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Tectonophysics 290 (1998) 197–210

TECTONOPHYSICS

Crustal structure and tectonics of the Hidaka Collision Zone, Hokkaido (Japan), revealed by vibroseis seismic reflection and gravity surveys

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Received 21 November 1996; accepted 16 December 1997

Abstract

This study is the first integrated geological and geophysical investigation of the Hidaka Collision Zone in southern Central Hokkaido, Japan, which shows complex collision tectonics with a westward vergence. The Hidaka Collision Zone consists of the Idon'nappu Belt (IB), the Poroshiri Ophiolite Belt (POB) and the Hidaka Metamorphic Belt (HMB) with the Hidaka Belt from west to east. The POB (metamorphosed ophiolites) is overthrust by the HMB (steeply eastward-dipping palaeo-arc crust) along the Hidaka Main Thrust (HMT), and in turn, thrusts over the Idon'nappu Belt (melanges) along the Hidaka Western Thrust (HWT). Seismic reflection and gravity surveys along a 20-km-long traverse across the southern Hidaka Mountains revealed hitherto unknown crustal structures of the collision zone such as listric thrusts, back thrusts, frontal thrust-and-fold structures, and duplex structures. The main findings are as follows. (1) The HMT, which dips steeply at the surface, is a listric fault dipping gently at a depth of ~7 km beneath the eastern end of the HMB, and cutting across the lithological boundaries and schistosity of the Hidaka metamorphic rocks. (2) A second reflector is detected 1 km below the HMT reflector. The intervening part between these two reflectors is inferred to be the POB, which is only little exposed at the surface. This inference is supported by the high positive Bouguer anomalies along the Hidaka Mountains. (3) The shallow portion of the IB at the front of the collision zone has a number of NNE-dipping reflectors, indicative of imbricated fold-and-thrust structures. (4) Subhorizontal reflectors at a depth of 14 km are recognized intermittently at both sides of the seismic profile. These reflectors may correspond to the velocity boundary (5.9–6.6 km/s) previously obtained from seismic refraction profiling in the northern Hidaka Mountains. (5) These crustal structures as well as the back thrust found in the eastern end of the traverse represent characteristics of collisional tectonics resulting from the two collisional events since the Early Tertiary. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: crustal structure; Hidaka Collision Zone; seismic reflection; gravity survey; collision tectonics; Hokkaido

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PII S0040-1951(98)00018-3

1. Introduction

The northern island of Japan, Hokkaido, is situated at the conjunction of two active island arc–trench systems; the Northeast Honshu Arc–Japan Trench and the Kuril Arc–Trench (Fig. 1a). Hokkaido is divided into three major provinces with regard to its pre-Neogene geology, the trend of which is oblique to these active arc–trench systems: Western, Central and Eastern Hokkaido (Fig. 1b). Western Hokkaido, which is a northern extension of Northeast Honshu, consists of Jurassic accretionary complexes intruded by Cretaceous granitic intrusions. Eastern Hokkaido is composed of Late Cretaceous to Palaeogene forearc sediments of the palaeo-Kuril arc–trench system (Kiminami and Kontani, 1983). Central Hokkaido, which geologically continues to Sakhalin, has a complicated geological assemblage. It has been occupied by two subduction–accretion systems between the palaeo-Eurasian and palaeo-North American Plates; the one in the west (the Sorachi-Yezo Belt, the Idon'nappu Belt and the Hidaka Belt) is a N–S-trending, westward-subducting system of Late Jurassic to Palaeogene age, and the other in the east (the Tokoro Belt) is an eastward-subducting system of Cretaceous age (Fig. 1b

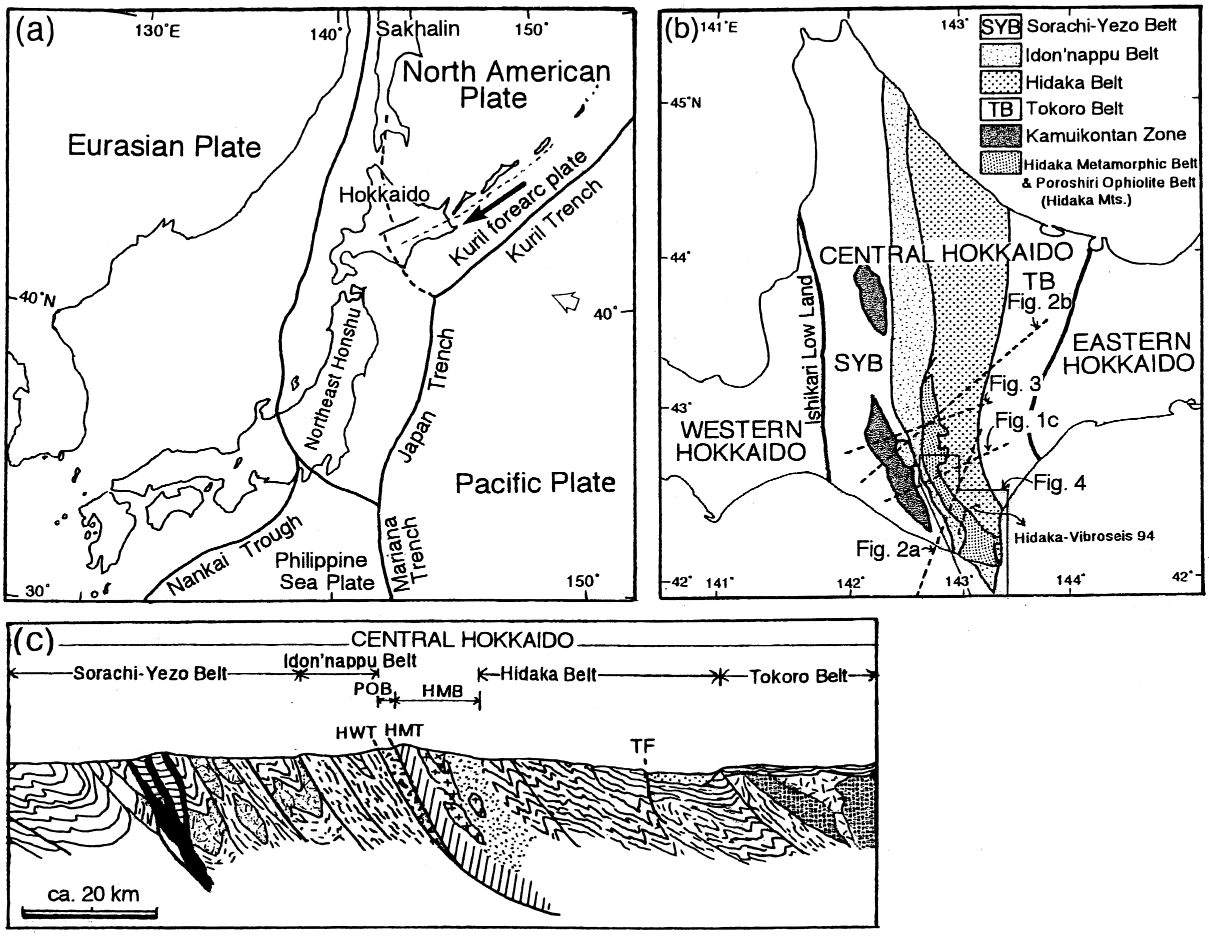

Fig. 1. (a) Sketch map showing plate tectonic setting around Japanese islands. Thick lines and dotted line show present and Tertiary plate boundaries, respectively. (b) Geologic divisions of Central Hokkaido. Profiling lines Fig. 1cFig. 2a,b, and 3 are shown. Modified from Kimura (1994). (c) Schematic geological cross-section of southern Central Hokkaido. *POB* = Poroshiri Ophiolite Belt, *HMB* = Hidaka Metamorphic Belt, *HWT* = Hidaka Western Thrust, *HMT* = Hidaka Main Thrust, *TF* = Tokachi Fault System. Cross-section line is shown in (b). Modified from Kimura (1986).

and c; Kiminami and Kontani, 1983; Sakakibara, 1986).

Central Hokkaido, especially its southern part, has undergone two stages of collisions since the Early Tertiary. The older oblique collision with a right-lateral sense of motion between the palaeo-Eurasian and palaeo-North American Plates during the Palaeogene resulted in the amalgamation of the Hidaka Metamorphic Belt in the east and the Poroshiri Ophiolite Belt in the west. The younger collision was caused by the westward migration of the Kuril fore-arc plate which started in the Late Miocene due to the oblique subduction of the Pacific Plate along the Kuril Trench (Fig. 1a; Kimura, 1986). The collision rapidly uplifted the Hidaka Metamorphic Belt as well as the Poroshiri Ophiolite Belt, producing the present Hidaka Mountains. The process of collision between the Eurasian Plate and the North American Plate (Kuril forearc plate) is still continuing.

Although the deformational features due to the above two collisions are also observed in the Sorachi-Yezo Belt, the Hidaka Mountains and their surroundings in southern Central Hokkaido show typically complex collisional features. They are therefore collectively termed as the Hidaka Collision Zone, which provides favourable opportunities for studying the characteristics and structure of deep crust similar to the Ivrea zone of the Alps and the Kohistan–Ladakh arc of the western Himalaya. It is important to elucidate the present deep-crustal structure of the Hidaka Collision Zone in order to understand the arc–arc collisional mechanism and the formation process of continental crust. Toward this end, we carried out vibroseis seismic reflection profiling along a 20-km-long traverse, and gravity measurements in the southern Hidaka Mountains.

2. Geophysical characteristics of the Hidaka Collision Zone

2.1. Seismic refraction

Seismic refraction experiments and natural earthquake data in and around the Hidaka Mountains have revealed the following complicated tectonic features (e.g., Den and Hotta, 1973; Okada et al., 1973; Takanami, 1982; Fujii and Moriya, 1983; Moriya, 1983; Miyamachi and Moriya, 1984; Furumura and Moriya, 1990; Miyamachi et al., 1994; Moriya et al., 1994; Ozel et al., 1996; Iwasaki et al., 1998);

(1) Beneath the Hidaka Collision Zone there are two seismic zones: a shallower zone (20 to 50 km deep) likely related to the collision of the Eurasian and North American Plates, and a deeper zone (over 70 km deep) related to the subduction of the Pacific Plate.

(2) In the southern Hidaka Mountains a low-velocity zone (5.5 km/s) dips eastward from the western coast, and reaches a depth of about 30 km beneath the Hidaka Mountains (Fig. 2a).

(3) The seismic velocity structure of both sides of the Hidaka Mountains is relatively clear, but that beneath the mountains is monotonous or not determinable (Fig. 2).

(4) Lateral variation in seismic velocity due to different geological units is found across the Hidaka Collision Zone. In particular, seismic waves are attenuated under the Idon'nappu Belt on the western part of the Hidaka Mountains.

(5) The Moho discontinuity is not clearly visible as it may be deeper than 50 km (Fig. 2a), although Miyamachi et al. (1994) reported a crustal thickness of 32 km beneath the Hidaka Mountains.

2.2. Magnetotellurics

A recent magnetotelluric survey (Ogawa et al., 1994) across the Hidaka Collision Zone (about 70 km north of the present survey area: Fig. 3) shows that a 2-km high-resistivity (1000–2000 Ω m) layer of high-grade Hidaka metamorphic rocks is followed by a relatively conductive (500–1000 Ω m) layer of accretionary prism at depths of 5 to 10 km, which is underlain again by a high-resistivity (30,000 Ω m) layer of probably high-grade metamorphic rocks. This suggests an interfingered complex structure or crustal delamination beneath the Hidaka Collision Zone probably due to the above-mentioned two collision events.

3. Geological outline of the Hidaka collision zone with special reference to the surveyed area

The Hidaka Collision Zone is occupied by the N–S-trending accretionary and melange complexes consisting of the Idon'nappu and Hidaka Belts (eg.,

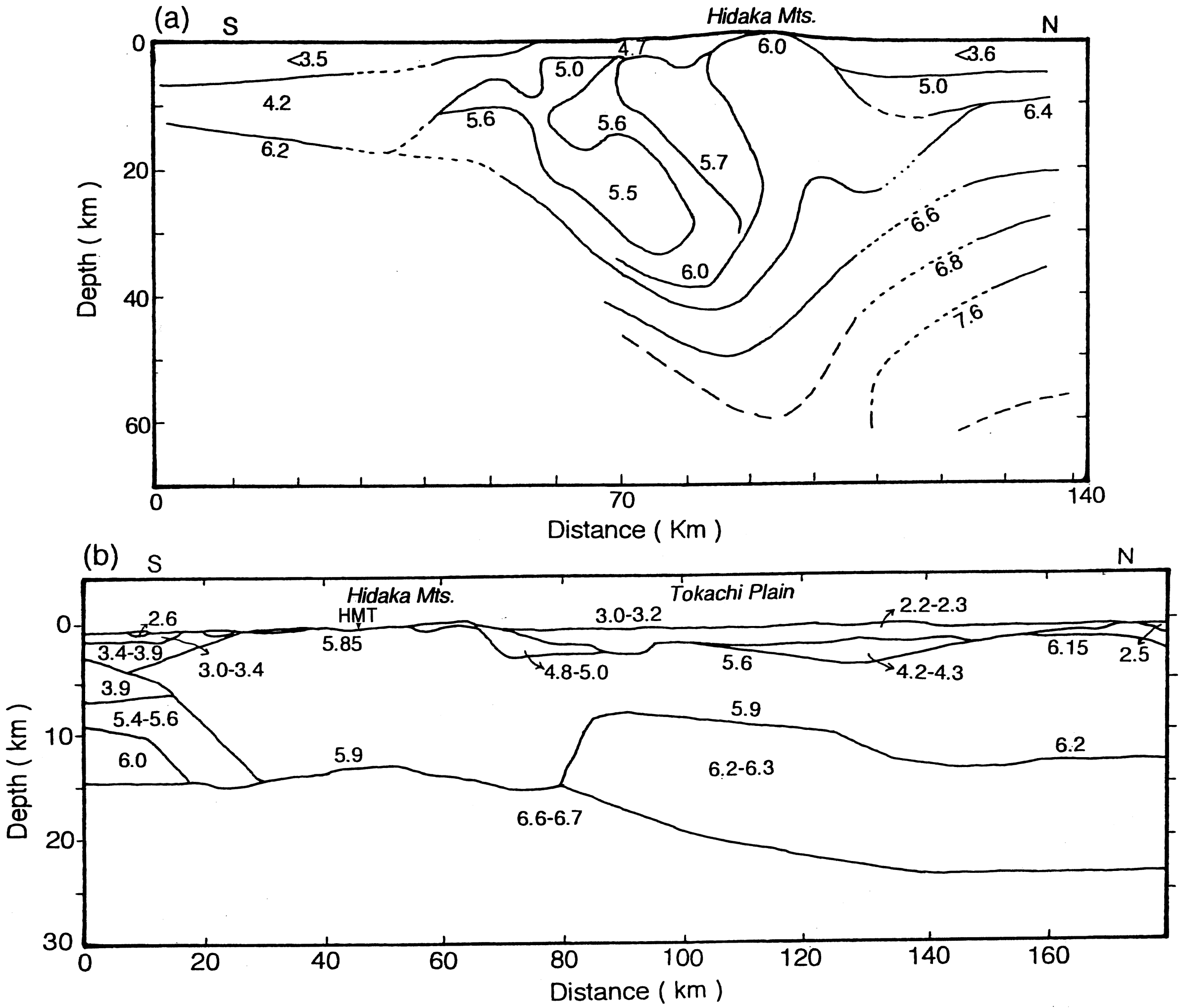

Fig. 2. (a) Seismic velocity structures (km/s) across the southern Hidaka Mountains (after Moriya et al., 1994). (b) Seismic velocity structures (km/s) across Central Hokkaido revealed by seismic refraction profiling (after Ozel et al., 1996). *HMT* = Hidaka Main Thrust. Both profiling lines are shown in Fig. 1b.

Kiminami and Kontani, 1983; Kiyokawa, 1992; Kimura, 1994). The Hidaka Mountains (the Hidaka Metamorphic Belt and the Poroshiri Ophiolite Belt) are situated between the Hidaka Belt and the Idon'nappu Belt (Fig. 1b). The Hidaka Collision Zone presently shows westward vergence and a curvature with a westward convex shape due to the above-mentioned collision of the westward-plunging Kuril forearc plate.

The Hidaka Metamorphic Belt presently displays steeply eastward-tilted metamorphic and magmatic sequences with a general NNW trend, but originally it had a west-side-down geometry before the amalgamation of the Hidaka magmatic arc and the Poroshiri ophiolites. It is considered to have formed in the western part of the Hidaka Belt during the oblique collision of the palaeo-Eurasian and palaeo-North American Plates during the Palaeogene (Komatsu et al., 1983); this view, however, has been debated (e.g., Kimura et al., 1983; Komatsu et al., 1989; Maeda, 1990; Toyoshima, 1991; Maeda and Kagami, 1996). According to radiometric dating (Arita et al., 1993), the present steeply eastward-dipping structure of the Hidaka Metamorphic Belt had formed before

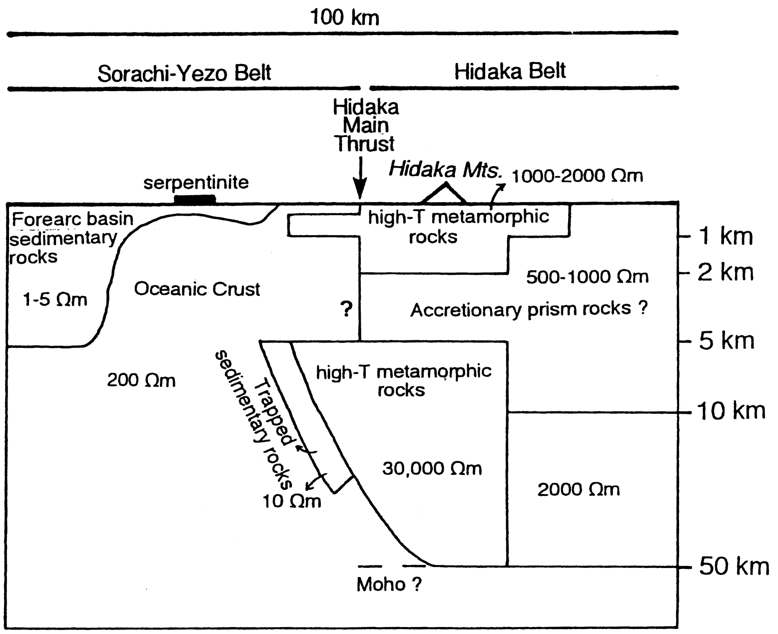

Fig. 3. Interpreted resistivity structure across the Hidaka Collision Zone (after Ogawa et al., 1994). Cross-section line is shown in Fig. 1b.

the Middle Miocene. The Hidaka Metamorphic Belt consists of a lower metamorphic sequence (granulite-facies rocks and orthopyroxene tonalites) in the west and an upper metamorphic sequence (biotite–muscovite gneisses and schists) in the east (Fig. 4). It decreases gradually in metamorphic grade from the granulite facies in the west to the greenschist facies eastward, and in general grades into the weakly metamorphosed turbidites of the Nakanogawa Group (the Hidaka Belt) of Palaeogene age (Fig. 4: Osanai et al., 1986; Komatsu et al., 1994). These metamorphic rocks have been intruded by a large amount of various intrusive rocks, e.g., gabbroic and dioritic rocks and S-type orthopyroxene tonalites in the lower metamorphic sequence and cordierite tonalite and granite in the upper metamorphic sequence (Komatsu et al., 1986; Shimura et al., 1992). The granulite-facies rocks in the western part are highly mylonitized near the Hidaka Main Thrust (HMT), along which the Hidaka Metamorphic Belt overthrusts the Poroshiri Ophiolite Belt to the west. The mylonites suffered dextral ductile shear deformation under the conditions of greenschist facies (Arita et al., 1986; Toyoshima, 1991).

In the surveyed area the mylonitized granulites and tonalites have strong metamorphic and mylonitic foliations striking N30°–50°W and steeply dipping to the east. The cordierite tonalite, which occupies the crestline of the Hidaka Mountains, is massive, but has a weak foliation striking N20°–40°W and dipping steeply eastward on the margin. The upper metamorphic sequence has the same strike and dip as those of the tonalite. The Nakanogawa Group shows a monotonous lithology consisting of slate and shale with some intercalations of sandstone. The turbidites dip steeply east, being repeated by folding and vertical faulting.

The Poroshiri Ophiolite Belt is composed of faulted and tightly folded metamorphosed ophiolites, the original succession of which has been reconstructed from a basalt to harzburgite tectonite with a total thickness of at least 5 km (Miyashita, 1983). The rocks of the Poroshiri Ophiolite Belt display a lot of intense ductile deformational features representing dextral transpression caused by the oblique collision (Jolivet and Miyashita, 1985; Arita et al., 1986; Arai and Miyashita, 1994). Although the Poroshiri Ophiolite Belt is widely distributed in the northern half of the Hidaka Mountains, it occurs sporadically as a narrow zone along the HMT (serpentinite of only 80 m wide in the surveyed area), and often is missing in the southern half (Fig. 4). The Poroshiri ophiolites

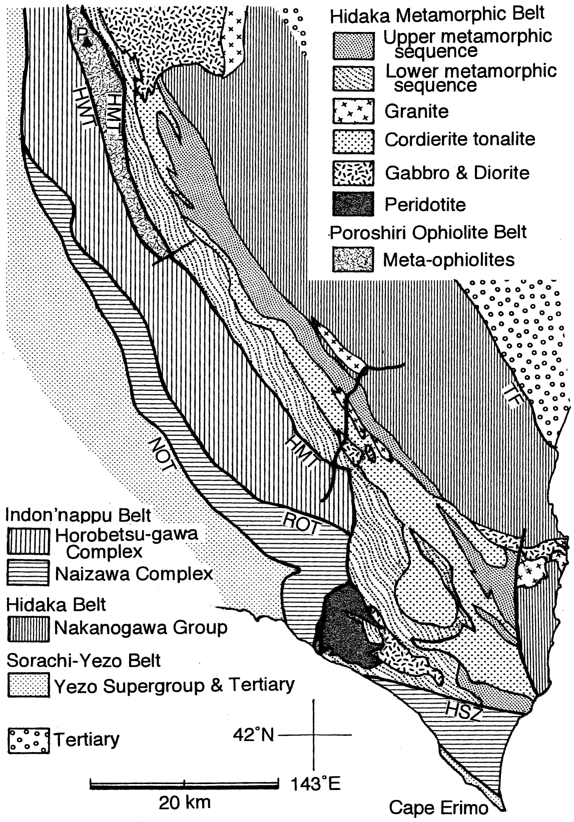

Fig. 4. Generalized geological map of the central and southern Hidaka Mountains. *HWT* = Hidaka Western Thrust, *HMT* = Hidaka Main Thrust, *ROT* = Redatoi–Okada Thrust, *NOT* = Nitarachi–Oshorobetsu Thrust, *HSZ* = Horoizumi Shear Zone, *TF* = Tokachi Fault System, *P* = Mt. Poroshiri-dake. Thick line is a seismic reflection line (Fig. 5).

overthrust the Idon'nappu Belt on the west along the Hidaka Western Thrust (HWT) (Fig. 1c and Fig. 4).

The Idon'nappu Belt is divided lithotectonically into two units by the east-dipping Redatoi-Okada Thrust associated with thin serpentinite bodies (Ueda et al., 1995), namely the Naizawa Complex in the west and the Horobetsu-gawa Complex in the east (Fig. 4). Both complexes are composed of melange and accretionary sediments. Slaty cleavages in these complexes generally strike NW–SE, and steeply dip to the east, although their bedding planes are mostly west-facing (Ueda et al., 1995). The double collision has made the Idon'nappu Belt a frontal zone of the Hidaka Collision Zone showing a dextral strike-slip duplex structure with apparent westward vergence especially in the Horobetsu-gawa Complex (Kiyokawa, 1992; Ueda et al., 1995). The Idon'nappu Belt is in tectonic contact with the Cretaceous Yezo Supergroup (the Sorachi–Yezo Belt) and the Miocene formations on the west along the east-dipping Nitarachi–Oshorobetsu Thrust (Fig. 4). The Miocene sandstones occur along these faults as well as within the Idon'nappu Belt.

4. Vibroseis seismic reflection profiling

Vibroseis seismic reflection profiling was performed along a 20-km-long traverse on Route 236 across the southern Hidaka Mountains. A standard seismic data processing sequence was used, including post-stack coherency filtering and finite-difference migrations and depth corrections using a 1-D velocity model (Table 1).

Fig. 5 shows an unmigrated depth section in which the supposed reflection phases are indicated by arrows with numbers. Each phase is interpreted as follows (numbers correspond to those in Fig. 5).

(1) The intermittent reflectors are clearly traceable from the HMT on the surface (around RP 150) northeastward with an angle of 45° to a depth of 7 km below the eastern margin of the Hidaka Metamorphic

Table 1
Field parameters used in the vibroseis seismic reflection experiment

Source information	
Source type	4 vibrators (Y-2400, MK-IV)
Interval	50 m
Sweep frequency	8–45 Hz
Sweep length	16 s
Number of sweeps	10 sweeps/VP
Sweep mode	linear up sweep
Phase control	ground force locking
Receiver information	
Natural frequency	8 Hz
Interval	25 m
Number of geophones	18 geophones/RP (3 series ×6 parallel)
Layout	1.4 m interval, linear array
Recording information	
Number of channels	240
Sample interval	4 ms
Record length	24 s (after cross-correlation)
Low cut frequency	4 Hz, 18 dB/oct
High cut frequency	90 Hz, 72 dB/oct

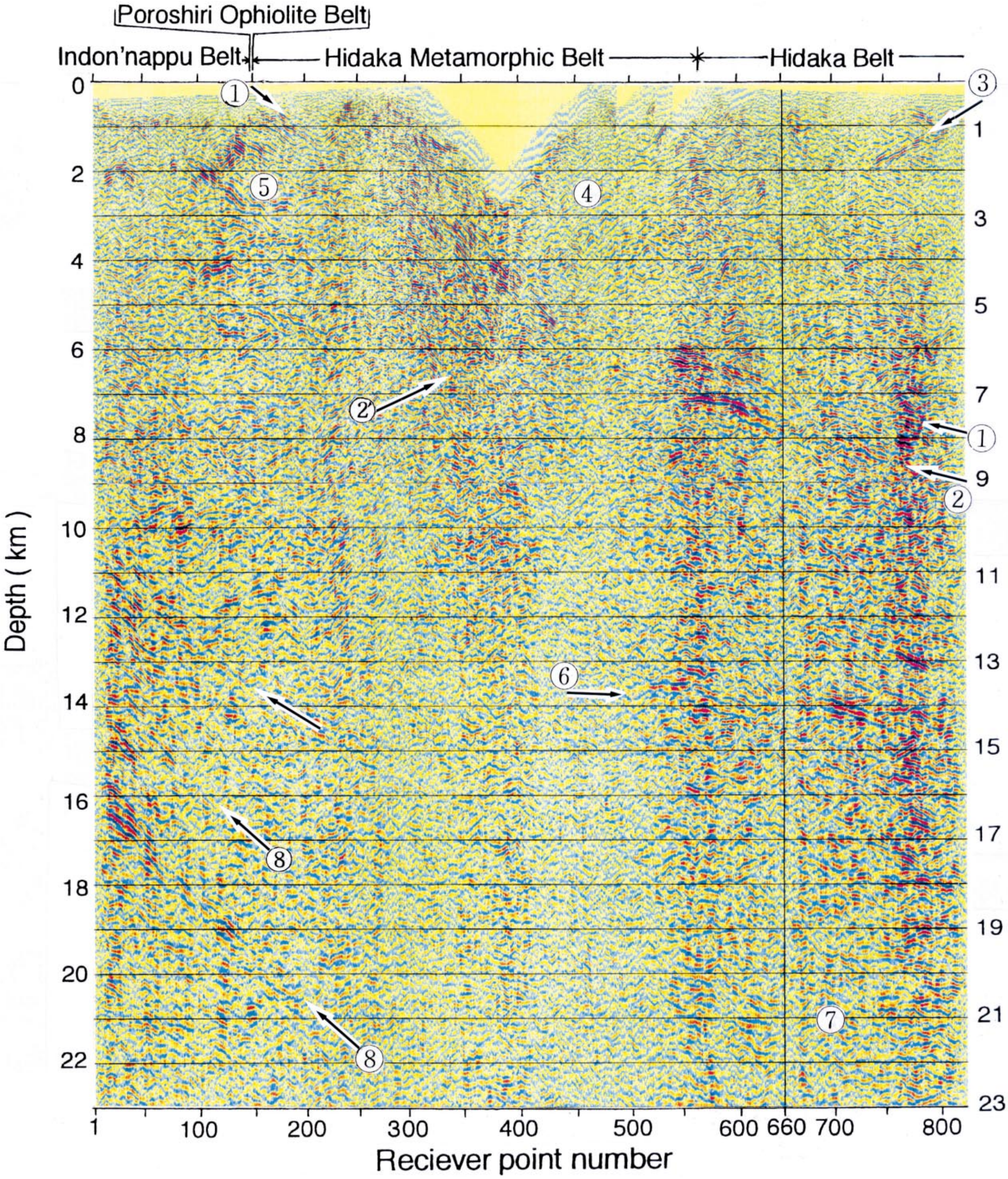

Fig. 5. Unmigrated depth section across the southern Hidaka Mountains. The interpreted reflection phases are shown by arrows numbered *1* through *8* which correspond to numbers in the text. Note a sharp eastward bend of the stacking line at RP 660.

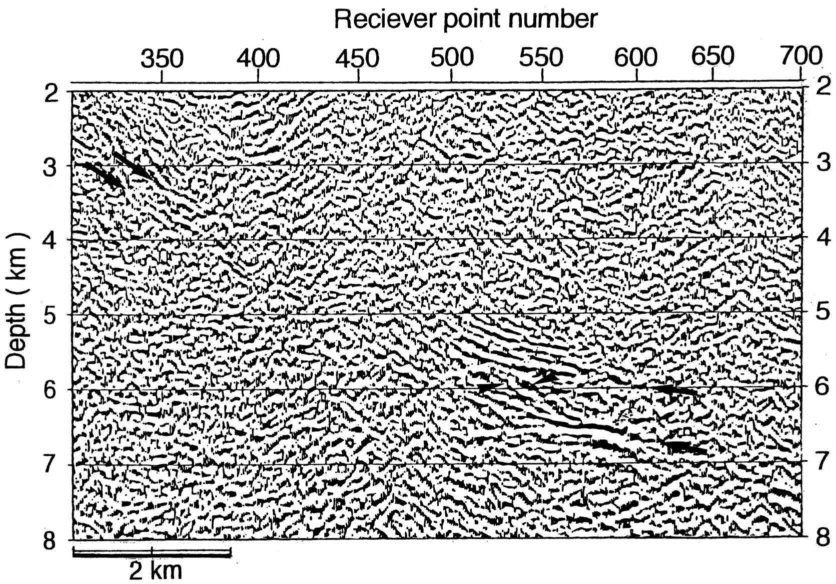

Fig. 6. An enlarged migrated depth section showing two listric-shaped reflectors corresponding to the Hidaka Main Thrust (top) and Hidaka Western Thrust (bottom) and a duplex structure between them.

Belt. These reflection phases are boundaries between the complex area in the west and the rather transparent area in the east. After migration, the HMT reflectors show a listric geometry (Fig. 6). The HMT is likely to cut across the foliation of metamorphic rocks and boundaries of lithofacies at depth.

(2) The HWT reflector is not observable at shallow levels. At deeper levels, however, a rather clear reflection phase is recognized about 1 km below that of the HMT beneath the eastern flank of the Hidaka Mountains (between RP 550 and 800), and interpreted to be the HWT. The layer between these two strong events is considered to be the Poroshiri Ophiolite Belt, and appears to have a duplex structure in an enlarged migrated depth section (Fig. 6). In the unmigrated section the west-dipping reflectors (2′) look to be traced intermittently from a depth of 6.5 km below RP 550 southwestward, although the traces become vague after migration.

(3) A back thrust dipping west is found around the northeasternmost part of the traverse.

(4) There is no clear reflectivity in the Hidaka metamorphic rocks. P-wave velocities in the subsurface estimated by processing 240-channel data obtained from the refraction method are almost identical between the different rock units of the Hidaka Metamorphic Belt. This suggests poor contrast of impedance among the rocks of the Hidaka Metamorphic Belt.

(5) Beneath the Idon'nappu Belt some complex reflection phases are recognized at depths of several km. These reflectors may be suggestive of a frontal thrust-and-fold structure or tectonic stacking of the Idon'nappu Belt in front of and below the Hidaka Metamorphic Belt.

(6) Some subhorizontal reflection phases can be observed at a depth of ~14 km beneath the eastern part of the Hidaka Metamorphic Belt and the Hidaka Belt. A few similar sub-horizontal reflection phases become visible beneath the Idon'nappu Belt after migration.

(7) Possible short reflectors at a depth of ~20 km are likely to be lower crustal lamination.

(8) Steep reflection planes are observed at depths of over 11 km beneath the western margin of the seismic line. After migration, these steep planes are moved outside the traverse. These planes are presumed to be of the Nitarachi–Oshorobetsu Thrust and faults in the Sorachi–Yezo Belt (Fig. 4).

5. Gravity survey

Gravity surveys in and around the Hidaka Mountains (Geographical Survey Institute, 1955; Hagi-

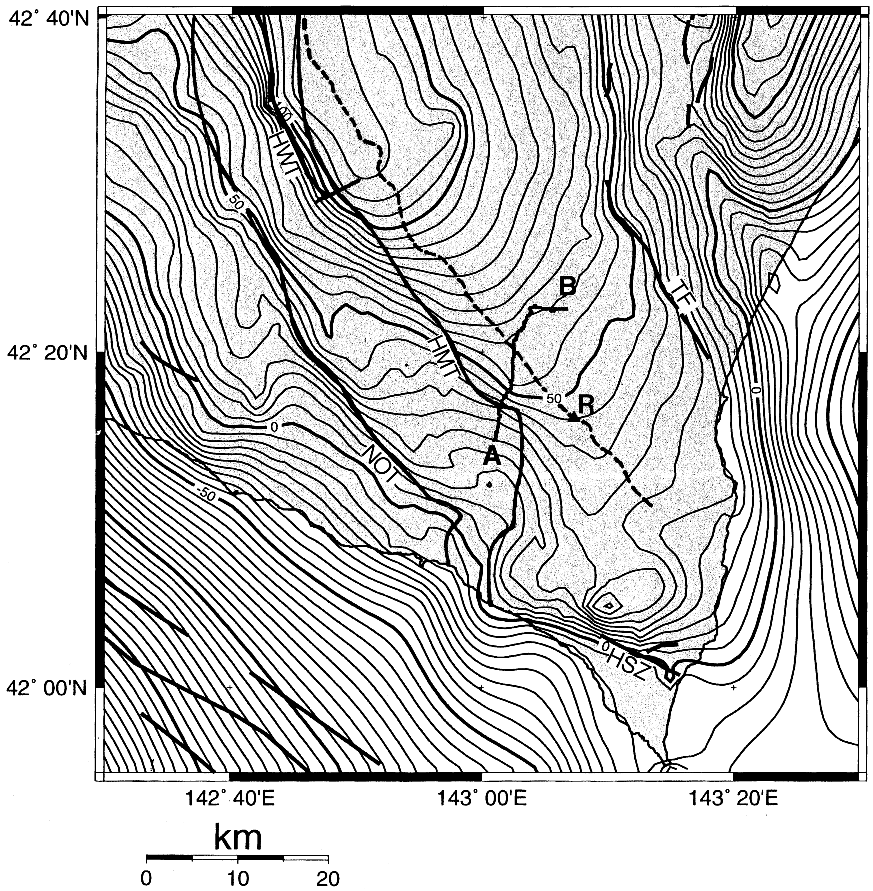

Fig. 7. Distribution map of the Bouguer anomaly in the southern part of the Hidaka Mountains with a contour interval of 5 mGal after terrain correction. *A–B* is a gravity and seismic traverse. Thick lines are faults. The broken line is the crestline of the Hidaka Mountains. *HWT* = Hidaka Western Thrust, *HMT* = Hidaka Main Thrust, *NOT* = Nitarachi–Oshorobetsu Thrust, *HSZ* = Horoizumi Shear Zone, *TF* = Tokachi Fault System, *R* = Mt. Rakko-dake (1472 m).

rawa, 1967; Miyamachi et al., 1987) indicate that the Bouguer anomalies along the mountains are highly positive, reaching up to +140 mGal in the northern part (Maruyama et al., 1991). The high positive anomaly is considered to be due to mafic and ultramafic rocks in the Poroshiri Ophiolite Belt and the Hidaka Metamorphic Belt. This is also supported by a high V_p/V_s ratio of over 1.8 in the western flank of the Hidaka Mountains (Moriya, 1983). The first precise gravity measurement was performed along a seismic line (A–B in Fig. 7, more than 200 stations) and in the surroundings (more than 300 stations) in order to evaluate crustal structure models beneath the Hidaka Mountains.

5.1. Bouguer anomaly

The optimum density for gravity reductions in the study area was estimated to be 2.6615 g/cm^3 using the method proposed by Murata (1993). The obtained Bouguer anomaly distribution map of the study area is shown in Fig. 7. A remarkably high gravity anomaly belt (about 30 km wide) is located along the crestline of the Hidaka Mountains. This positive anomaly reaches its maximum near the western periphery of the crestline. It is noted that the correlation of the Bouguer anomaly with topography is significantly positive in the Hidaka Mountains, which suggests that little crustal 'root' exists beneath the mountains. In both the eastern and western foothills of the mountains, an abrupt decrease in the Bouguer anomaly is observed, but the patterns of anomalies are asymmetric, and the Bouguer anomaly gradients of both sides are different (Fig. 7). The eastern abrupt gravity decrease corresponds to that of the Tokachi Fault System which is an active fault (Research Group for Active Faults of Japan, 1991). Another abrupt decrease is observable on the western flank of the mountains including the area along the seismic line, although no large fault system is situated there. Along the seismic line, the positive gravity anomaly increases abruptly around the HMT on the surface, and reaches its maximum in the norther half of the seismic line, and then gradually decreases toward the eastern margin of the Hidaka Mountains. At the eastern foot of the mountains, there is a gravity anomaly trough characterized by a strong negative Bouguer anomaly. It corresponds to the boundary zone between the Hidaka and Tokoro Belts, which is buried by a thick pile of Late Tertiary to Quaternary sediments.

5.2. Crustal structure

Based on the present seismic reflection results and the gravity and geological constraints, a simple block model is constructed for crustal structure along the seismic line (Fig. 8, upper). The eastward-dipping reflector, which is interpreted as the HMT, continues to a depth of 7 km. Beneath the plane, a narrow layer of the Poroshiri Ophiolite Belt is probably situated. A nearly horizontal reflection plane is recognized at a depth of 14 km. In the model construction, the gravitational effects of the downgoing slab of the Pacific Plate were ignored because they are considered to be nearly uniform on the traverse which is parallel to the Kuril Trench (Fig. 1a). Fig. 8 (lower) shows a preliminary crustal model along the seismic line

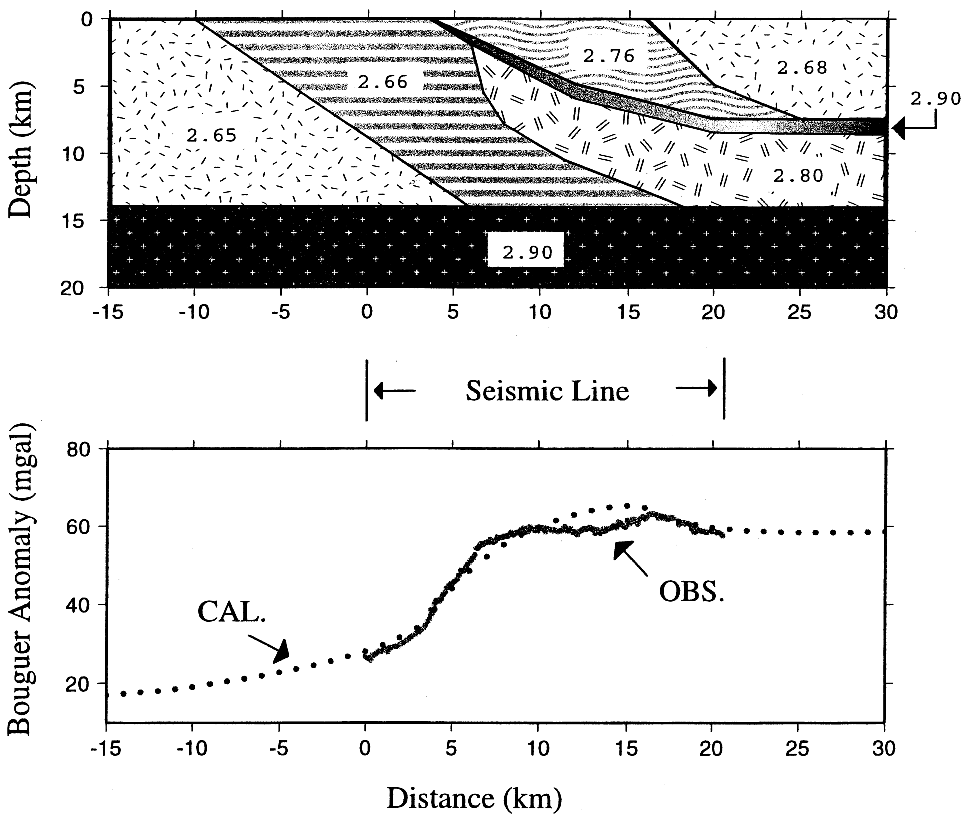

Fig. 8. A density structural model along the seismic line A–B in Fig. 7 used for the computation (top) and a comparison of observed and calculated Bouguer anomalies (bottom) computed after Talwani et al. (1959).

based on Talwani's method (Talwani et al., 1959). The model Bouguer anomaly fits well with the observed gravity especially for the western and eastern parts of the profile, whereas in the central part the computed gravity shows a systematic increase within several mGal.

6. Discussion: crustal structure of the Hidaka Collision Zone

On the basis of seismic refraction data, Den and Hotta (1973) suggested large-scale thrusting of the crust of Eastern Hokkaido over Western Hokkaido and vast sedimentation in the foredeep west of the thrust. They attributed the thrust boundary to a plate boundary between the Okhotsk (the North American) and Eurasian Plates during the Mesozoic. Such a tectonic scheme around the Hidaka Mountains (Fig. 2a) has been supported also by recent geophysical studies (e.g., Takanami, 1982; Miyamachi and Moriya, 1984; Miyamachi et al., 1994; Moriya et al., 1994).

Although the present integrated study of geological and geophysical work could not detect the Moho, it could image the collision tectonics beneath the Hidaka Mountains such as the listric-shaped HMT, a back thrust, a fold-and-thrust structure and a subhorizontal reflector at a depth of 14 km (Fig. 9).

As already stated, the Hidaka Metamorphic Belt is considered to be an upthrust magmatic arc (palaeo-Hidaka arc) tilting steeply eastward similar to the HMT on the surface, and therefore the deep rocks of the palaeo-Hidaka arc occur in its western part. The granulite-facies rocks outcropping in the western part of the study area are intensely mylonitized, but, in general, the thermobarometric analyses of the granulite-facies rocks indicate pressure and temperature conditions corresponding to those at a depth of ~23 km (Osanai et al., 1986). This thickness is almost the same as the total thickness of the reconstructed crustal sequences of the Hidaka arc including the Nakanogawa Group (Komatsu et al., 1983). Therefore, the depth of the HMT beneath the Hidaka Belt should be expected to be more than 23 km, assuming

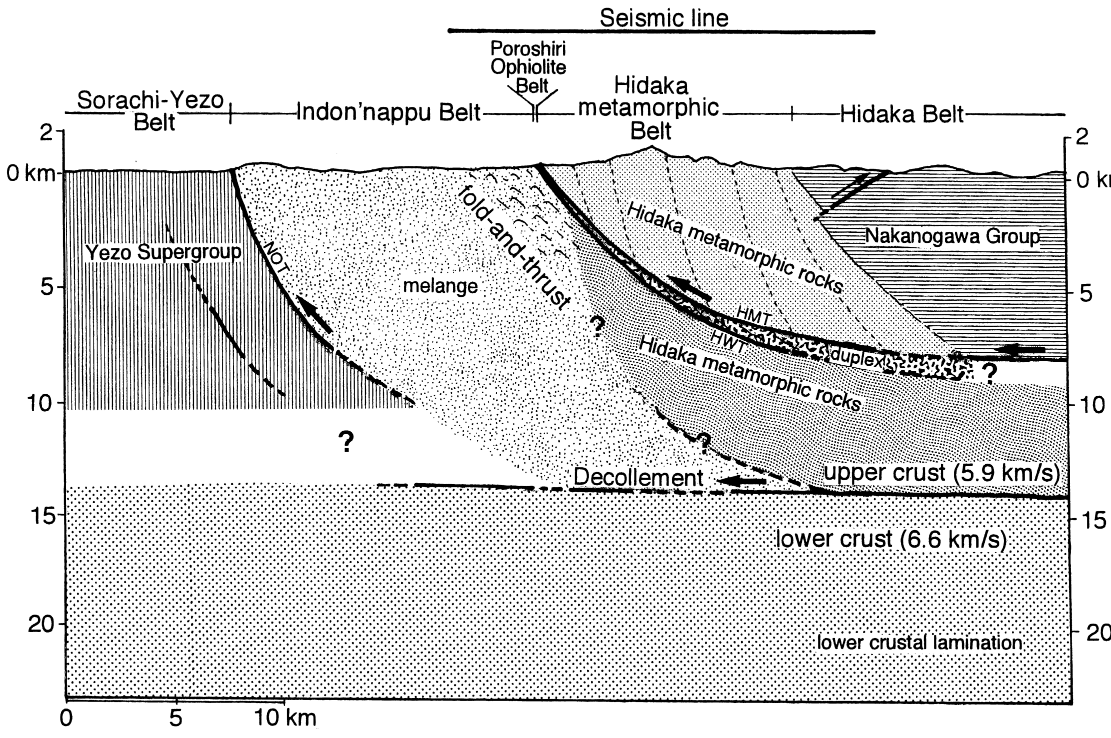

Fig. 9. An interpreted crustal model of the southern part of the Hidaka Collision Zone. *HWT* = Hidaka Western Thrust, *HMT* = Hidaka Main Thrust.

that the observed parallel relationship on the surface between the HMT plane and the lithologic boundary and foliation planes of the Hidaka metamorphic rocks is maintained at the deeper levels. The seismic reflection profiling, however, proves the HMT to be a listric fault, and by far shallower than that estimated before. Hence the HMT most probably cuts across the lithological boundaries and foliations at depth (Fig. 9). The Hidaka Main Thrust sheet (Hidaka Metamorphic Belt) is found to be much thinner than it has been generally expected. It is noted that the HMT seems to continue eastward to the velocity boundary between the 5.9–6.0 km/s layer and the 6.2–6.3 km/s layer deduced from the seismic refraction profiling beneath the Tokachi Plain in the north (Fig. 2b: Ozel et al., 1996; Iwasaki et al., 1998), although both areas are about 60 km from each other. The HMT is the most significant tectonic feature traceable along the whole Hidaka Mountains, and is thought to have been a plate boundary until the Tertiary. However, the HMT is just a listric fault situated at the middle of the upper crust, and consequently the true palaeo-plate boundary is expected to exist beneath the HMT at depth.

In the northern half of the Hidaka Mountains, the Poroshiri Ophiolite Belt reaches up to 5 km in width (Miyashita, 1983), and large gabbroic bodies occur in the western part of the Hidaka Metamorphic Belt (Fig. 4). These mafic rocks are attributed to the high positive Bouguer anomaly of up to 140 mGal. On the other hand, in the southern half only small bodies of the ophiolitic rocks occur intermittently along the HMT like in the study area. Nevertheless, the positive Bouguer anomaly is still high in the present area (Fig. 7). A 1-km-thick Poroshiri Ophiolite Belt detected at depth by seismic reflection may be responsible for the positive Bouguer anomaly. This may be supported by the existence of a conductive layer between resistive layers beneath the northern Hidaka Mountains (Fig. 3), although their depth and thickness are different from each other. The difference in the Bouguer anomaly gradients between the eastern and western sides of the Hidaka Mountains and the rapid increase of the anomaly from the HMT eastward (Fig. 7) also suggest that the Poroshiri ophiolites gently dip eastward and become thicker to the east. It is interesting to note that seismic profiling is suggestive of a duplex structure between the HMT and HWT reflectors (Fig. 6). The serpentinized ophiolitic layer is considered to play an important role as a mechanical flow plane for the westward thrusting of the Hidaka metamorphic rocks along the HMT. In the unmigrated section the HWT reflector is distinct beneath the northeastern part of the profile, and looks to branch off downward around RP 550, being traceable intermittently southwestward (2′ in Fig. 5). If the reflection phase is true, this may imply an existence of a tectonic wedge of Indon'nappu melange which splits the upper crust of the Hidaka arc into two parts. Further detailed analyses are required to ascertain the southwest-dipping reflector.

In the shallow part of the Indon'nappu Belt, a number of NNE-dipping reflectors appears, indicative of a fold-and-thrust structure. Ueda et al. (1995) reported a duplex structure with a right-lateral strike-slip sense of motion having resulted from dextral transpression between the Hidaka arc crust and an oceanic crust (Poroshiri ophiolites) in the Late Oligocene to Early Miocene (Arita et al., 1986). The duplex structure probably evolves into the fold-and-thrust structure at depth.

A west-dipping reflector is seen clearly at the northeastern end of the seismic traverse. On the surface some faults are observed, but the sense of their movement is not clear because of the monotonous lithology of the Nakanogawa Group. The reflector, however, is presumed to be a back thrust on the basis of a general tectonic flame.

The very weak subhorizontal reflectors at $\sim$14 km depth at both sides of the seismic profile are significant (Fig. 9). Such a 14-km-deep subhorizontal boundary was also detected as a clear velocity boundary between the 5.9 km/s layer and the 6.6–6.7 km/s layer by seismic refraction profiling in the northern Hidaka Mountains (Fig. 2b: Ozel et al., 1996; Iwasaki et al., 1998). These layers are supposed to be the upper and lower crusts, respectively. In the northern Hidaka Mountains, the distinct boundary is traceable widely from the Sorachi–Yezo Belt through the Hidaka Mountains, and dips gently eastward to the Tokachi Plain (Fig. 2b). Beneath the Tokachi Plain a middle velocity layer (6.2–6.3 km/s) exists between the layers of 5.9 km and 6.6 km/s in the northern Hidaka Mountains (Fig. 2b). The boundary between the layers of 5.9 km/s and 6.2–6.3 km/s is located at about 8 km depth. It is worth to note that the boundary seems to be the eastern continuation of the HMT, although these two are far from each other.

Further seismic profiling is required eastward for a detailed imaging of the Hidaka crustal structure and westward for understanding the tectonics in the collisional front.

Acknowledgements

We would like to thank R. Sorkhabi for critical reading and improvements of an earlier draft of the manuscript. This paper has been greatly improved through the efforts of S. Klemperer and two anomymous reviewers. N. Oshima, H. Yokota and K. Kameda helped us with the seismic line measurement. Thanks to Y. Murata for providing a computer program for calculating the Bouguer anomaly by the ABI method. Financial support for this work was provided by a grant from the Grant-in-Aid for Scientific Research of the Ministry of Education, Science, Sports and Culture, Japan (06402018) to K.A.

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