iwasaki, Takashi Iidaka, Shin'ichi Sakai

Earthquake Research Institute, University of Tokyo, Tokyo 113, Japan

Gen Aoki

Earthquake and Tsunami Observation Division, Japan Meteorological Agency Tokyo 100, Japan

and

Sadaomi Suzuki

Department of Earth and Planetary Sciences Faculty of Science, Kyushu University, Fukuoka 812, Japan

(Received November 17, 1995)

Abstract

The tectonic structure of Hokkaido is interpreted as forming by plate motions and associated secondary movements. Especially the Modern Kurile arc-trench system between Okhotsk and Pacific plates and also westward movement of Outer Kurile Arc has an important role on the tectonic evaluation in Hokkaido. To contribute to better understanding of this subject, a seismic refraction experiment was carried out by the Research Group of Explosion Seismology of Japan in Hokkaido in the autumn of 1992. The profile extends from Tsubetsu in the northwest of Hokkaido to Monbetsu in the southeast, running through the main tectonic belts : Sorachi-Yezo, Hidaka Mountains and Tokoro belts, from west to east.

Four shots varying in size from 450 kg to 700 kg of explosives were detonated along the 180 km-long profile. The shots were recorded in mostly digital form at 184 recording sites. The results from this study indicate very complex structure under the Central Hokkaido. The upper part of the crust down to 20 km is resolved well by the refraction data.

The P-wave velocity model shows lateral variations in velocities and thicknesses. The uppermost part of the crust is characterized by sedimentary layers with velocities from 2.5 km/s to 5.2 km/s, increasing with depth. Thicknesses of these sedimentary layers reaches at 4 km under the Tokachi area and at 7-8 km under the southwestern edge of the profile. The basement velocity has remarkable lateral changes. Under the central part of the profile it averages at 5.8 km/s but it is found as high as 6.1-6.2 km/s between Shot-1 and Shot-2. The middle part of the crust is delineated by locally upward warping layer with the velocity of 6.4 km/s and a boundary dipping towards northeast from 17 km to 21 km. The velocity under this boundary is found as 6.7 km/s. The 6.4 km/s mid-crustal layer vanishes under the Hidaka Mountains.

Obtained crustal structure shows structural contrast between the western and eastern part of the Hidaka Mountains, suggesting a large-scale thrust in this region.

1. Introduction

Hokkaido, the Kurile islands and the Kamchatka peninsula constitute an island-arc system. On the other hand, the old geological structures of Hokkaido and Sakhalin are located rather perpandicularly to the general trend of this island-arc system. Many scientists suggested that the tectonic structure in this region were formed by the interactions amongst the Eurasian plate, the Pacific plate and the North American plate. These interactions has resulted in a wide area of distributed deformation rather than in a simple linear plate boundaries. The interaction area covers whole Hokkaido region. Major tectonic belts in the central part of Hokkaido is interpreted by the westward movement of the Outer Kurile Arc which is considered as associated secondary movements caused by the subduction of the Pacific plate under the Okhotsk plate along the Kurile arc-trench.

Numerous geological and geophysical studies have been carried out to unravel the geologic and tectonic structure of the region. Previous nearby seismic refraction studies include Okada et al. (1973), in the profile from off Cape-Erimo to off Shakotan peninsula; Asano et al. (1979), in the deep sea terrace off Hidaka; Den and Hotta (1972); Iwasaki et al. (1989), in the southernmost part of the Kurile trench. Okada et al. (1973) found, based on the time-term method, a monotonous crustal structure under the profile, consisting of regional surface layer, the granitic layer and the basaltic layer with the fairly low velocities. They also found unusually low upper mantle velocity as 7.5 km/s. Asano et al. (1979), suggested that thick sediments covered the area between the north part of Honshu and the south west part of Hokkaido. The thicknesses of the sediments increased towards southwest coast of Hokkaido and amounted to 16 km depth. In other study, Iwasaki et al. (1989) obtained a typical oceanic structure consisting of three layers with the P-wave velocities of 1.8, 3.8-6.5 and 6.5-7.0 km/s. The depth of the crust-mantle boundary (Moho discontinuity) was 8 km and the upper mantle velocity was found as 7.9 km/s in the south part of the Kurile arc by the same study. Apart from these refraction studies, the velocity structure in and around Hokkaido was also investigated by Takanami (1982), Zhao et al. (1992) and Miyamachi and Moriya (1987) and Miyamachi et al. (1994). According to these studies, upper crust-lower crust boundary (Conrad discontinuity) lies at a depth range of 12-22 km and dips towards west. Crust-mantle boundary lies at a depth range of 28-36 km and shows concave geometry whose deepest parts are located in the west part of the Hidaka Mountains.

The Research Group for Explosion Seismology of Japan (hereafter referred to as RGES), consisting of many universities and research institutes, has been carrying out seismic refraction experiments in the Japanese Islands under the Japan earthquake prediction program. The refraction experiments in the period of 1979-1988 mostly focused on determining the uppermost crustal structure by 50-70 km-long profiles. As a next step of the program, refraction studies are, starting from 1989, aimed to reveal the detailed structures of lower crust and upper mantle by relatively long profiles of 150-200 km. Within this framework of the RGES, a seismic refraction experiment was deployed across the central part of Hokkaido in the autumn of 1992 in order to provide a good picture of crustal structure beneath the central Hokkaido and thereby contribute to a better understanding of the tectonic processes that generated very complex structure.

In this seismic refraction experiment, the four shots with the charges of 450-700 kg were recorded mostly in digital form at the 184 recording sites along the 178 km-long profile running from Monbetsu in southwest part of Hokkaido to Tsubetsu in the northeast. Based on the seismic refraction data, a two dimensional crustal model has been developed for the Central Hokkaido through ray trace forward modeling (Iwasaki, 1988). Especially, the upper part of the crust was modeled down to 20 km in detail since dense receiver spacing and also the shot point spacing of approximately 50-60 km provided quite good data. But the deeper parts of the crust and the upper mantle, on the other hand, cound not be modeled at the same reliability because of insufficient resolution of the data to corralate later arrivals. Therefore, the evaluation of the deeper parts is not included in this study.

2. Regional tectonics

Recently the tectonic evolution of Hokkaido has been intensively discussed on the basis of plate tectonics. The studies lead to the conclusion that tectonic structures of Hokkaido are the products of plate movements and the associated secondary movements.

In general Hokkaido has predominant N-S trends of geological structures and is roughly divided into three parts ; West, Central and East Hokkaido (Fig. 1). The Central Hokkaido is defined as the region from the eastern part of Ishikari Lowlands to the Abashiri Tectonic Line through the Hidaka Mountains. The Paleozoic-Mesozoic Group of this region is also subdivided into the Sorachi-Yezo Belt, the Hidaka Metamorphic Belt and the Tokoro Belt, from west to east. These N-S trending tectonic zones are formed by the Mesozoic arc-trench subduction systems between the Eurasian and Pacific Plates and the oblique collision system between the Okhotsk and Pacific Plates (Oka, 1986).

In addition to the N-S trending structures, the East Hokkaido and middle to south part of the Central Hokkaido have ENE-WSW trending zonal structures, NE-SW trending en-echelon structures and westward protruding arc structures. The zonal structures are the products of the Paleo and Modern Kurile arc-trench subduction systems. Also subduction of the Pasific Plate

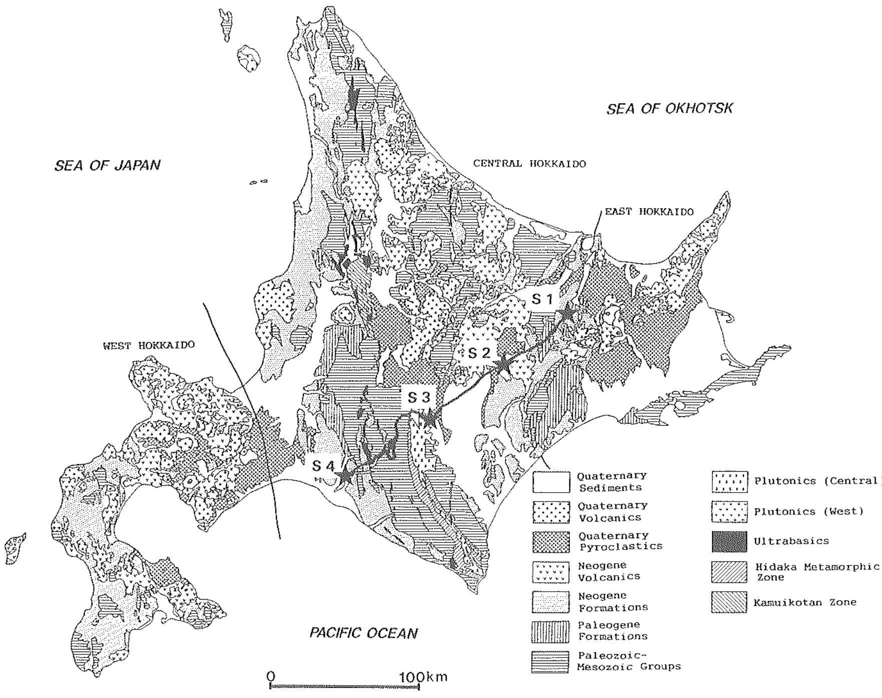

Fig. 1. Geological map of Hokkaido (Geological Survey of Hokkaido, 1992) and the location of the profile.

obliquely from east in the Modern Kurile Arc-trench system resulted in the right-lateral strike-slip movements along the volcanic front in the southern part of the Kurile arc and these movements formed en-echelon structures of NE-SW trend in the inner Kurile Arc (including the middle part of the Central Hokkaido) and westward protruding arc structures in the frontal Outer Kurile Arc (Oka, 1986).

The Modern Kurile arc-trench oblique-subduction system and the westward shifting of the Outer Kurile Arc has an important role for determining the tectonic evolution in Hokkaido. Detailed analysis of geodetic surveys in Hokkaido has also revealed horizontal crustal deformation in the southwestern part of the Kurile Arc. These geodetic surveys showed that the Outer Kurile Arc moved toward southwest and collided against middle Hokkaido along the Obihiro tectonic line : this tectonic line is considered to be the tectonic boundary between the Outer Kurile Arc and middle Hokkaido (Tada and Kimura, 1987).

One of the important N-S trending tectonic belt in Hokkaido is the Hidaka Metamorphic Belt which is situated in the southern part of the axial zone of Hokkaido at the junction of the northeast Honshu and Kurile Arcs. In association with the movement of the Okhotsk Plate, original volcanic arc on the collision zone was elongated in the N-S direction. As a result of the elongation, present arrangement showing N-S trending distribution of the plutonic rocks in Hidaka Belt is observed and layer uplifting of the metamorphics in the Hidaka Mountains have been triggered from the southwestward migration of the Outer Kurile Arc caused by the oblique subduction of the Pasific Plate (Kimura and Miyashita, 1986). The belt, according to the recent studies (Komatsu et al., 1986) consists of two different geologic units : the main zone and western zone. The former one thrusts over ther latter at the Hidaka Main Thrust.

3. The experiment

The Research Group for Explosion Seismology (RGES), consisting of many universities and research institutes in Japan, carries out seismic refraction experiments in tectonically characteristic places every year as a part of the earthquake prediction program. Within this framework of RGES, a seismic experiment was deployed across the central part of Hokkaido in the autumn of 1992. The arrangement of the seismic refraction shot points and recording sites along 178 km profile is shown in Fig. 2. The profile was extended from Monbetsu in southwest to Tsubetsu in northeast, crossing trough the main geological belts which are the Sorachi-Yezo Belt, the Hidaka Mountains, the

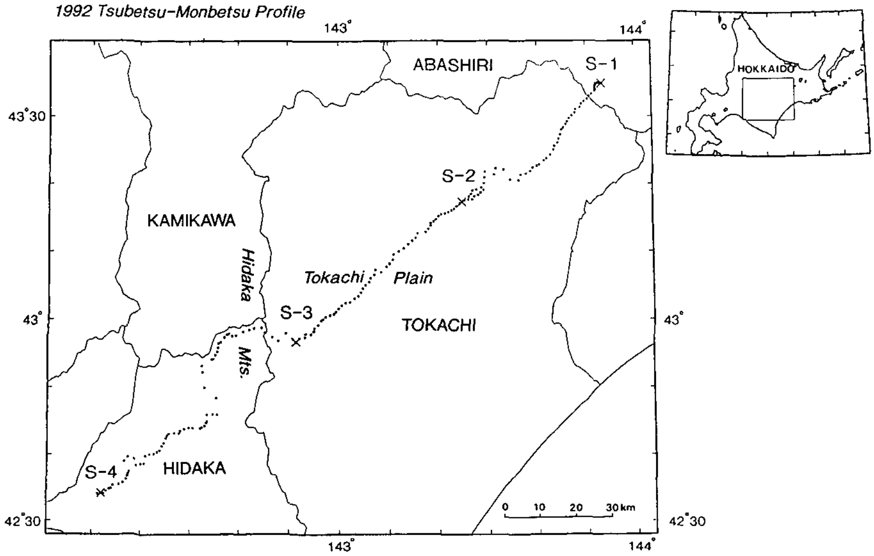

Fig. 2. Map of Central Hokkaido showing the positions of shot points (crosses) and recording sites (small circles).

Tokachi Plain and the Tokoro Belt, from west to east (Fig. 1). Four shots, varying in size from 450 kg to 700 kg of explosives, were detonated in 30-40 m-deep drill holes. Technical shot point information is given in Table 1. Shot point locations along the profile have an average spacing of approximately 60 km. The in-line shots (Shot-2 and Shot-3) provided velocity control on the upper 10 km of the crust within the spread. The other two profile-end shots (Shot-1 and Shot-4) provided information about deeper parts of the crust.

A number of 184 recording instruments spaced in approximately 1 km apart

Table 1. Shot point data for the experiment.

SHOT POINT	COORDINATES		ELEV (m)	CHARGE (kg)	DEPTH (m)
	LATITUDE	LONGITUDE			
SHOT-1 (1)	43 34′ 51.4″	143 53′ 17.4″	209.0	350	27.95
SHOT-1 (2)	43 34′ 50.7″	143 53′ 17.0″	209.2	350	28.36
SHOT-2	43 17′ 22.6″	143 24′ 41.0″	238.9	450	33.6
SHOT-3	42 56′ 47.4″	142 51′ 37.7″	388.5	450	34.35
SHOT-4 (1)	42 34′ 10.5″	142 12′ 07.4″	92.5	350	28.62
SHOT-4 (2)	42 34′ 09.4″	142 16′ 06.7″	92.1	350	27.95

were deployed at presurveyed sites in this experiments. About two third of the instruments consisted of digital recorders and the rest were anolog cassette recorders. In the vicinity of each shot point six additional recording points were set with a spacing of 100 m for direct measurement of surface velocities. Both digital and anolog systems utilized vertical component geophones with a natural period of about 2 Hz.

4. Data processing

The recording success rate in this experiment was 80% and in general high quality data was acquired. The data were mostly recorded in digital form at various sample rates and some in anolog form. Those recorded in anolog form were later digitized at the Earthquake Research Institute's laboratory of Tokyo University and then all the data were reduced to common 100 Hz sample rate. The predominant frequency range of the data was 5-10 Hz.

Shot and recording sites were located on 1 : 25,000 scale topographic maps

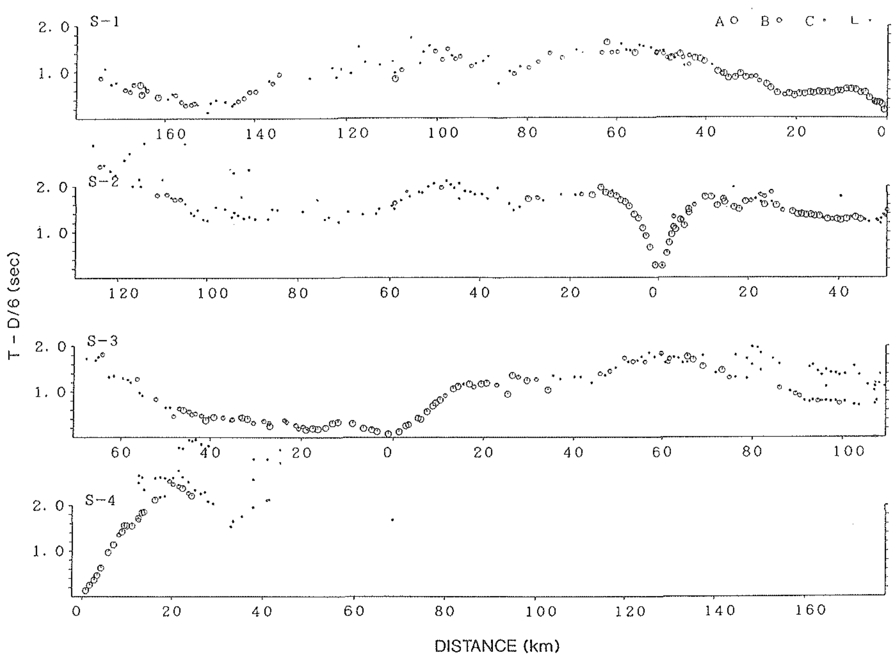

Fig. 3. Arrival times of each shot. The reduction velocity is taken as 6.0 km/sec. The size of circles shows the data quality as given on the upper right.

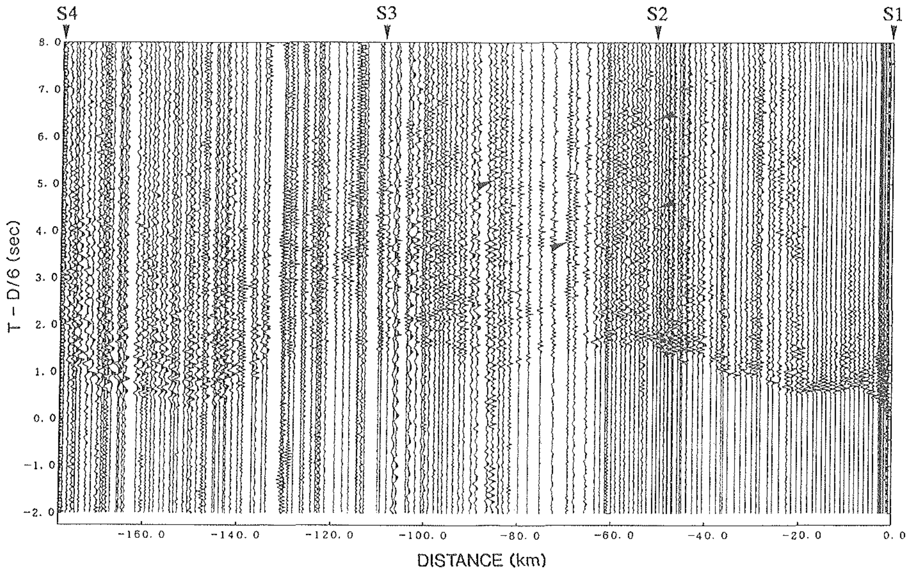

Fig. 4. Record section for Shot-1. Each trace is normalized by its maximum amplitude and filtered by 3-15 Hz band pass filter. The reduction velocity is 6.0 km/sec.

that provided a satisfactory accuracy in surface locations and in elevations. Also satisfactory timing accuracy was achieved through Japan Standart Time (JJY) signals either recorded simultaneously with the seismic signal or used to rate internal clocks of the instruments. This timing system allowed us to correct timing errors caused by drifting time code generators or fluctuation of tape speeds in the recording systems.

Arrival time data used for travel time analysis were picked up on non-filtered traces since filtering usually distorts onsets of seismic signals. The impulsive character of the first arrivals ensured that arrival times were accurately picked and correlated along the record sections. However, as the offset distances increased, diminishing signal strength made picking arrival times difficult. The reliability of the picked arrival times are ranked by A, B, C which indicate reading errors of 0.01s, 0.03s, 0.05s respectively and L being more than 0.05 which are not usable in the calculations (L). Fig. 3 shows arrival times picked for each shot and their degree of reliability. To supress noise and to make clear amplitudes of later phases, all of the traces were filtered by 3-15 Hz digital band pass filter and plotted in trace normalized mode, i.e. each trace was normalized by its maximum amplitude. After these steps the data were

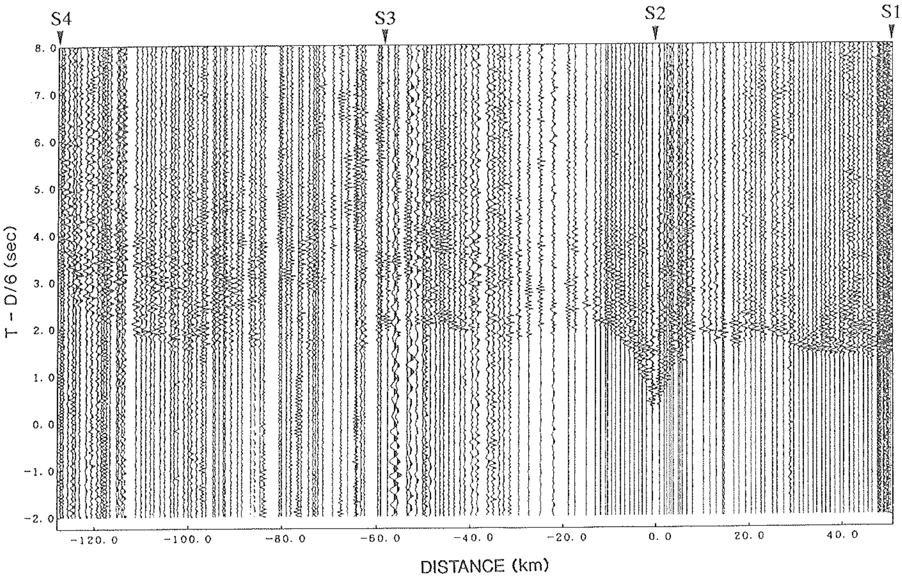

Fig. 5. Record section for Shot-2. Each trace is normalized by its maximum amplitude and filtered by 3-15 Hz band pass filter. The reduction velocity is 6.0 km/sec.

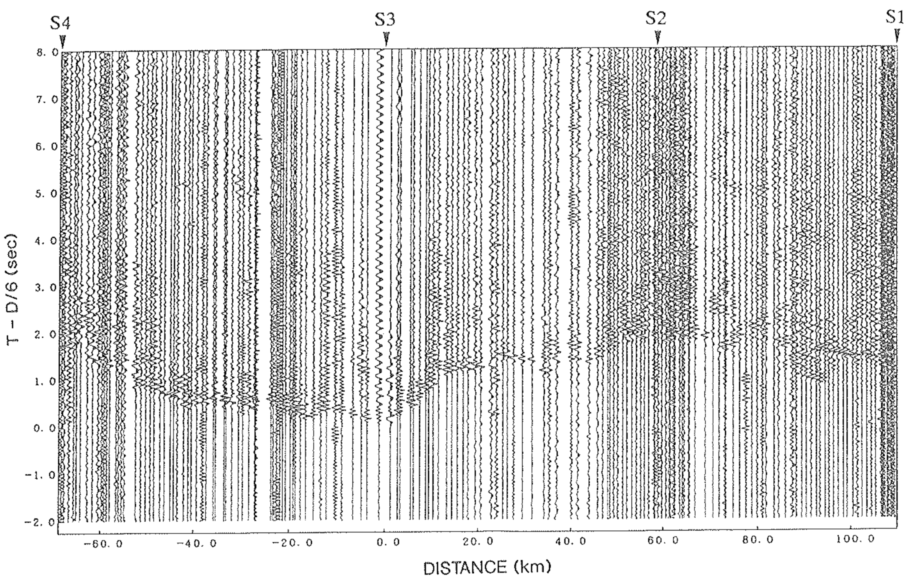

Fig. 6. Record section for Shot-3. Each trace is normalized by its maximum amplitude and filtered by 3-15 Hz band pass filter. The reduction velocity is 6.0 km/sec.

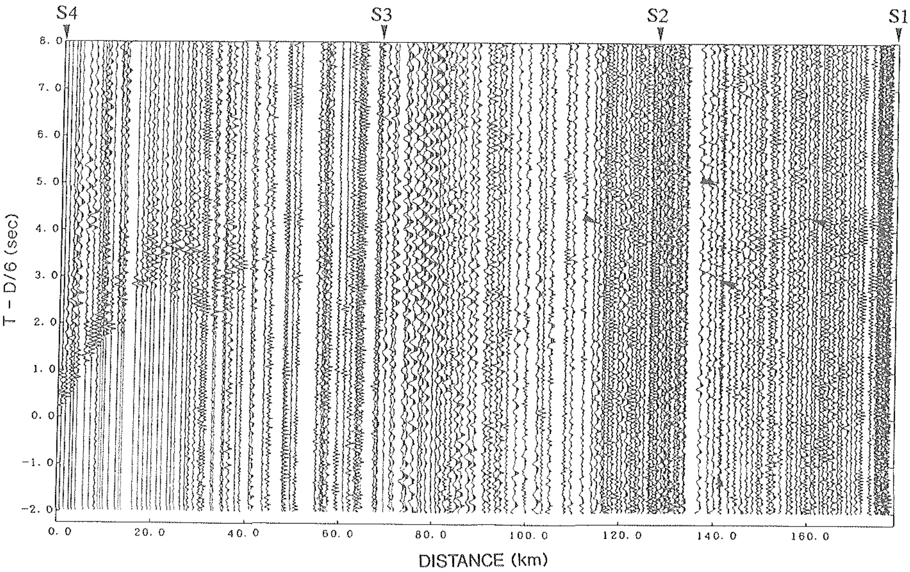

Fig. 7. Record section for Shot-4. Each trace is normalized by its maximum amplitude and filtered by 3-15 Hz band pass filter. The reduction velocity is 6.0 km/sec.

compiled into seismic record sections by reducing with a reduction velocity of 6.0 km/s. Filtered record sections are shown in Figs. 4-7. These data processing steps mentioned above were performed by the Analysis Committee of RGES.

5. Method of interpretation

The aim of the seismic refraction investigation is to develop a two-dimensional (2-D) seismic velocity distribution under the profile, based on the P-wave data. The first procedure for constructing a 2-D velocity model was to determine the velocity structure for the uppermost part of the crust, in other words determining the thicknesses and velocities of the sedimentary layers, geometry of the basement and its velocity. As a first step for obtaining an approximate model assuming horizontal and homogeneous layering, a one-dimensional (1-D) velocity-depth function was derived for each shot point from apparent velocities and intercept times of the travel time curves with offset distances less than 20 km. The velocities of the upper most sedimentary layers just beneath the shot points were calculated from the up-hole data (Fig. 8). Moreover, to get information about uppermost velocities in between the shot points, the Travel Time

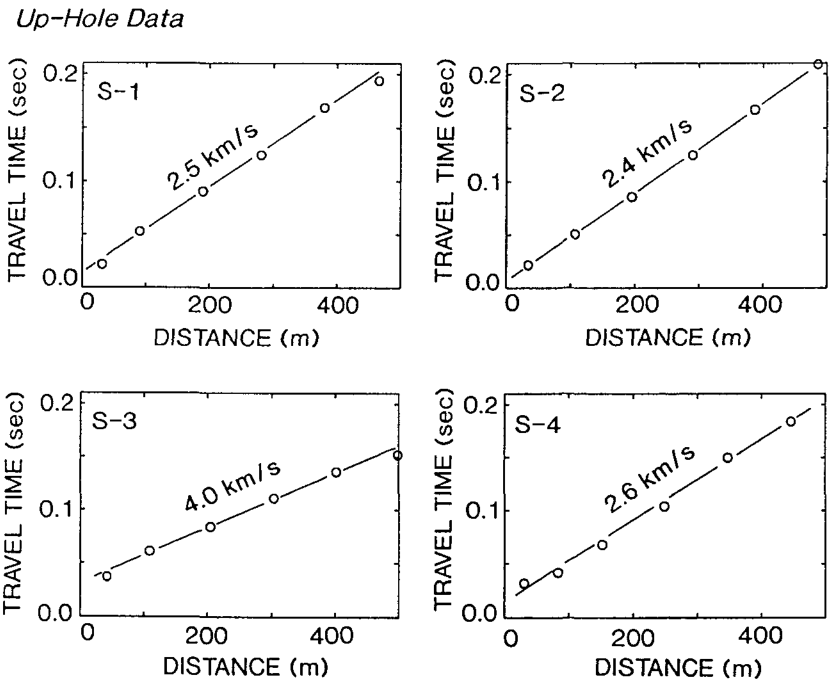

Fig. 8. Travel times of near-shot recordings for each shot with the estimated velocities of the shallowest part of the crust.

Differences Method was applied to the arrival time data. The 1-D velocity-depth functions are given in Fig. 9. These discrete velocity values from the individual 1-D velocity-depth functions for each shot point provided a basis for constructing an approximate 2-D velocity model which serves as a starting model for the ray tracing program.

As a next step, by applying the ray tracing program developed by Iwasaki (1988) this starting model was modified again in several iterations until the best fit is achieved between the model-derived travel times and observed travel times (trial and error method). The program was firstly applied between the sequential shots. After getting a satisfactory fit between the calculated and observed travel times, and hence information about the shallow part, the program was applied skippingly between the shot points that provided velocity information about the deeper parts of the crust. At the end of these interpretation steps, a 2-D velocity model down to about 20 km was obtained. This model obtained by the refraction data is given in Fig. 10.

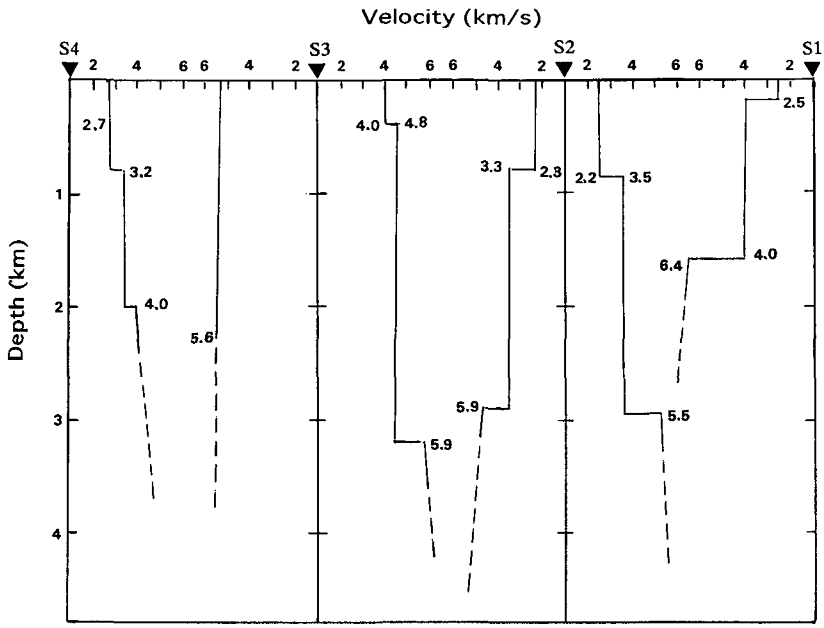

Fig. 9. 1-D Velocity-depth function under each shot.

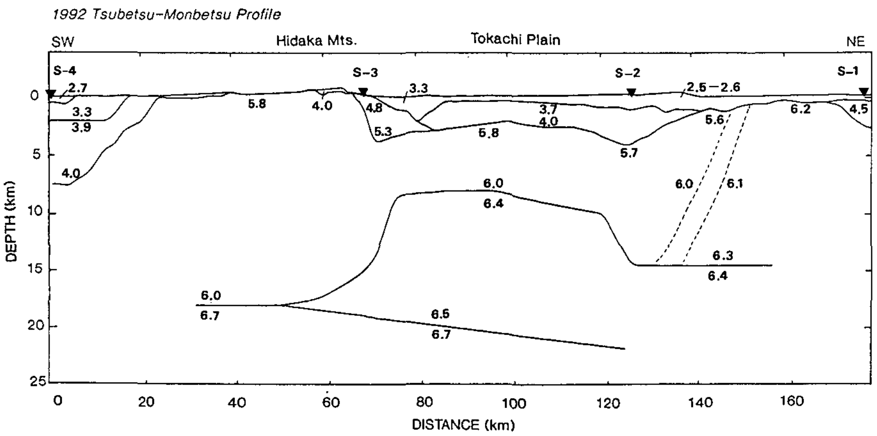

Fig. 10. Seismic velocity structure model down to 25 km under the profile. Dashed lines denote gradual velocity increase but not velocity discontinuity.

6. Data characteristics

Preliminary examinations of the record sections (Figs. 4-7) observed along the profile show that the travel time curves indicate strong curvature, i.e. a rapid change in apparent velocities in the distance range between 0-20 km. This means a strong velocity gradient in the uppermost part of the basement. Especially in between Shot-1 and Shot-2, both vertical and lateral velocity gradients are comparatively higher than those of other parts. First arrivals at offset distances from 10 km to 90 km can be correlated by a continuous travel time curve with local irregularities for each shot, except Shot-4. These arrivals correspond to refracted waves within the upper part of the crust. Noticable undulations on the travel time curves between Shot-2 and Shot-3 are due to the thick sedimentary layers. This is also evident from the intercept times of first arrivals of refracted waves in the upper part of the crust for Shot-2 (in both sides) and Shot-3 (towards Shot-2). Those for Shot-2 and Shot-3 have larger intercept times if compared with the same first arrivals for Shot-1. This part of the travel time curves corresponds to the Tokachi Plain where is well known as an area of thick sedimentation (Matsushima and Okada, 1990).

At the offset distances between 100 km and 140 km from Shot-1, the data in the record section of Shot-1 show remarkable decrease in amplitudes. This fact can also be seen in the travel time picks on Fig. 3. The reliability of the picked arrival times in this distance range is mostly ranked by C being comparatively less reliable readings. These arrivals picked and plotted as first arrivals are not first arrivals refracted in the lower part of the crust but are attributed to later arrivals of reflections from the intracrustal boundary. Thus refracted first arrivals are likely hidden in the traces. This is also referred in the next section.

The record section of Shot-4 (Fig. 7) does not contain as much information as the other record sections have, because of some obscure reasons. At the offset distances about 35 km onwards from Shot-4, there is no any visible first arrival. This phenomena may be explained by existence of a low velocity layer and/or locally high attenuation zone, which is not possible to detect by the data of this experiment. On the other hand, weak later arrivals denoted by arrows on the same record section (Fig. 7) are observed at offset distances between 115 km and about 160 km from Shot-4. These later arrivals are correlated as reflections from crust-mantle boundary. Also another set of later arrivals in the same distance range can be correlated as the reflections from a boundary in the upper mantle. For the record section of Shot-1 (Fig. 4), correlative later arrivals can be seen at comparatively shorter offset distances of 50 km onwards. These two sets of arrivals are also attributed to the same boundaries as those for Shot-4.

7. The crustal model

Fig. 10 shows the upper crustal model down to about 20 km under the profile, constructed from refraction data. The sedimentary layers and upper crust are densely covered with rays and therefore this part of the crust is well constructed. The uppermost part of the crust is characterized by the sedimentary cover of which thickness is very variable along the profile. The total thickness of the sedimentary layers increases between Shot-2 and Shot-3 where, a part of the Tokachi Plain and it amounts to about 4 km in which the velocities, increasing with depth, vary from 2.5 km/s to 5.3 km/s while the thickness between Shot-2 and Shot-1 averages at about 1 km. Also the velocity of the shallowest part of the sedimentary layers laterally varies from 2.5 km/s around Shot-1 to 3.4 km/s at the northeast part of Shot-3. At the southeast part of the Shot-3, the average velocity is found as 4.0-4.1 km/s. Further to the southwest from Shot-3, sedimentary cover vanishes and basement rises to the surface. The total thickness of the sedimentary layers increases again towards Shot-4 and reaches at about 7-8 km. The velocities in this region vary from 2.6 km/s to 4.0 km/s.

The described uppermost structures along the profile are underlain by a basement with the laterally changing velocity. Generally, the basement velocity averages at 5.8 km/s but it changes remarkably and reaches at 6.1-6.2 km/s under the northeast part of the profile. On the contrary, it decreases towards southwest end of the profile. Assuming no lateral velocity change in the upper crust, between Shot-1 and Shot-2 i.e. by taking the basement velocity as averagely 5.8 km/s travel times were calculated and plotted by dashed lines on Fig. 11 to compare with observed ones. As can be seen from Fig. 11, first arrivals passing through upper crust became late indicating that higher basement velocities are required between Shot-1 and Shot-2 to get a good fit between the travel times. Moreover, between Shot-1 and Shot-2, a steep velocity discontinuity from 5.7 km/s to 6.1 km/s could be introduced instead of transitional zone showed by dashed lines in the model. The data can not be used to distinguish between the two cases since the both do not make any difference in comparison of travel times.

As for the middle part of the crust, the most remarkable feature is the

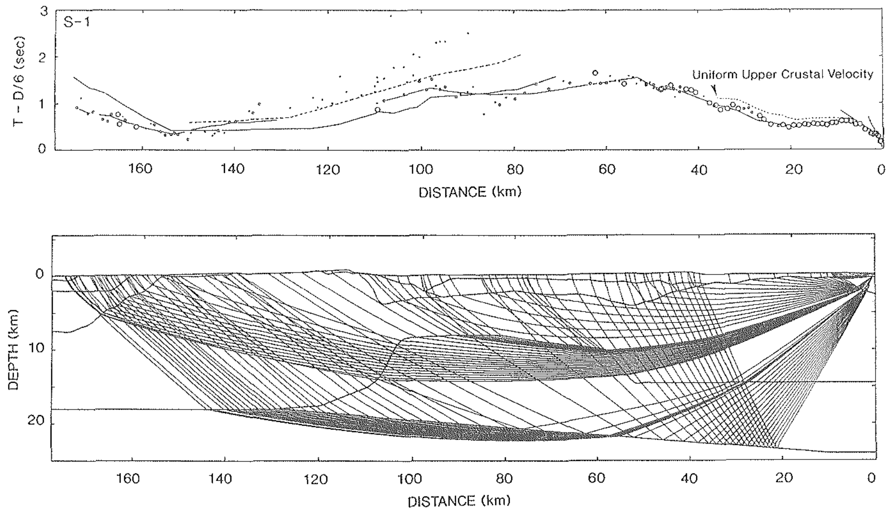

Fig. 11. Ray diagram and the complarison of calculated and observed travel times for Shot-1.

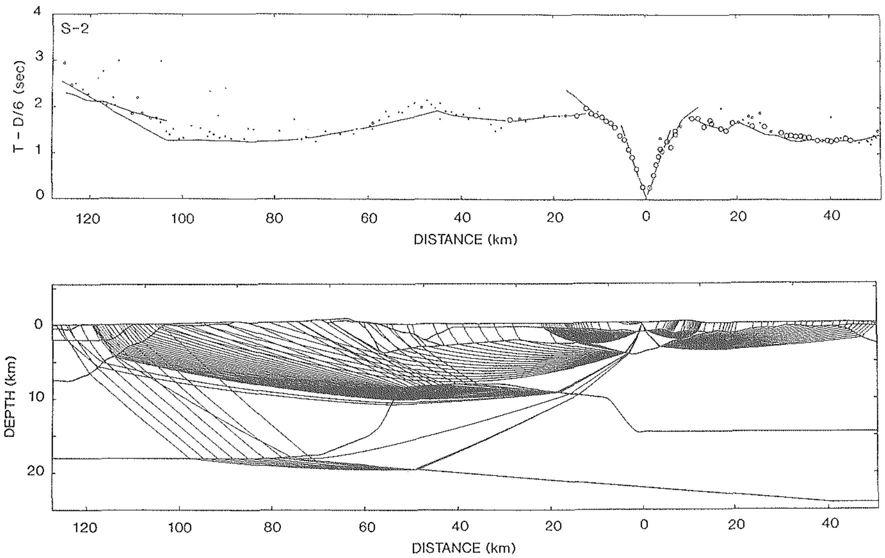

Fig. 12. Ray diagram and the comparison of calculated and observed travel times for Shot-2.

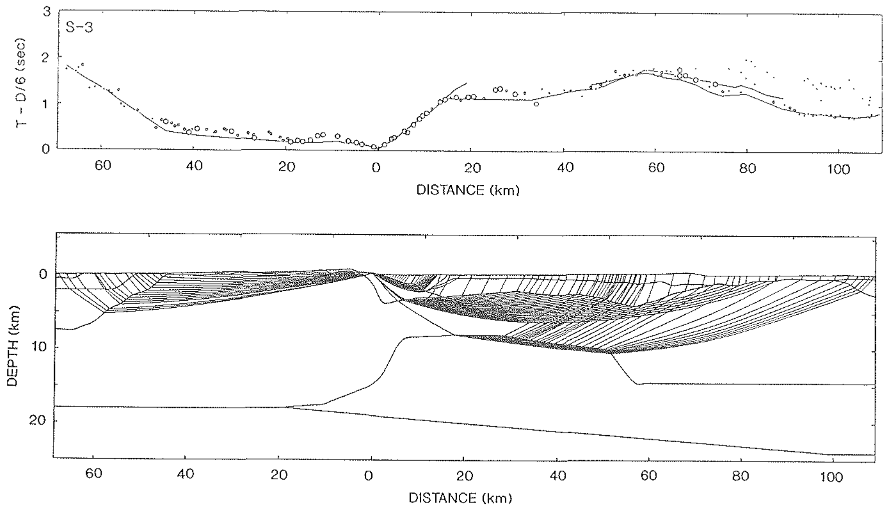

Fig. 13. Ray diagram and the comparison of calculated and observed travel times for Shot-3.

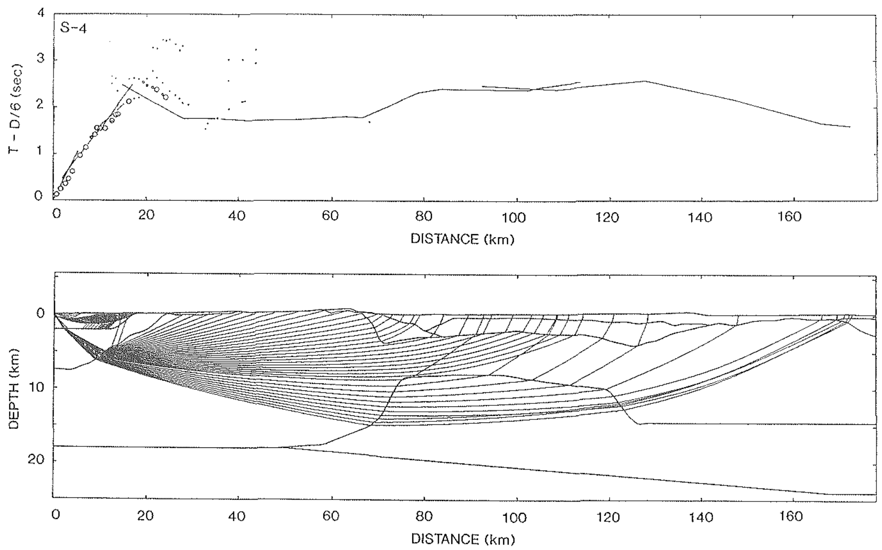

Fig. 14. Ray diagram and the comparison of calculated and observed travel times for Shot-4.

geometry of the 6.4 km/s layer. This mid-crustal layer locally warps upward and rises up to about 8 km between Shot-2 and Shot-3. This mid-crustal layer no longer exists beneath the southwest part of the profile. The geometry of upper boundary of this layer is constrained from Shot-2 and Shot-3 data. Fig. 12 and Fig. 13 show the ray-path diagrams and travel time comparisons for both shot. The first arrivals for both Shot-2 (towards southwest) and Shot-3 (towards northeast) at the offset distances of 50-60 km onwards show higher apparent velocity than that of first arrivals at shorter distances. In order to get a good fit between calculated and observed travel times at these distances, arrivals of rays passing through such a 6.4 km/s mid-crustal layer are required. Moreover, an attempt was made to show how the geometry of upper bondary of this layer changes. Assuming that this boundary lies straight, instead of bending down, in this case calculated travel times considerably differed from the observed travel times. The dashed lines in Fig. 12 shows the travel times calculated based on this assumption. Although it is not shown on the Fig. 13 for Shot-3, the same approach through Shot-3 data to the northeast part of this boundary gave the same result indicating the straight boundary.

Another important feature is that a layer with the velocity of 6.7 km/s is found at the depth of 17-20 km under the Hidaka mountains. The upper boundary of this layer rises towards southwest. Such a depth and slope of this boundary is established from Shot-1 data and can be confirmed in the distance range of 40-140 km from this shot point. Seismic response of this layer, i.e. first arrivals of the waves penetrating through this layer show well distinguishable onsets and noticably high amplitudes. Travel time picks are mostly A and B class (Fig. 3) which mean 0.01s and 0.03s reading error, respectively, although offset distances of these first arrivals are observed from 140 km onwards.

As mentioned in the previous section, it can be clearly seen from the travel time comparison and ray-path diagram for Shot-1 (Fig. 11) that, at the offset distances between 100-140 km, the first arrivals of the waves penetrating 6.4 km/s mid-crustal layer do not fit to the observed travel times at all. On the other hand arrival times of the reflected waves from the upper boundary of 6.7 km/s layer show quite good fit. These reflections are shown by dashed lines in Fig. 11. Hence the picked arrivals in this distance range are not the first arrivals. Refracted first arrivals are not visible due to low signal-noise ratio at these offset distances.

Although the upper part of the crust down to about 20 km is resolved well by the refraction data, the deeper parts of the crust and crust-mantle boundary, on the other hand, could not be modelled at the same reliability since the resolution of the data was not sufficient. Weak reflections on both record sections of Shot-1 and Shot-4 can be barely correlated. In an attempt to reveal the deeper parts, wide-angle reflection study was performed by using Shot-1 and Shot-4 data but not included in this study.

8. Discussion

The seismic P-wave velocity model derived from refraction and wide-angle reflection data of the seismic experiment along the profile running through the Central Hokkaido provided important knowledge of the upper part of the crust.

The uppermost part of the crust is characterized by sedimentary cover varying in thickness and by lateral changes in basement velocities. The tectonic thickening of sedimentary layers which reaches at 3-4 km under the Tokachi Plain in the model, where the Tokoro complex thrusts onto Hidaka complex (Komatsu, 1986 ; Oka, 1986), can be interpreted as a result of collision of the Outer Kurile Arc against the middle Hokkaido. Moreover, the transition zone showing remarkable lateral changes in the upper crustal velocity between Shot-1 and Shot-2 (denoted by dashed lines in Fig. 10) corresponds to the Abashiri Tectonic Line formed by also the westward movement of the Outer Kurile Arc (Tada and Kimura, 1987).

As a characteristic feature of the middle part of the crust, an upward warping layer with the velocity of 6.4 km/s is found. Moreover an intracrustal boundary is delineated at the depth range of 17-21 km. This boundary dipping northeast in the middle crust can be interpreted as Conrad discontinuity. This depth range is cosistent with that found by Zhao et al. (1992) as 12-22 km beneath whole Japan. The geometry of the upper boundary of the midcrustal layer of 6.4 km/s together with the uprising lower crustal layer of 6.7 km/s under the Hidaka Mountains suggests that midcrustal layer vanishes under the Hidaka Mountains. The vanishing of this layer might be related with the uplifting process in this region.

On the other hand the data do not suggest that the upper crust under the west part of the Hidaka Mountains is composed of a few layers seperated by significant velecity discontinuities. Instead, the upper crust is interpreted to consist of positive velocity gradients extending from the basement with the velocity of 5.8 km/s to the intracrustal boundary at the depth of 17-21 km with 6.0 km/s velocity.

The P-wave velocities in the upper crust and the lower crust under Hokkaido and surrounding areas have been investigated in detail by explosion studies (Yoshii and Asono, 1972 ; Okada et al., 1973 ; Okada et al., 1978 ; Research Group for Explosion Seismology, 1986 ; Iwasaki et al., 1993). According to these studies, Pwave velocities are 5.9 km/s for the upper crust, 6.6 km/s for the lower crust and 7.5 km/s for the upper mantle. These velocities are similar to those obtained by the present study, except the southwestern edge of the profile.

The obtained velocity structure model was compared with the Bouguer anomaly data (Yamamoto and Moriya, 1989). The observed gravity anomaly values strongly changes in the range from −60 mgal to 80 mgal, under the profile. Observed values are taken as maximum and minimum values within 10 km band along both side of the profile. On the other hand velocities were converted to densities using an empirical P-wave velocity-density relationship (Ludwig et al., 1968) and the corresponding theoretical two-dimensional gravity response was calculated by Talwani's method (1968). A constant density value

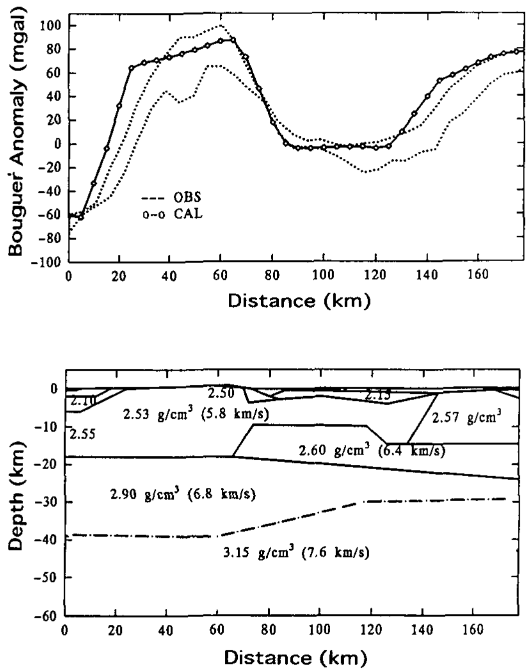

Fig. 15. Density structural model (lower figure) and a comparison of observed and model derived gravity anomalies (upper figure). Solid line represents model-calculated gravity anomalies and dashed lines represent observed maximum and minimum gravity anomalies within 10 km band along the both side of the profile (upper figure).

was assigned to each layer using an average layer velocity and slight perturbations ($\pm 0.05\ g/cm^3$) were made to densities of some layers through a trial and error method until the agreement between theoretical and observed gravity values was satisfactory except the western part. This level of agreement is reasonable considering the wide scatter of empirical measurements upon which the velocity-density relationship is based and suggests that seismic velocity model and observed gravity are consistent with each other (Fig. 15). In the comparison, high gravity anomalies correspond to the areas where basement outcrops or is very shallow. Reversely, low gravity anomalies correspond to where sedimentary layers thicken.

9. Conclusions

The crustal structure beneath the Central Hokkaido can be interpreted as forming by various events such as thrusting, uplifting etc. that the westward movement of the Outer Kurile Arc plays an important role on these tectonic event. The P-wave velocity structure along the main profile from Tsubetsu to Monbetsu can be summarized as follows (Fig. 8) ;

a) locally thick sedimentation areas varying in thicknesses and velocities. Sedimentary layers thicken under the Tokachi Plain and the southwestern edge of the profile. The velocities vary from 2.5 km/s to 5.2 km/s increasing with depth and from 2.5 km/s to 4.1 km/s laterally ;

b) remarkable lateral changes in basement velocity. It is found as 6.2 km/s between Shot-1 and Shot-2, and as low as 5.4 km/s under the southwestern edge. But this velocity of 5.4 km/s is not constrained as reliable as the velocity of 6.2 km/s. The basement velocity averages at 5.8 km/s elsewhere. Velocity gradients in the upper crust in the west part of the Hidaka Mountains are less than those in the east part ;

c) locally upward warping midcrustal layer with the velocity of 6.4 km/s. The refraction data suggest that this midcrustal layer disappears under the Hidaka Mountains ;

d) an intracrustal boundary dipping northeast from 17 km to 21 km. The velocity of the lower part of the crust under this boundary is found as 6.7 km/s and 6.9 km/s at the bottom of the lower crust.

It can be inferred from the results given above that the crustal structure in the western part of the Hidaka Mountains differs from that of the eastern part. As it is possible to seperate the crust in the eastern part with upper, middle and lower crust having locally varying thicknesses, in the western part this seperation seems to be disturbed.

Acknowledgments

The authors are grateful to all members of Research Group for Explosion Seismology for data collection in the field. We also thank to Prof. Hiroshi Okada for his constructive comments, to Akihiko Yamamoto for the comments on the gravity modelling of the data.

References

Asano, S., N. Den, H. Hotta, T. Yoshii, Y. Ichinose, S. Sakajiri and S. Sasatani, 1979. Seismic refraction and reflection measurements around Hokkaido, Part 2, Crustal structure of the continental slope off Hidaka. J. Phys. Earth, **27**, 497-509.

Den, N. and H. Hotta, 1972. Seismic refraction and reflection evidence supporting plate tectonics in Hokkaido. Papers in Meteorology and Geophys., **24**, 31-54.

Geological Survey of Hokkaido, 1992. Geological Map of Hokkaido.

Iwasaki, T., 1988. Ray-tracing program for study of velocity structure by ocean-bottom seismographic profiling. Zisin (J. Seism. Soc. Japan), **41**, 263-266 (in Japanese).

Iwasaki, T., H. Shiobara, A. Nishizawa, T. Kanazawa, K. Suyehiro, N. Hirata, T. Urabe and H. Shimamura, 1989. A detailed subduction structure in the Kurile trench deduced from ocean-bottom seismographic refraction studies. Tectonophysics, **165**, 315-336.

Iwasaki, T., T. Yoshii, T. Moriya, A. Kobayashi, M. Nishiwaki, T. Tsutsui, T. Iidaka, A. Ikami and T. Masuda, 1993. Seismic refraction study in the Kitakami region, Northern Honshu, Japan. J. Phys. Earth, **41**, 165-188.

Kimura, G. and S. Miyashita, 1986. Triple junction of trench-trench-oblique collision zone and origin of the Hidaka Metamorphic belt. Monograph. Assoc. Geol. Collab. Japan, **31**, 451-458 (in Japanese with English abstract).

Komatsu, M., S. Miyashita and K. Arita, 1986. Composition and structure of the Hidaka metamorphic belt, Hokkaido —historical review and present status—. Monograph. Assoc. Geol. Collab. Japan, **31**, 189-203 (in Japanese with English abstract).

Komatsu, M., 1986. Tectonics of the Hidaka Metamorphic belt. Monograph. Assoc. Geol. Collab. Japan, **31**, 441-450 (in Japanese with English abstract).

Ludwig, J.W., E. Nafe and L.C. Drake, 1968. Seismic refraction. *The Sea*, A.E. Maxwell, ed., 1970, Vol. **4**, 74.

Matsushima, K. and H. Okada, 1990. Determination of deep geological structure under urban areas, BUTURI-TANSA, **43**, 21-33.

Miyamachi, H. and T. Moriya, 1987. Velocity structure and aftershock distribution of the 1982 Urakawa-Oki Earthquake. J. Phys. Earth, **35**, 309-326.

Miyamachi, H., M. Kasahara, S. Suzuki, K. Tanaka and A. Hasegawa, 1994. Seismic velocity structure in the crust and upper-mantle beneath northern Japan. J. Phys. Earth, **42**, 269-301.

Oka, T., 1986. Distribution and tectonic evolution of Late Cenozoic basins. Monograph. Assoc. Geol. Collab. Japan, **31**, 295-320 (in Japanese with English abstract).

Okada, H., S. Suzuki, T. Moriya and S. Asano, 1973. Crustal structure in the profile across the southern part of Hokkaido, Japan, as derived from explosion seismic observations. J. Phys. Earth, **21**, 329-354.

Okada, H., T. Moriya, T. Masuda, T. Hasegawa, S. Asano, K. Kasahara, A. Ikami, H. Aoki, Y. Sasaki, N. Hurukawa and K. Matsumura, 1978. Velocity anisotropy in the sea of Japan as revealed by big explosions. J. Phys. Earth, **26**, Supll., 491-502.

Research Group for Explosion Seismology, 1986. Upper crustal structure in the western part of the Hidaka Mountains deduced from seismic refraction experiment. Abstr. Ann. Meet. Seism. Soc. Jpn, **1**, 291 (in Japanese).

Tada, T. and G. Kimura, 1987. Collision Tectonics and crustal deformation at the southwestern margin of the Kuril Arc. Jour. Seis. Soc. Japan, **40**, 197-204.

Takanami, T., 1982. Three dimensional seismic structure of the crust and upper mantle beneath the orogenic belts in southern Hokkaido Japan. J. Phys. Earth, **30**, 87-104.

Talwani, M., 1968. Computer usage in the computation of gravity anomalies, in *Methods in computational physics*, Vol, **13**, No. 2.

Yoshii, T. and S. Asano, 1972. Time-term analysis of explosion seismic data. J. Phys. Earth, **20**, 47-57.

Zhao, D., S. Horiuchi and A. Hasegawa, 1992. Seismic velocity structure of the crust beneath the Japan Islands. Tectonophysics, **212**, 289-301.