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ORIGINAL PAPER

Estimation of the 2D crustal velocity structure in the Hidaka and Iburi Subprefectures, Hokkaido, Japan

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Abstract Applying the iterative shooting/bisection technique for rapid forward modeling to the seismic explosion data, we could refine the crustal velocity structure model of the western part of the Hidaka collision zone, Hokkaido, Japan. We used only the precise P-wave first arrival data obtained by the Research Group for Explosion Seismology, which set up a 113.4-km-long profile in August 2000 along with 327 observation points and four shot points with TNT charges from 100 to 300 kg. We could estimate a two-dimensional inhomogeneous crustal velocity structure model with a velocity decrease in the eastern direction at a depth of 15.7 km, several portions of velocity reversals with depth and a low velocity anomaly proposed in previous studies. The root-mean-square of travel-time residuals was improved from 0.398 s for the previous structure model to 0.176 s for the present model with a reduction of 55.8%.

Keywords Hidaka collision zone · Inhomogeneous crustal structure · Shooting/bisection technique

Introduction

Hokkaido is one of the three regions affected by arc–arc collision in the Japanese islands, including central Japan and Kyushu (e.g., Kimura 1996). At the Late Jurassic to the Early Cretaceous, the collision between the Okhotsk and the Kamuikotan–Nukabira paleoland was started. Also, the Okhotsk–Chukotka's acidic volcanism began, leading to the Rebun and Kabato volcanoes. The Pacific margin was affected by a left lateral strike-slip fault system. Since the Late Miocene, the Kuril fore-arc sliver moved southwestward and collided with the Northeastern Japan arc (e.g., Jolivet 1986; Kimura 1981, 1986, 1996). The southwestward migration of the Kuril fore-arc sliver was raised by oblique subduction of the Pacific plate along the southern Kuril trench (e.g., Kimura 1996; Earthquake Research Committee 1998). The Hidaka shear zone and the Tartary shear zone were created by right-lateral strike-slip movements of the Eurasian and Okhotsk plates and the compression along the Hidaka shear zone was being provoked with quicker movement of the Kuril arc toward the west. Simultaneously the opening of the Japan Sea started with a pull-apart mechanism in the Eocene to the Early Miocene. Recently, the deformation zone jumped to the Japan Sea margin (Jolivet 1986).

Because of its complicated tectonic setting as stated above, the Hidaka collision zone has been a subject of many researches, e.g., Iwasaki et al. (1998, 2001, 2004), Arita et al. (1998), Ozel et al. (1996), and Fujii and Moriya (1983). Most of these researches have discussed the central, northeastern, or southern parts of Hokkaido. For instance, Arita et al. (1998) have investigated the crustal structure of the area, ranging only to the south of latitude 43° and to the east of longitude 142°, which is also called the Hidaka collision zone. The forward modeling based on a 2D ray tracing technique was adopted by Iwasaki et al. (2004) to investigate the same area of interest using a set of 624 observing points of the experiments conducted on 1999 and 2000. In the present study, we investigate and propose the 2D crustal velocity structure of the western part of the Hidaka collision zone by using the seismic ray inversion technique. To clarify the competence of the adopted method, we compare the results of previous studies with those of the present one.

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2D crustal velocity structure estimated from seismic refraction data

During the period from 1984 to 2000, five seismic refraction experiments were accomplished to investigate the deep crustal structure of the Hidaka collision zone. The last two experiments, whose profiles were set up from east to west in the southern part of Hokkaido, were conducted by the Research Group for Explosion Seismology (RGES) in August 1999 and August 2000 (Fig. 1). The present study used the seismic data from the 2000 RGES's experiment that possessed the profile of 113.4 km in length with 327 observation points and four shot points, for which charges of TNT were ranged from 100 to 300 kg. Concerning the quality of the seismic data used, its tendency was effectively demonstrated in the case of the first shot with 300 kg TNT charge: errors of first arrivals were within 0.01 s to the western side of the shot point until epicentral distances less than 20 km, where those dropped to 0.05 s: errors of first arrivals were 0.05 s at epicentral distances longer than 5.5 km to the eastern side of the shot point. The last three shot points consumed 100 kg of TNT for each site and show lower quality data. The second shot point (S-2) shows a drastic change of picking error from 0.01 to 0.05 s at distances more than 7.05 and 10.46 km to the west and east of the explosion site, respectively. This observing distance with reduction of data quality is farther than 10.5 and 7.7 km to the west and east of shot point S-3, respectively, and 5.9 km to the west of shot point S-4.It was noticed by Iwasaki et al. (2004) that shot points S-2 to S-4 show travel-time jumps, and the record from both the sides of S3 presented significant travel-time delays. Other details about data acquisition and characteristics of seismic records have been mentioned by Iwasaki et al. (2004). The precise first P-wave arrivals only were used for investigating the present two-dimensional crustal velocity structure model along the profile line. The initial model in this research was assumed to be the same as proposed by Iwasaki et al. (2004).

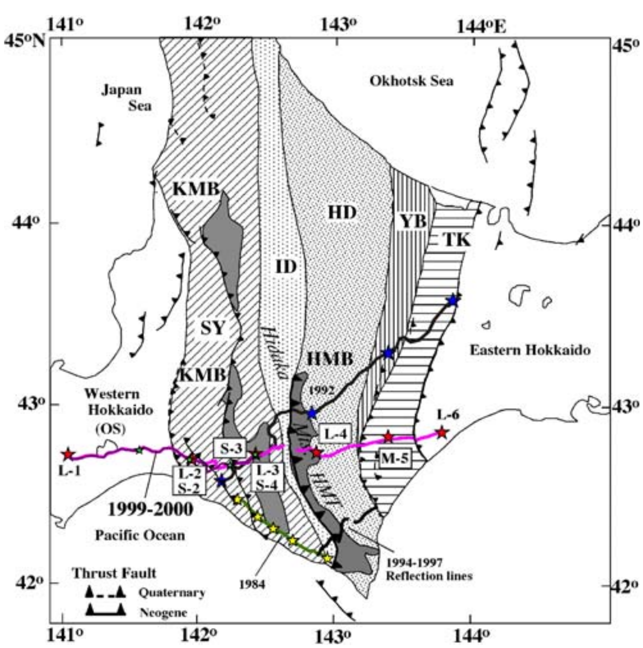

Fig. 1 Tectonic division in the central part of Hokkaido Island (Iwasaki and Moriya 2001). *Stars* indicate shot points. *OS* Oshima Belt; *SY* Sorachi-Yezo Belt; *KMB* Kamuikotan Metamorphic Belt; *ID* Idonnappu Belt; *HD* Hidaka Belt; *HMB* Hidaka Metamorphic Belt; *YB* Yubetsu Belt; *TK* Tokoro Belt; *HMT* Hidaka Main Thrust. The profile line of 1999 (*red stars showing shot points*) and 2000 (*shot points are represented in green stars*) is also shown

The model space of the velocity structure was divided into four layers and 45 trapezoids having four boundaries in the *x*–*z* plane. The number of nodes and spacing were arbitrarily determined and the layer boundary had to be extended left to right (i.e., west to east) in the entire model space. Although velocity discontinuities across layer's boundaries were assumed, the velocity was assumed to be continuous laterally across vertical boundaries within each layer. A velocity value at any point within a trapezoid was determined to be linearly interpolated from the specified values of corner velocities. Coefficients for the linear combinations of the corner velocities were calculated for all trapezoids prior to ray tracing (Zelt and Smith 1992). On the basis of zero-order asymptotic ray theory, rays were traced in the velocity structure model by solving the ray tracing equations numerically (e.g., Červeny et al. 1977; Zelt and Smith 1992). The iterative shooting/bisection technique (search mode; Zelt and Ellis 1988) was applied for the present rapid forward modeling. This technique is efficiently used for complex structural models, and it is more cogent and needs less intensive computation than the two-point ray-tracing technique (Roland and Ellis 1989; Zelt and Smith 1992). Assuming a laterally homogeneous model, we could calculate analytically the initial takeoff angles to be used in the search mode.

The two-dimensional seismic ray inversion algorithm developed by Zelt and Ellis (1988) was utilized to estimate the present velocity structure model. Concerning the initial model consisting of four layers and 45 trapezoidal blocks having different geometries and velocity values, we assumed that the corners of each block coincided with both velocity nodes and layer boundary nodes. The present initial model was set up by referring the model by Iwasaki et al. (2004). The first run of the inversion analysis was performed to get the solution along with tracing rays to observation points. Running of the damped least squares inversion was needed to check the RMS and travel-time residuals for the estimated model.

After several iterations of the same procedures as stated above, adopting different models with different geometries and velocity values, we could get the final model. The differences between the rays' paths of the initial and final models are remarkable as shown in Figs. 2 and 3. Earthquake Prediction Research Council (2001) and Iwasaki et al. (2004) have tried to get deeper ray penetrations to investigate the deeper part of the velocity structure in the study area. Iwasaki and Moriya (2001) have indicated the presence of two reflectors dipping eastward beneath the Hidaka Mountains, which shows an evidence of the abduction of the Kuril fore-arc onto the Northeastern Japan arc. However, the deeper part of the structure was not necessarily clarified in the present study because of relatively small amounts of TNT charges used in the 2000 experiment. The RMS of the travel-time residuals was 0.398 s for the initial model at 697 data points, while that for the final model was improved to be 0.176 s with a reduction of 55.8%. However, the number of data points used in the final model was 717. There were vast differences of the velocity values between the initial and final models (Fig. 4). The two models were found to be significantly different concerning both the values of the RMS of travel-time residuals and the chi-square.

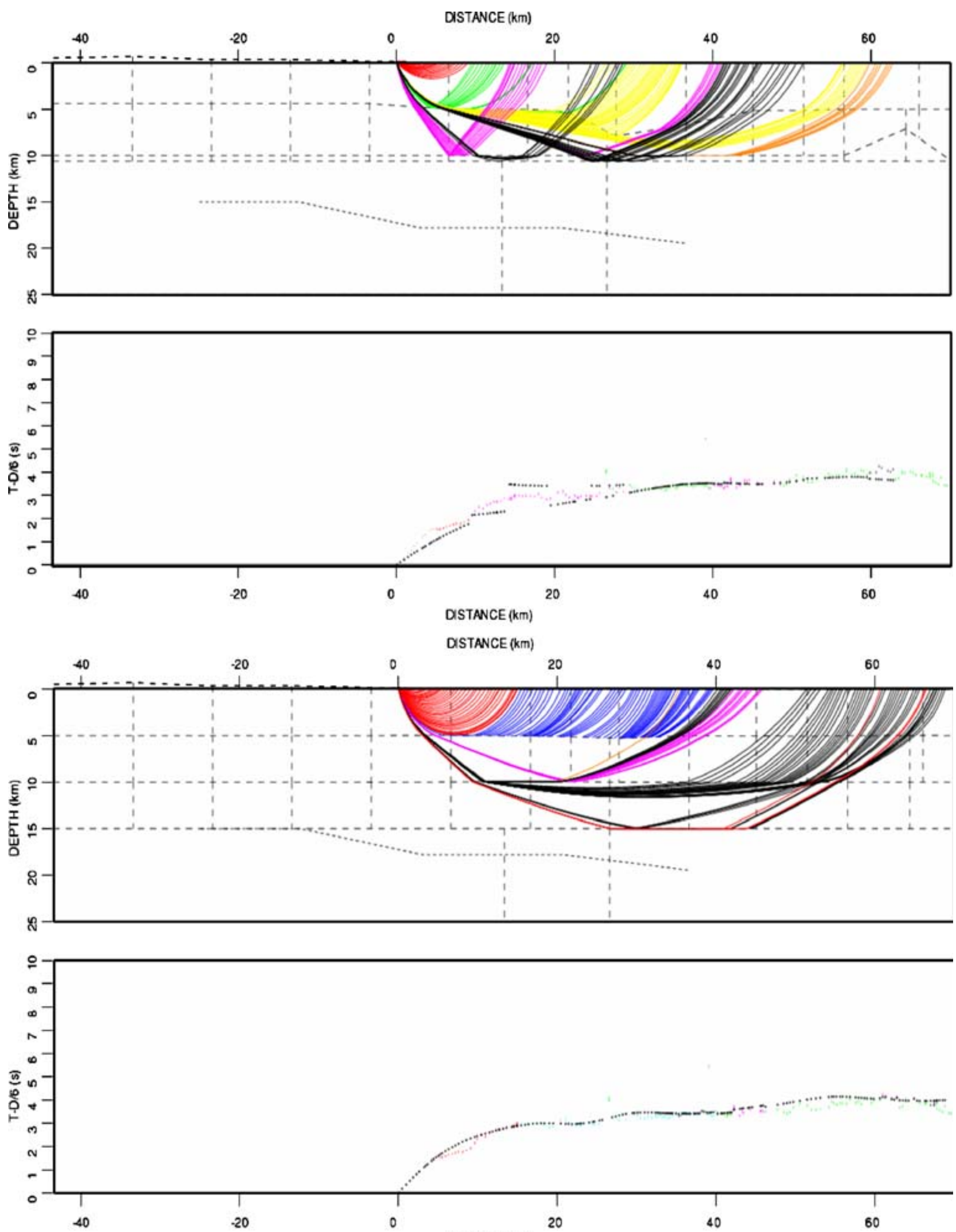

Fig. 2 Tracing of rays generated by the first shot using the initial model (*top*) and the final model (*bottom*). The *black points* are the calculated arrivals. The higher difference between observed and calculated data on the initial model is clear for distances less than 30 km

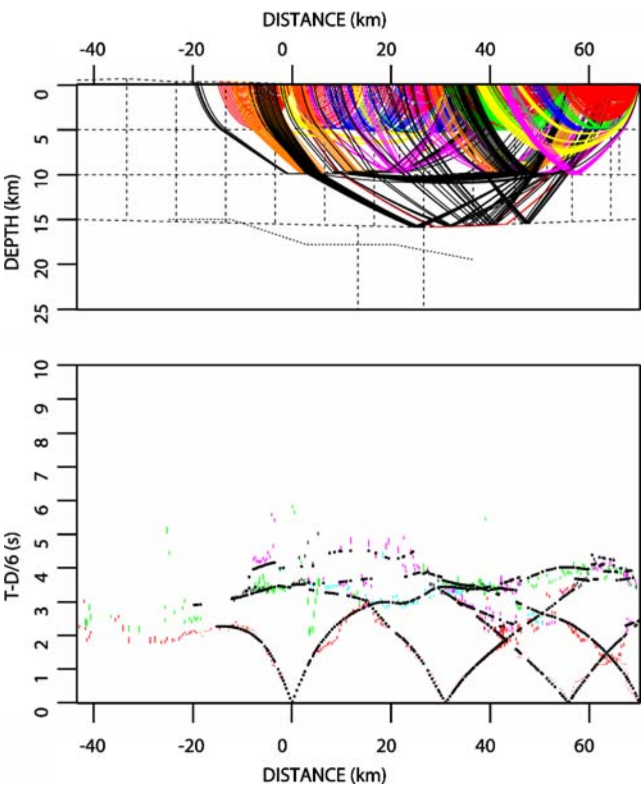

Fig. 3 Tracing of rays generated by shot 1 (*left*) to shot 4 (*right*) using the final model. The height of each observed point (*the colored dots*) indicates the error in retrieving the observed values in our calculation. These values are lower than calculated ones using the intial model

Result and discussions

The present final model is shown in Fig. 5. The characteristics of the model were collected as follows: (1) the velocity reversal at a depth of 15.7 km extending from west to east; (2) the gradual lateral change of velocity beneath the 15 km depth near the central part of the model. The lateral inhomogeneities in the velocity structure have been also proposed by different authors (e.g., Takanami 1982; Ozel et al. 1996; Iwasaki et al. 1998). Iwasaki et al. (1998) have found that there is a velocity reversal beneath the Kamuikotan metamorphic belt at a depth of 2 to 5 km. Such a velocity structure was also in agreement with the present model, which indicated the velocity reversal at a depth of 15.7 km (Table 1). Murai et al. (2003) has proposed the presence of low-velocity anomalies in the depth interval from 9 to 25 km extending from the western side to the central part of the Hidaka Mountains. Such a low velocity anomaly is also represented in Fig. 5 by a yellow-gray-colored zone extending from a distance of 16 km toward the eastern part of the present model at a depth range of 9–15 km.

Iwasaki et al. (2004) have mentioned the difficulty to use travel-time inversion to investigate a region of complex structure similar to the area of interest. However, we presented the similar results in this study using less number of data, which clarified the efficiency of the adopted method.

The model obtained in this study indicated some misfits about travel times of seismic rays, specifically, the rays reaching the points in the eastern side of the profile for the first and third shots and those in the western side for the fourth shot. These misfits might be associated with relatively large errors of the first P-wave arrivals from the first shot. Concerning the other two shots, it was difficult to control velocity values at boundary nodes because of the complex geology and the presence of faults with different trends and dips. However, the quality of the final model was not so much affected by several worse travel-time residuals.

Conclusions

We applied the iterative shooting or bisection technique for the present rapid forward modeling to investigate the crustal velocity structure in the western side of the Hidaka collision zone. This method is more efficient for estimating the inhomogeneous structural model as expected from the complex geological structure. The present study indicated velocity reversals in the central part of the model at a depth of 15.7 km. Also, we proposed a horizontal velocity change extending from its central part beneath the Ishikari-Tomakomai lowland toward the block beneath the western flank of the Hidaka Mountains. The extension of the low-velocity anomaly zone proposed in previous studies was

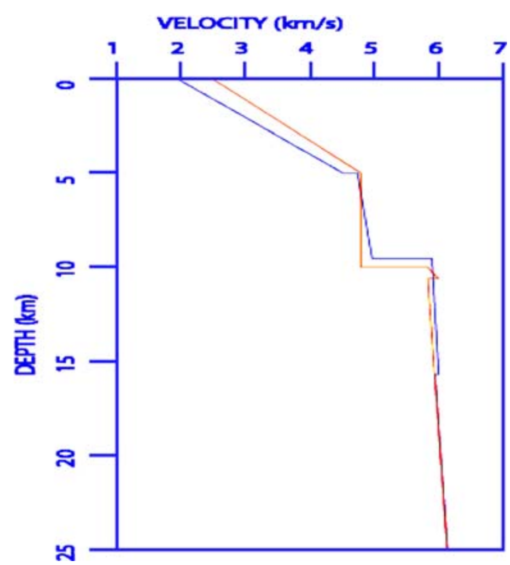

Fig. 4 Comparison between the initial velocity values (*pink*) and final values (*blue*). The initial model shows more simplified trend and does not show the effect of velocity changes at deeper parts (deeper than 10 km)

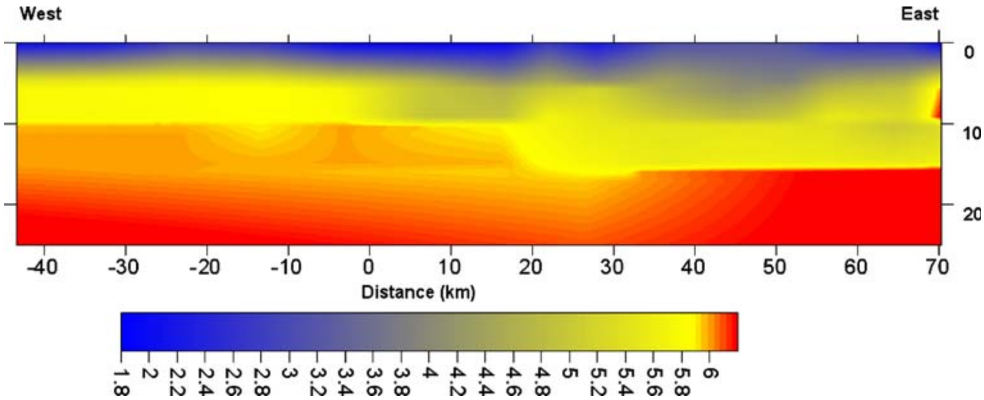

Fig. 5 Final model showing velocity reversal at 15.71 km depth, high velocity body near the eastern border of the model and low velocity anomaly extending from the center to the east of study area at a depth range from 9 to 15 km

Table 1 Comparison of velocity values of the initial model (left) and final model (right)

Layers	Depth range (Km)	Velocity values (Km/s)	Depth range (Km)	Velocity values (Km/s)
1	0.00	1.83	0.00	1.93
	5.00	4.80	5.04	4.52
2	5.00	5.80	5.04	4.74
	10.00	6.14	9.59	4.97
3	10.00	6.20	9.59	5.90
	10.61	6.30	15.71	6.00
4	10.61	5.95	15.71	5.94
	25.00	6.14	25.00	6.14

indicated in this study. The root-mean-square of travel-time residuals was improved from 0.398 s for the initial model to 0.176 s for the final model. The methodology and algorithm used in this study could be utilized to investigate other areas with similar complex structures and tectonics (e.g., Oman Mountain belt, Western Arabian Peninsula).

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