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Has the plate boundary shifted from central Hokkaido to the eastern part of the Sea of Japan?

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Abstract

A NS trending Cenozoic fold-and-thrust belt has developed in the western part of the Hidaka Collision Zone (HCZ), central Hokkaido, Japan. A quantitative estimation of the late Cenozoic convergence rate at the front of the Hidaka thrust system is important in revealing the plate tectonic framework around northern Japan. High-resolution seismic reflection profiling across the active fault-related folds was carried out to ascertain the temporal change in the crustal shortening rate. Overlapping ramp anticlines and growth folds within thrust sheets were examined using balanced cross-sections combined with industry seismic and drilling data. The rate of shortening was examined using a 3.5 Ma horizon and late Quaternary horizons at 115 and 41 ka. These horizons show that the convergence rate of the Hidaka thrust system has not decreased during the last 3.5 Ma. This suggests that the plate boundary between the Eurasian (Amurian) and North American (Okhotsk) plates has not jumped from the central part of Hokkaido to the eastern part of the Sea of Japan since 3.5 Ma and that a significant amount of plate convergence is still being absorbed in the Hidaka Collision Zone.

Keywords: Growth-fault-related fold; Active folding; High-resolution seismic reflection profiling; Collision zone; Plate boundary; Hidaka thrust system; Hokkaido

1. Introduction

The position of the plate boundary between the Eurasian (Amurian) and the North American (Okhotsk) plates in northern Japan is poorly con-

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strained (Fig. 1). Chapman and Solomon (1976) estimated the position for the plate boundary to be along the central part of Hokkaido (A in Fig. 1). However, in the early 1980s, Nakamura (1983) and Kobayasi (1983) proposed that the plate boundary has been shifted to the eastern part of the Sea of Japan (B in Fig. 1) since 1–2 Ma (Nakamura, 1983) or 0.5 Ma (Seno, 1987). Along the eastern part of the Sea of Japan, late Cenozoic reverse faulting and folding has been reported (e.g., Okamura, 2000), and major earthquakes by reverse faulting with magnitude 7 or more have also occurred (Fukao and Furumoto, 1975).

Determining whether the plate boundary jumped from the central part of Hokkaido to the eastern part of the Sea of Japan is essential if one wants to properly understand the plate tectonic setting in northern Japan. An important key in solving this problem is determining whether there has been any temporal change in the rate of shortening across central Hokkaido.

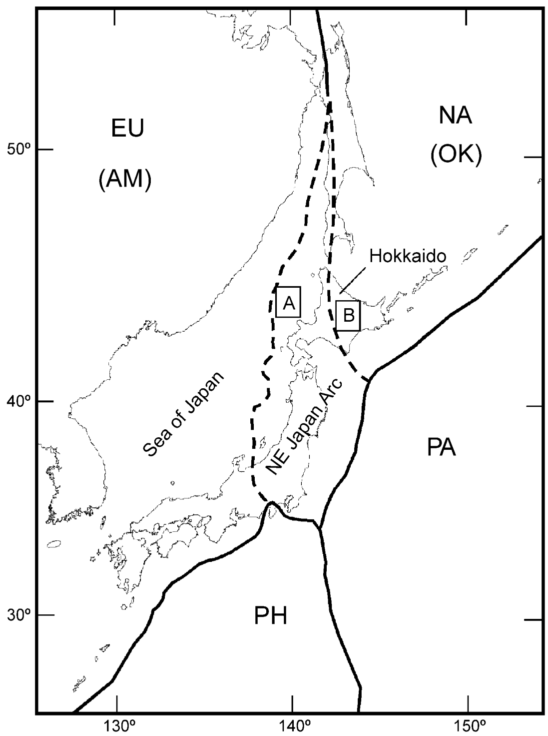

Fig. 1. Possible plate boundaries in northern Japan. (A) Boundary proposed by Nakamura (1983) and Kobayasi (1983). (B) Boundary proposed by Chapman and Solomon (1976). EU: Eurasian plate; AM: Amurian plate; NA: North American plate; OK: Okhotsk plate; PA: Pacific plate; and PH: Philippine Sea plate.

Deep seismic experiments were carried out across the axial part of Hokkaido in 1999 and 2000 (Research Group for Explosion Seismology, 2002a,b). During these experiments, high-resolution seismic reflection data were acquired at the front part of the Hidaka thrust system in two areas: the Umaoi hills (Kato et al., 2002) and the Yufutsu area (Sato et al., 1998; Fig. 2A). This paper describes the geologic development of the growth-fault-related folding in the front of this thrust system, constrains temporal changes in the rate of shortening across Hokkaido, and discusses the plate tectonic framework in northern Japan.

2. Geologic setting

In the central part of Hokkaido, a north–south trending Cenozoic fold-and-thrust belt was formed west of the Hidaka Collision Zone (HCZ) (Fig. 2A,B). The collision of the Kuril and NE Japan arcs at the HCZ started in the Middle Miocene (Ito, 2000). Before the collision, the central part of Hokkaido was in the dextral shear zone associated with the extension in the Sea of Okhotsk and spreading in the Kuril Basin (Fournier et al., 1994; Worrall et al., 1996; Schellart et al., 2003).

In the sedimentary basin west of the HCZ, thick Cenozoic sedimentary rocks were accumulated, unconformably covering the late Cretaceous granitic rocks (Kurita and Yokoi, 2000). The oldest deposits, the middle Eocene Ishikari Group, consist of fluvial to deltaic sedimentary rocks with interbedded coal (Fig. 3B). In contrast, the mud of the late Eocene to Oligocene Poronai Formation accumulated in upper bathyal and shelf environments. From a reconstruction of Maeda (1990), these sediments were deposited in a backarc environment to the west of the Hidaka magmatic arc. The shallow marine to fluvial sediments of the late Oligocene Minami–Naganuma Formation were deposited within trans-tensional pull-apart basins associated with extension in the Sea of Okhotsk (Kurita and Yokoi, 2000; Schellart et al., 2003). Since the early Miocene, a foreland basin has been developed west of the HCZ and the fluvial

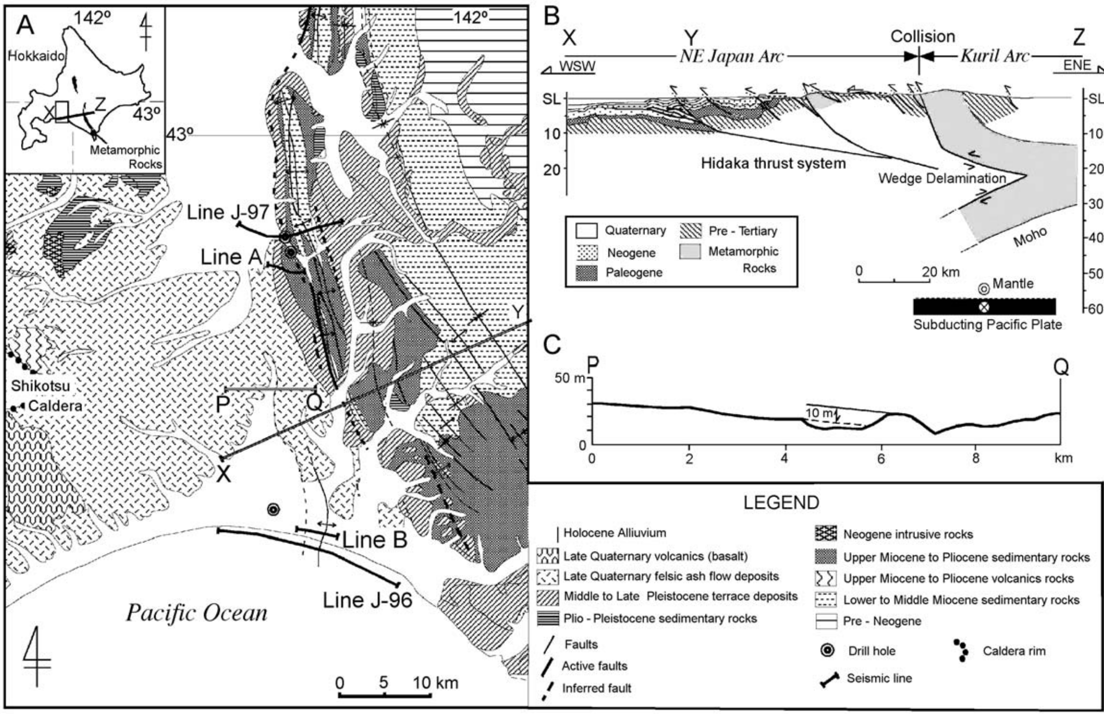

Fig. 2. (A) Generalized geological map of the front part of Hidaka thrust system (modified from Sangawa et al., 1984). Line A: Umaoi 2000 seismic line; Line B: Yufutsu 1997 seismic line; Line J-97: JNOC (1997) seismic line and Line J-96: JNOC (1996) seismic line. (B) Schematic diagram showing the crustal structure across the central part of Hokkaido after Ito (2002). The location of the cross section is shown in inset map of panel (A). (C) Topographic profile of the depositional surface of an ash flow tuff erupted from the Shikotsu caldera at 41 ka. The location of the caldera is shown in panel (A).

to marine Takinoue Formation has been deposited. The following mid to late Miocene Kawabata and Biratori–Karumai Formations consist of turbidites and shallow marine facies. The shortening deformation of the HCZ probably began at the middle Miocene, and the Hidaka Mountains have supplied the gravels to the foreland basin since at least 13 Ma (Arita et al., 2001; Miyasaka et al., 1986; Sagayama et al., 1992). During the late Miocene and Pliocene, the silt dominated Nina Formation was deposited in shelf to shallow marine environments in the foreland basin. During the late Pliocene and Pleistocene, shallow marine to fluvial sediments, including the Atsuma and Hongo Formations, were deposited followed by thick ash flow deposits derived from the Shikotsu caldera.

Tsumura et al. (1999) revealed the crustal structure beneath the Hidaka Mountains by deep seismic reflection profiling. Lower crustal delamination and wedge thrusting of the upper crust of the Kuril arc were described (Ito, 2000, 2002). He also shows that the compressional deformation and thrusting in the axial part of Hokkaido began first in the eastern parts and migrated towards the west. Many seismic investigations and drilling have been carried out in the exploration for oil and natural gas (e.g., JNOC, 1996, 1997). As shown in Fig. 3, west-verging thrusts and related folds are well displayed by the industry data. At the front of the Hidaka thrust system, active faults and folds can also be mapped using tectonic geomorphological features (Ikeda et al., 1996). However, due to the lack of high-resolution seismic imaging across the shallow part of the Hidaka thrust system, up until this research, late Quaternary tectonic movements were still poorly constrained.

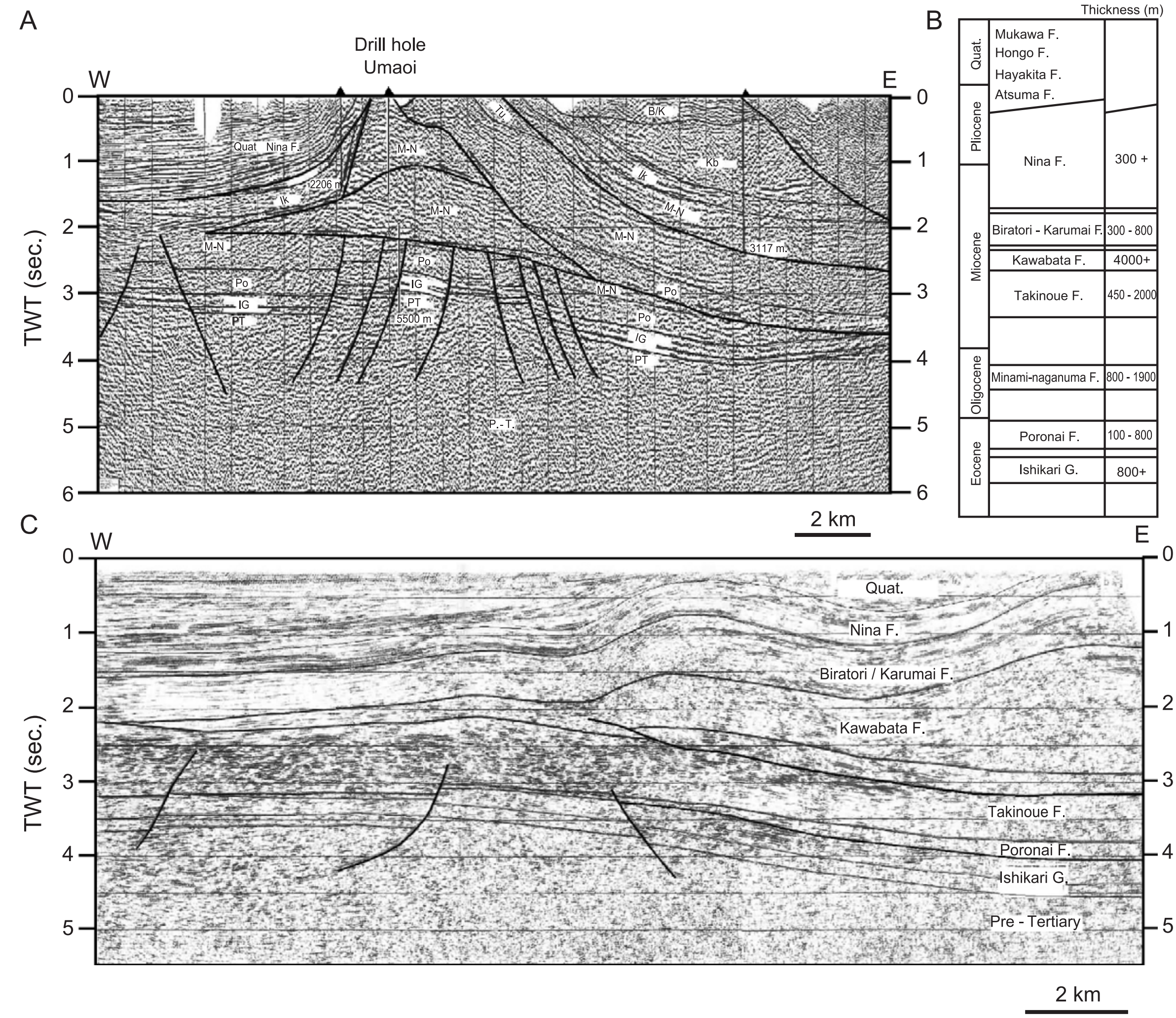

Fig. 3. Industry seismic sections (JNOC, 1996, 1997) and a generalized columnar geologic section (Kato, 2002). (A) Post-stack migrated time section across the Umaoi hills after JNOC (1997). Seismic line is shown as line J-97 in Fig. 2A. B/K: Biratori/Karumai Formation; Kb: Kawabata Formation; Tk: Takinoue Formation; M–N: Minami–Naganuma Formation; Po: Poronai Formation; IG: Ishikari Group. (B) Generalized columnar geologic section showing the stratigraphy of Cenozoic system in the southern part of the Ishkari low land. (C) Poststack migrated time section in Yufutsu area after JNOC (1996). Seismic line is shown as line J-96 in Fig. 2A.

In this study, we collected seismic data from two areas near the front of the Hidaka thrust system. The Umaoi hills show an anticlinorium with some reverse faults and have been interpreted as overlapping ramp anticlines formed by west-directed thrusting (JNOC, 1997, Fig. 3A). At Yufutsu, fault-related folds are associated with east-dipping thrusts (JNOC, 1996, Fig. 3C).

3. High-resolution seismic reflection profiles across the toe of Hidaka thrust system

3.1. Data acquisition and processing (mini-vibrator truck)

High-resolution seismic reflection profiles were acquired across the western flank of the Umaoi hills

(Umaoi 2000 seismic line) and across the blind active anticline in Yufusu (Yufutsu 1997 seismic line) in order to detect the rate of Quaternary tectonic movements. The data acquisition parameters are shown in Table 1. A mini-vibrator truck was used as a seismic source with sweep frequency 10–120 Hz. To obtain a high-resolution profile, the shot and receiver interval was 10 m. Seismic data were recorded by digital telemetry system (JGI, G-daps 4) and processed following the conventional common mid-point (CMP) method including post-stack migration and depth conversion (Kato et al., 2002). Static correction for weathering layer was applied based on refraction analysis using the time-term method (Iwasaki, 2002).

3.2. Data interpretation

3.2.1. Umaoi 2000 Seismic Line

The depth converted seismic section of Umaoi 2000, located on the western flank of the Umaoi hills, is shown in Fig. 4A. Westward dipping reflectors dominate within the section. Below horizon y in Fig. 4A, reflectors show that the thickness of strata is constant from west to east towards the Umaoi hills. In contrast, the strata above horizon y, including the youngest beds in the shallowest part of the seismic section, thin towards the east, suggesting uplift in the Umaoi hills region synchronous with the deposition of the strata above horizon y.

Judging from nearby drill hole data (e.g., JNOC, 1997), horizon x is interpreted as the top of the Nina Formation, dated at 3.5 Ma by Akiba (1986). Horizon y is interpreted to correspond to the 5.5 Ma episode of lowered global sea level (Haq et al., 1987), because onlapping facies are recognized on the upper surface of horizon y and can be traced throughout Hokkaido. The discordance of the reflectors observed on the summit of Umaoi hills coincides with an active fault known as the Izumisato fault, which dips 30° towards the west and displaces upper Pleistocene strata (Oka et al., 2001). Judging from its geometry, the Izumisato fault is interpreted as an out of the syncline fault (McClay, 1992), produced by differences in the flexural rigidity between the hanging wall and the footwall strata.

Table 1
Data acquisition parameters of the Umaoi 2000 and Yufutsu 1997 seismic lines

Seismic line	Umaoi 2000	Yufutsu 1997
Source parameters		
Source	Mini-vibrator IVI T15000	
Sweep frequency	10–100 Hz	10–120 Hz
Sweep length	20 s	15 s
No. of sweeps	5 (standards)	
Shot interval	10 m	
Receiver parameters		
Receiver interval	10 m	
No. of channels	180 channels	
Natural frequency	10 Hz	28 Hz
Recording parameters		
Instruments	GDAPS-4	
Sampling intervals	2 ms	
Recording length	3 s	4 s

3.2.2. Yufutsu 1997 Seismic Line

The seismic reflection profile of Yufutsu 1997 portrays a growth anticline as shown in Fig. 4B. A geologic interpretation of horizons in Yufutsu 1997 was carried out by tracing known horizons of drill cores onto the reprocessed industry seismic data (Orito, 2000). Horizon x' and z' in Fig. 4B are interpreted as the top horizon of the Nina Formation and Biratori–Karumai Formation, respectively. Since the upper surface of horizon y' was onlapped, horizon y' is interpreted to correspond to the period of lowered sea level dated at 5.5 Ma similar to Umaoi 2000. Below the horizon y' in Fig. 4B, the thickness of strata represented by reflectors is constant towards the axis of the growth anticline. In contrast, the strata above the horizon y' thin towards the axis of the growth anticline, suggesting uplift of the anticline.

4. Discussion

4.1. Deformation processes at the front of the Hidaka thrust system

The deformation processes are examined using the balanced cross-section technique based on the seismic profiles (Figs. 3 and 5). The Umaoi hills are considered to be overlapping ramp anticlines formed by westward thrusting (Fig. 5A). The most western

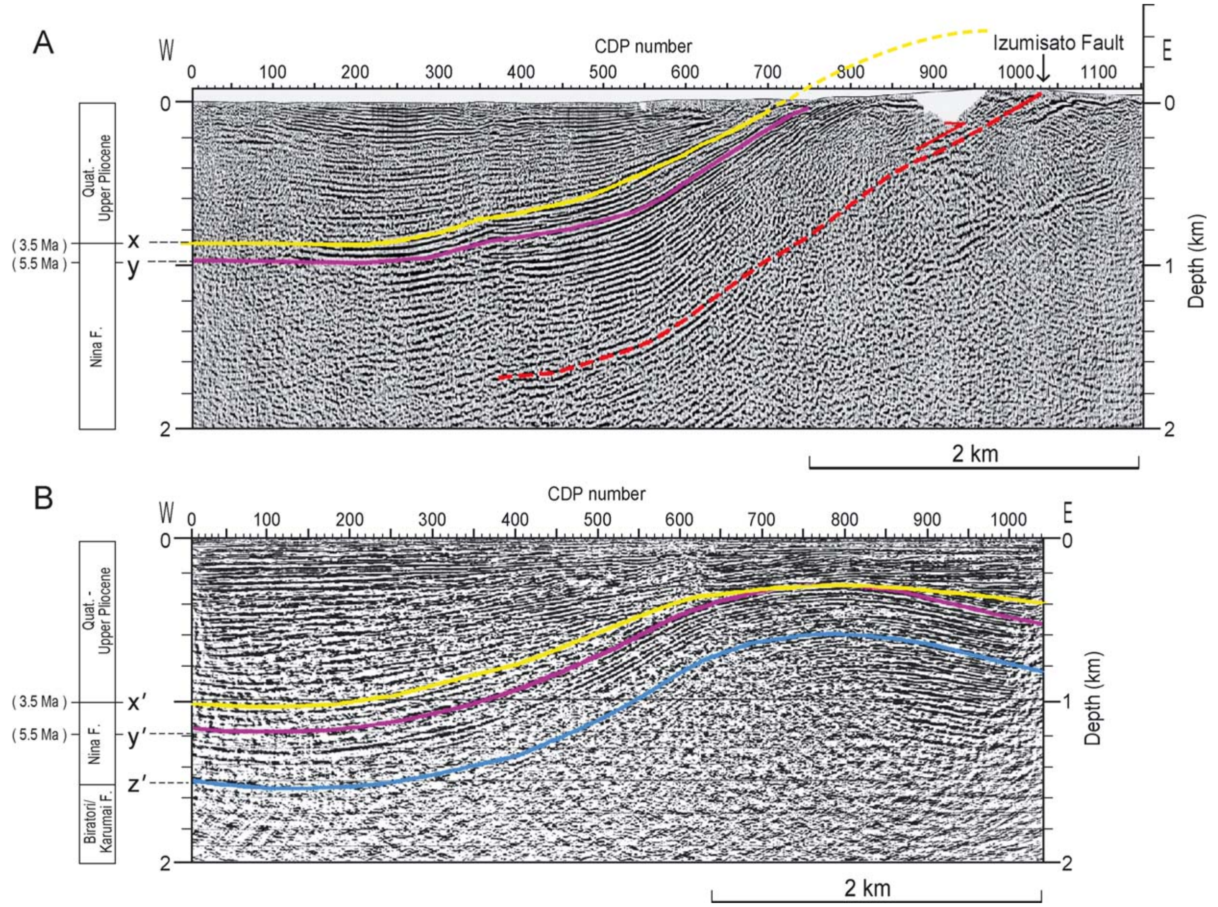

Fig. 4. Interpreted high resolution seismic profile. (A) Seismic profile acquired across the western flank of the Umaoi hills (Umaoi 2000). Seismic line is shown as line A in Fig. 2A. (B) Seismic profile across the blind active anticline at Yufutsu (Yufutsu 1997). Seismic line is shown as line B in Fig. 2A.

thrust beneath the Umaoi hills forms a wedge thrust on the western flank of the Umaoi hills. Since strata in the western flank of the hills (Fig. 4A) show limb rotation of the anticline, the anticline was formed as a fault-propagation fold in its final stages. The footwall of the most eastern thrust sheet yields diatom fossils (Kurita and Yokoi, 2000) of the 10.5 Ma *Thalassiosira yabei* zone (Berggren et al., 1985). The most eastern thrust therefore began after 10.5 Ma.

The geologic cross stions showing the development of the anticlines beneath Yufutsu are shown on Fig. 5B. An asymmetric anticline with steeper dipping reflectors on its western flank can be recognized in the seismic section shown in Fig 3C. As the growth strata on the western flank show limb rotation, the anticline is interpreted as a fault-propagation fold. The tip of thrust is in the Kawabata Formation. Growth strata do not exist below horizon y' on either flank of the anticline (Fig. 4B). It is thus inferred that the thrusting to form the blind anticline started after 5.5 Ma.

4.2. Rate of vertical displacement

The uplift of the Umaoi hills and Yufutsu anticline is closely linked to the movement of the Hidaka thrust system. To constrain temporal changes in the slip rate of the main thrust, we estimated the rate of vertical displacement since the late Miocene or early Pliocene

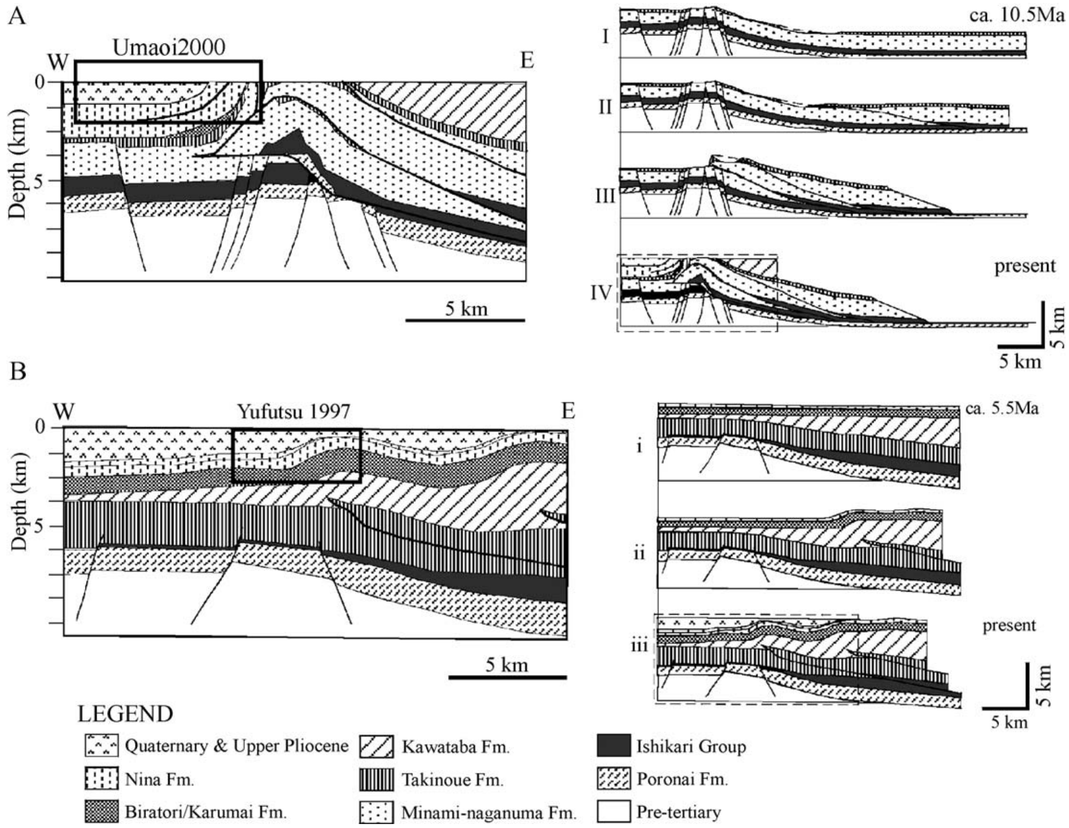

Fig. 5. Geologic cross sections showing sequential deformation processes across the front part of the Hidaka thrust system. (A) Geologic cross-sections during the last 10.5 million years across the western flank of the Umaoi hills. (B) Geologic cross-section during the last 5.5 million years across the blind active anticline at Yufutsu.

using shallow seismic reflection profiles and estimated the rate since the Quaternary using shallow drill cores and surface displacements.

4.2.1. Rate of vertical displacement since the late Miocene

The rate of uplift of the Umaoi hills was estimated using horizon x (top of the Nina Formation) and has also been dated at 3.5 Ma (Akiba, 1986). The lowest point of its upper surface in the seismic profile is −900 m in altitude. The highest point that the Nina Formation crops out is 100 m in altitude, but to take into account the amount of erosion on the Umaoi hills, the maximum height of the upper surface of the Nina Formation is estimated to be 400 m in altitude by extrapolating horizon x skyward by following the general structure of the anticline (Fig. 4A). If we assume that horizon x was originally horizontal, the total amount of its vertical displacement is 1000–1300 m and the uplift rate is calculated to be 0.29–0.37 mm/year.

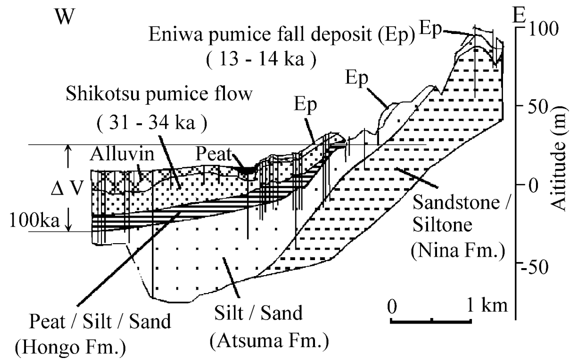

Fig. 6. Geologic cross section based on drill core array along the western flank of the Umaoi hills, compiled after the drill core data of Oka et al. (2001). Location is the same as that of line A in Fig. 2A.

In Yufutsu area, using the same assumption mentioned above, the amount of vertical displacement of horizon x' is 850 m in Fig. 4B. Therefore, the uplift rate of the Yufutsu anticline is calculated to be 0.24 mm/year.

4.2.2. Rate of vertical displacement in the late Quaternary

Based on the array of shallow drill cores along the Umaoi 2000 seismic line (Oka et al., 2001), a shallow geologic cross-section was constructed (Fig. 6). Pleistocene strata thin towards the hills. The Atsuma Formation was deposited during the last interglacial stage (Kondo et al., 1996) and mainly consists of silt and sand (Oka et al., 2001). At the eastern flank of the Umaoi hills, marine diatom fossils were reported from the upper part of this formation (Umaoi Collaborative Research Group, 1987), and sand pipes were reported from the drill cores shown in Fig. 6 (Oka et al., 2001). The peat layers of the Hongo Formation cover the Atsuma Formation conformably and contain brackish molluscan fossils (Iwamizawa Collaborative Research Group, 1976). Both formations are interpreted to have been deposited in a quiet low-gradient environment, perhaps a coastal swamp to bay setting (cf. Umaoi Collaborative Research Group, 1987), with the depositional slope being almost horizontal. Since the peat layers now dip basinward, this indicates uplift of the hills after their deposition. Therefore, growth folding of the Umaoi hills has continued into the late Quaternary. The total difference in altitude across the base of the Hongo Formation is 50 m (Fig. 6). As the lowermost peat bed of the Hongo Fm. is dated at 115 ka (Kondo et al., 1996), the rate of uplift during the late Quaternary in the Umaoi hills is calculated to be more than 0.43 mm/year. This value is larger than the one estimated from the 3.5 Ma horizon.

A NS trending flexure is recognized on the depositional surface of the Shikotsu ash flow tuff dated at 41 ka (Soeng et al., 2001; Fig. 2C). The tuff was erupted from the Shikotsu caldera, with the outflow sheet having a thickness of 30 m in the vicinity of Misawa (Hirota et al., 1996; Fig. 2C). The top surface of the outflow sheet is well preserved as the present topographic surface (Moriya, 1979), and forms a subhorizontal plane which dips about 0.2° eastwards. However, a N–S trending flexure has uplifted the tuff about 10 m in the vicinity of Misawa. This flexure corresponds to the northern extension of the Yufutsu anticline shown in seismic reflection profiles of Asano et al. (1989) and some industry seismic lines (Orito, 2000). Thus, the rate of vertical displacement after 41 ka is calculated to be 0.24 mm/year, a value similar to the one obtained from the Yufutu anticline using the displacement of the 3.5 Ma horizon.

The above-mentioned values indicate that the slip rate of the Hidaka main thrust has not decreased in the late Quaternary. The significance of this finding for the plate tectonic setting of Hokkaido will be discussed later.

4.3. Horizontal displacement of the main thrust

Based on the balanced cross-section, the horizontal displacement of the front of the Hidaka thrust system was calculated in the Umaoi hills and Yuftsu area (Fig. 5). At Umaoi hills, the total amount of horizontal shortening is about 10 km. Since the earliest thrusting is interpreted to have begun at least 10.5 Ma, the minimum rate of horizontal shortening is ca. 1.0 mm/year.

On the other hand, at the Yufutsu anticline, it is considered that thrusting started after ca. 5.5 Ma. As the measured horizontal shortening was approximately 3.5 km, the minimum rate of shortening was ca. 0.6 mm/year. However, on Umaoi and Yufutsu seismic sections, about 80 % of the vertical displacement in the last 5.5 Ma occurred after 3.5 Ma. Thus, if we assume that the horizontal shortening was distributed in a similar manner, we find that the rate of shortening after 3.5 Ma to be ca. 0.8 mm/year.

Based on the data of deep seismic profiles and surface geology, Ito (2002) estimated a total amount of shortening of 60 km across the entire Hidaka thrust system. As the shortening deformation of the thrust system started in the middle Miocene (ca. 15 Ma), the rate of horizontal shortening is estimated to be 4 mm/year (Ito, 2002). This suggests that most of the convergence was accommodated by regional plastic deformation in the Hidaka thrust system with only one quarter of the convergence being taken up by the front part of the thrust system. According to Seno et al. (1996), the convergence rate between Eurasian and Okhotsk plates is estimated to be 7–9 mm/year in the

Hokkaido region, indicating that half of the plate convergence has been accommodated along the Hidaka thrust system. The remaining convergence is probably accommodated by reverse faults along the eastern part of the Sea of Japan (Okamura, 2000).

Our research shows the rate of shortening in central Hokkaido has been relatively constant since the Pliocene and that the convergence determined from relative plate motion is not accommodated in a single fault system. Other convergent plate boundaries, such as Syria (Brew et al., 2001) and Morocco (Gomez et al., 2000), also commonly show such a diffuse pattern of deformation. Northern Japan should be considered in a similar manner.

5. Conclusions

Along convergent continental plate boundaries, convergence is typically accommodated across a wide diffuse zone. Up until now, the plate boundary between the Eurasian (Amurian) and North American (Okhotsk) plates has been represented as a single line. However, our research has shown both that the rate of shortening in central Hokkaido has been relatively constant since the Pliocene and that about 50% of the convergence required by the relative plate motion is still being accommodated in the central part of Hokkaido. Obviously, the location of the plate boundary in northern Japan cannot be marked as a single line.

To construct a more quantitative model of the deformation of the continental crust in northern Japan, including the eastern part of the Sea of Japan, more regional and multidisciplinary research will be needed.

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