Available online at www.sciencedirect.com
ScienceDirect
Tectonophysics 466 (2009) 229 – 240
TECTONOPHYSICS
www.elsevier.com/locate/tecto

Crustal structure and deformation at the northern Manila Trench between Taiwan and Luzon islands

Chia-Yen Ku, Shu-Kun Hsu *

Institute of Geophysics, National Central University, Taiwan

Available online 21 November 2007

Abstract

The Philippine Sea Plate overrides the Eurasian Plate along the east-dipping Manila Trench between Taiwan and Luzon islands. From south to north, the plate convergence gradually evolves from normal subduction of the South China Sea lithosphere to initial collision of the Taiwan orogen. The subduction-related earthquakes become diffusive close to Taiwan; the accretionary prism is dramatically wider toward Taiwan. To understand the plate convergent features of this subduction-collision transition zone, we have analyzed twelve seismic reflection profiles across the Manila Trench between Luzon and Taiwan. The results show that the basement of northern South China Sea basin generally dips toward east and south. The northern Manila Trench accumulates more trench-fill sediments in the south than in the north. A sequence boundary t_0 is suggested to distinguish the hemipelagic and trench-fill sediments. Probably due to the collision in Taiwan, the sequence boundary t_0 displays more gentle slope or has been uplifted in the north. Structural analysis shows that the subducting crust in the northern Manila Trench area can be characterized by three distinctive zones: a normal fault zone (NFZ), a proto-thrust zone (PTZ) and a thrust zone (TZ). The NFZ is defined by the distribution of numerous normal faults in the top or upper portion of the subducting crust. The normal faults are gradually buried by trench-fill sediments when they are closer to the deep trench. It is suggested that normal fault may take place at the location where the crust starts to bend and induces gravity sliding of the upper sedimentary layers. Some buried normal faults could be reactivated to blind thrust faults because of stronger plate convergence near the accretionary prism. The PTZ is located between the NFZ and the frontal thrust of the accretionary prism; it contains blind thrust faults or folds instead of thrust faults. The successive distribution of the crustal structures of normal faults, blind thrust and thrust faults at the trench area suggests that the blind thrust faults develop along the location of pre-existing normal faults. The brittle deformation occurs at the lower part of the sedimentary layers probably because of stronger compaction and less water content; eventually blind thrust faults may propagate upward and become thrust faults at the seabed.

Keywords: Manila Trench; Subduction; Seismic reflection; Crustal structure; Plate convergence

1. Introduction

Between Taiwan and Luzon islands, the South China Sea lithosphere has been subducting eastward beneath the Philippine Sea Plate along the Manila Trench (Fig. 1). The northern Manila Trench is marked by a bathymetric depression and low free-air gravity anomaly (Bowin et al., 1978; Hsu et al., 1998; Liu et al., 1998; Hsu et al., 2004). The lowest gravity anomaly is however distributed along the North Luzon Trough, reflecting the uplifts of the Manila accretionary prism. West of Luzon island, the Manila Trench is convex seaward; however, the trench in the region between Taiwan and Luzon islands is concave seaward (Fig. 1). Such geometry is distinctively different from many other ocean trenches in the world whose trench axes are seaward convex. Incidentally, the Manila accretionary prism broadens from south to north. The trace of Manila Trench becomes unclear to the north of 21°N. The Manila subduction system progressively evolves from normal subduction to initial collision of the Taiwan orogen (e.g. Kao et al., 2000). To the north of 21.5°N, the Taiwan mountain belt has been formed by the northwestward convergence of the Luzon Arc against the Eurasian margin (e.g. Angelier, 1986; Teng, 1990; Sibuet and Hsu, 2004; Sibuet et al., 2004). Hayes and Lewis (1984) have studied the Manila Trench west of the Luzon island; however, there are rare studies focusing on the crustal features of the northern Manila Trench area. Hence, we

* Corresponding author. Tel.: +886 3 4268316; fax: +886 2 4222044.
E-mail address: hsu@ncu.edu.tw (S.-K. Hsu).

0040-1951/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2007.11.012

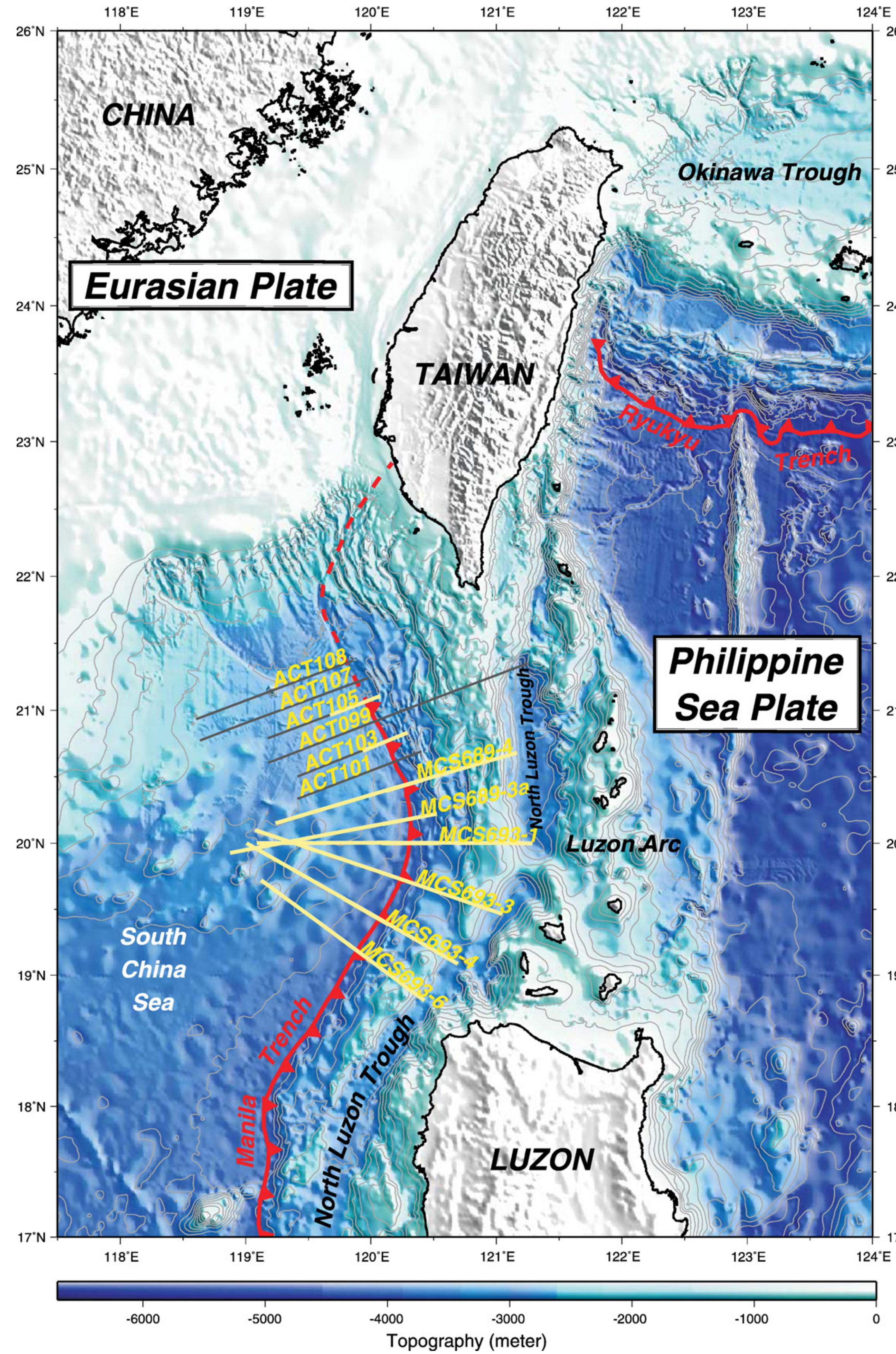

Fig. 1. Bathymetric map and tectonic setting of the Taiwan and Luzon region. Twelve seismic profiles (collected during ORI-689, ORI-693 and ACT cruises) used in this study are marked by black and yellow lines. The seismic profiles indicated by yellow segments are shown in this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

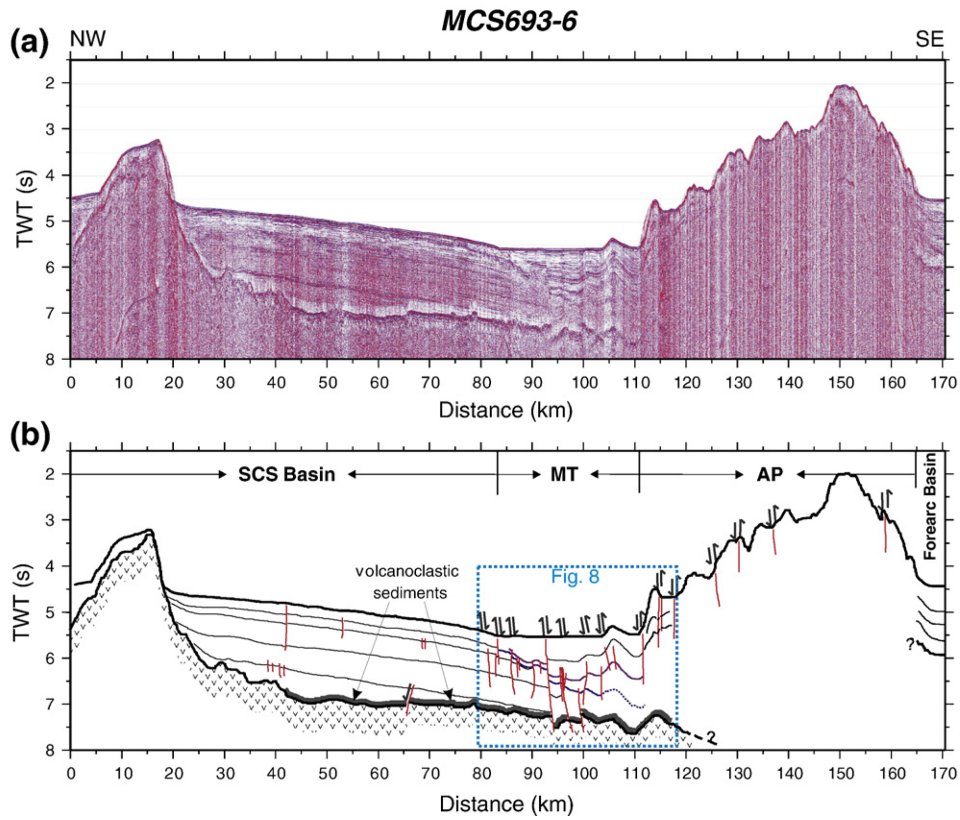

Fig. 2. (a) MCS693-6 migrated profile. (b) The interpretation of MCS693-6 (See location in Fig. 1). Detailed structures in the dotted box are shown in Fig. 8. It is noted that the stratigraphic sequences of South China Sea basin are covered by lots of trench-fill sediments close to the Manila Trench. SCS: South China Sea. MT: Manila Trench. AP: accretionary prism.

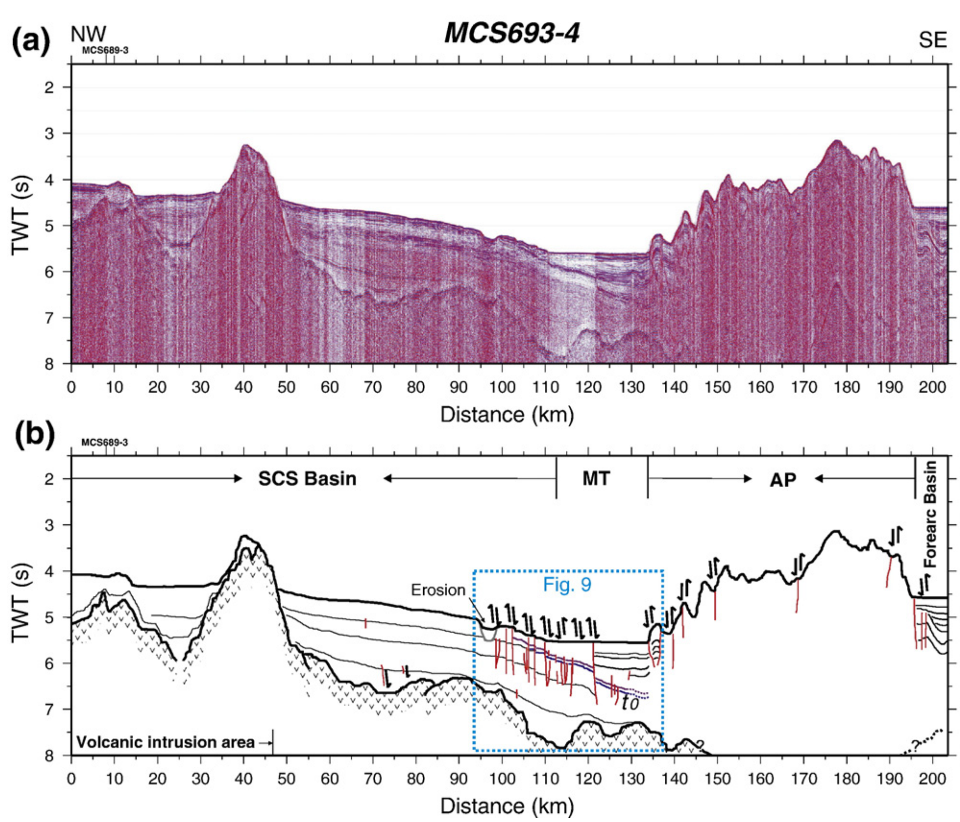

Fig. 3. (a) MCS693-4 migrated profile. (b) The interpretation of MCS693-4. Detailed structures in the dotted box is shown in Fig. 9.

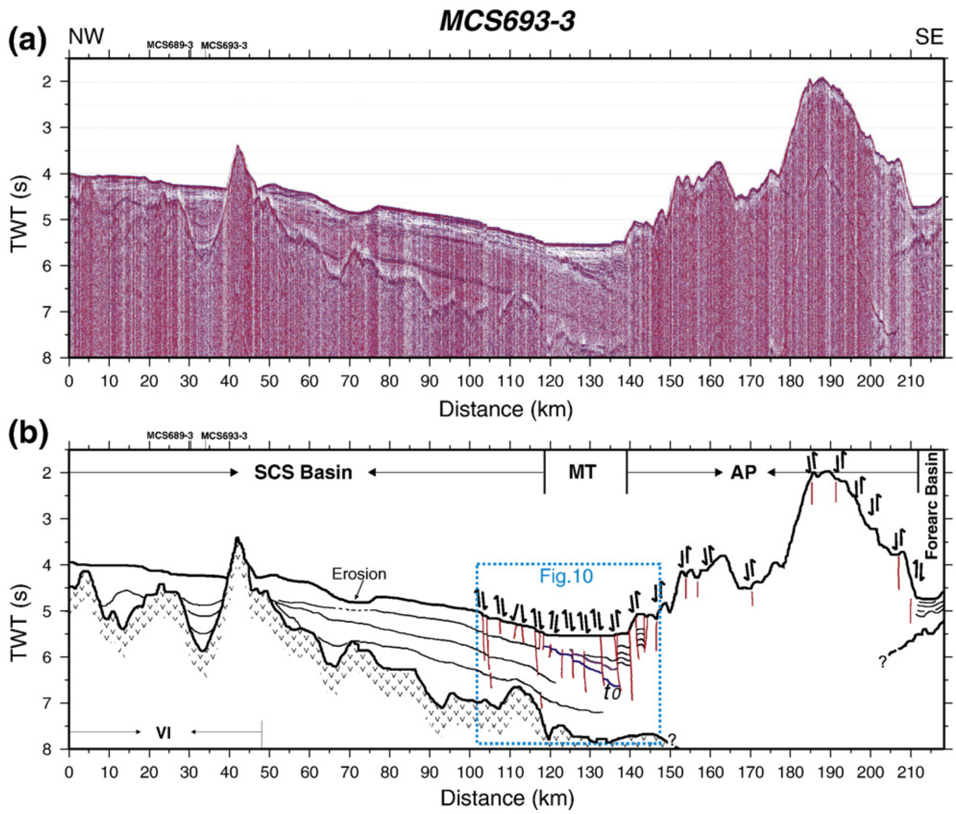

Fig. 4. (a) MCS693-3 migrated profile. (b) The interpretation of MCS693-3. Detailed structures in the dotted box is shown in Fig. 10.

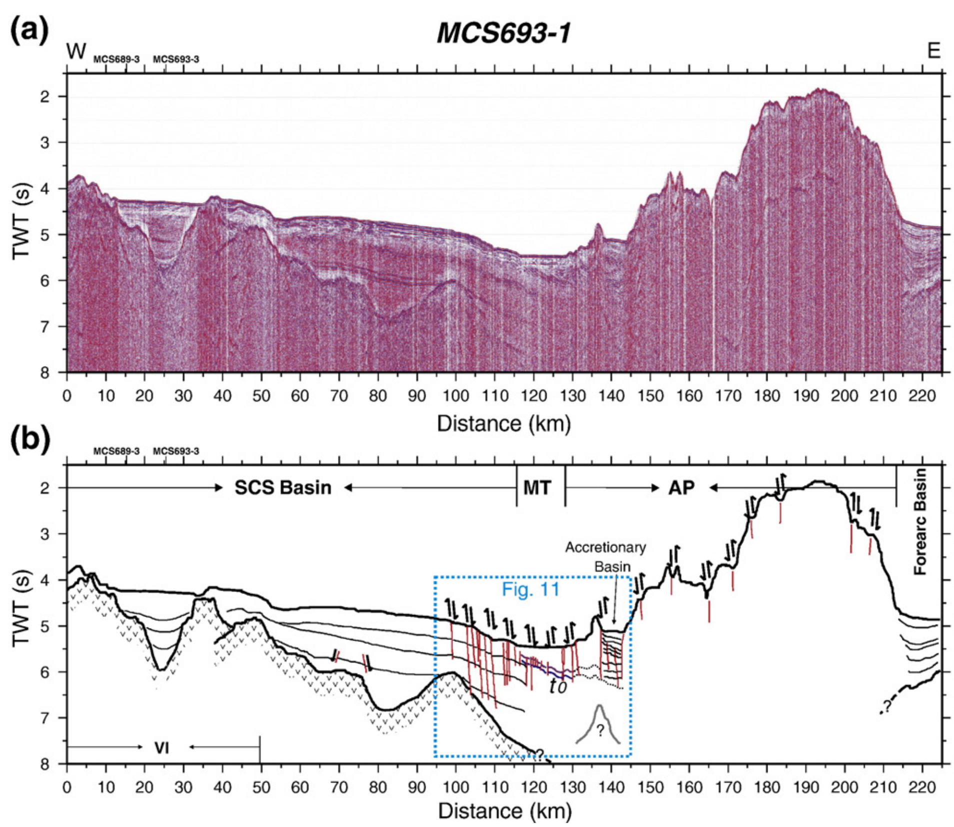

Fig. 5. (a) MCS693-1 migrated profile. (b) The interpretation of MCS693-1. Detailed structures in the box is shown in Fig. 11.

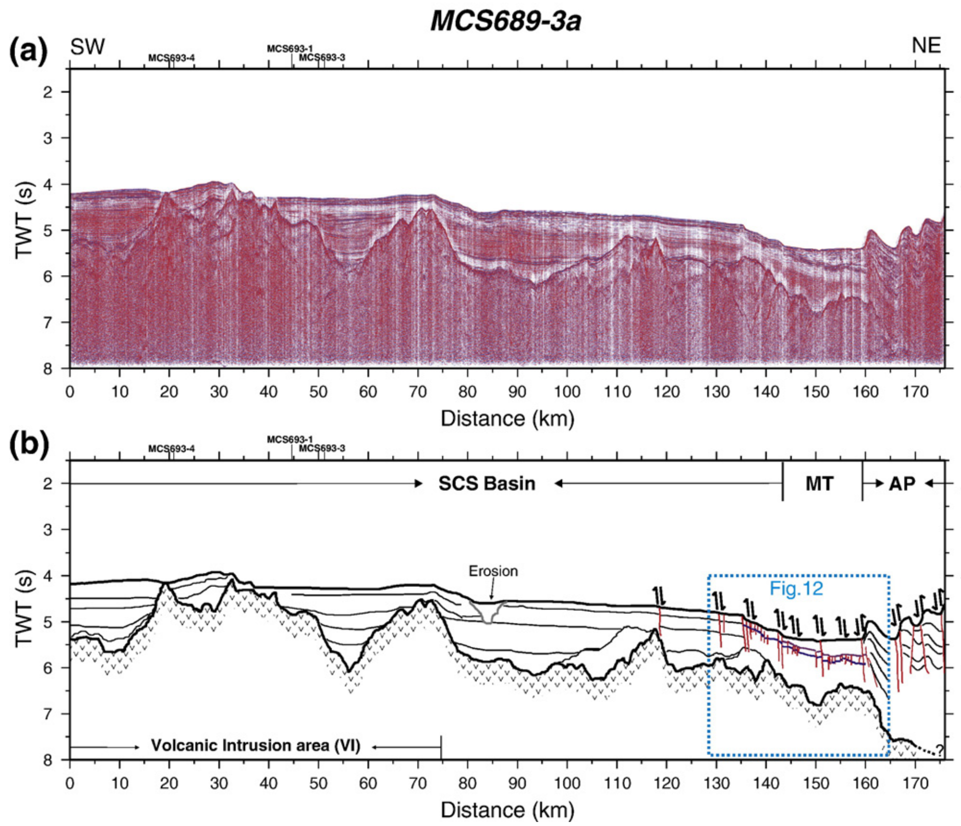

Fig. 6. (a) MCS689-3a migrated profile. (b) The interpretation of MCS689-3a. Detailed structures in the box is shown in Fig. 12.

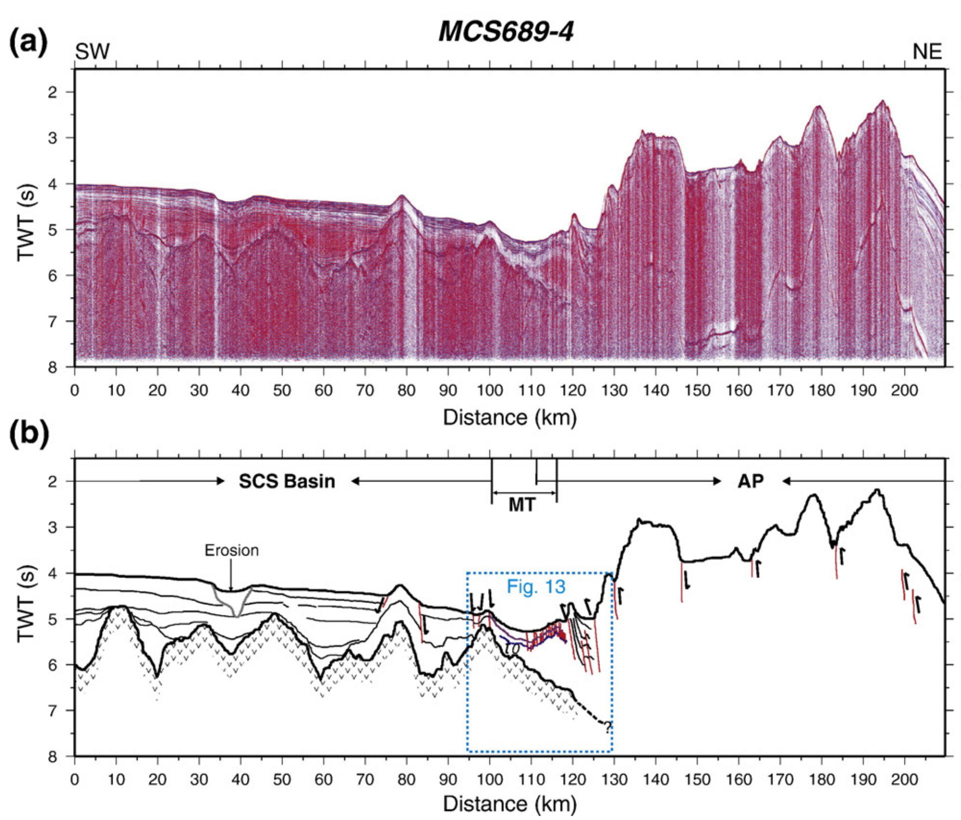

Fig. 7. (a) MCS689-4 migrated profile. (b) The interpretation of MCS689-4. Detailed structures in the box is shown in Fig. 13. It is noted that the sequence boundary t_0 has been uplifted as a result of initial collision of the Taiwan orogeny.

use newly collected and existing seismic reflection data to study the characteristics of the upper crustal structures and deformation pattern of this subduction-collision transition zone.

2. Seismic data acquisition and processing

Six multi-channels seismic reflection profile data were collected across the northern Manila Trench during two cruises (ORI693 in September 2003 and ORI689 in July 2003). We have also used six seismic profiles from the ACT cruise (Lallemand et al., 1997). All the seismic profiles are approximately perpendicular to the Manila Trench (Fig. 1). During the ORI689 and ORI693 cruises, an array of 3 guns consisting of two 500 in.^{3} and one 275 in.^{3} was used that fired at every 20 s (or 50 m at a ship speed of 5 knots). A 48-channel streamer of 600 m in length was deployed, and 2 ms sampling rate was adopted. However, because of streamer hydrophone problems occurred during the ORI693 cruise, we have muted the first 36 channels in the shot records. For the ACT cruise data, two GI guns with a total volume of 150 in.^{3} were used while traveling at a ship speed of 10 knots (Lallemand et al., 1997).

The ORI689 and ORI693 seismic profile data are processed with bandpass filter of 8-16-60-110 Hz, and minimum phase predictive deconvolution was performed. The normal moveout, stack and F-K migration are all applied by using a constant seawater velocity of 1480 m/s.

3. Interpretation

3.1. Volcanic basement in the northern South China Sea

The MCS profiles used here show the cross-sections from the South China Sea basin through accretionary prism to North Luzon Trough (Figs. 2–7). In general, the volcanic basement of the study area is of oceanic (Hsu et al., 2004), and the basement is dipping to the south and to the east (Yeh and Hsu, 2004). This phenomenon reveals the transition of plate convergence from the normal subduction near the Luzon Island to the collision in the Taiwan mountain belt.

In northern South China Sea basin, we can observe volcanic seamounts standing out above the seafloor. As shown in the profile MCS693-6 (Fig. 2), the basement displays gentle dipping and has been faulted. At the depth of 7 s twt from distance 43 km to 116 km in the profile MCS693-6 (Fig. 2), it indicates that there are some volcanoclastic sediments overlying the volcanic basement. The considerably flat and faulted volcanoclastic basement suggests that volcanic extrusion may occur after the formation of the South China Sea seafloor. After the extinction of the volcanic activity, the volcanoclastic basement

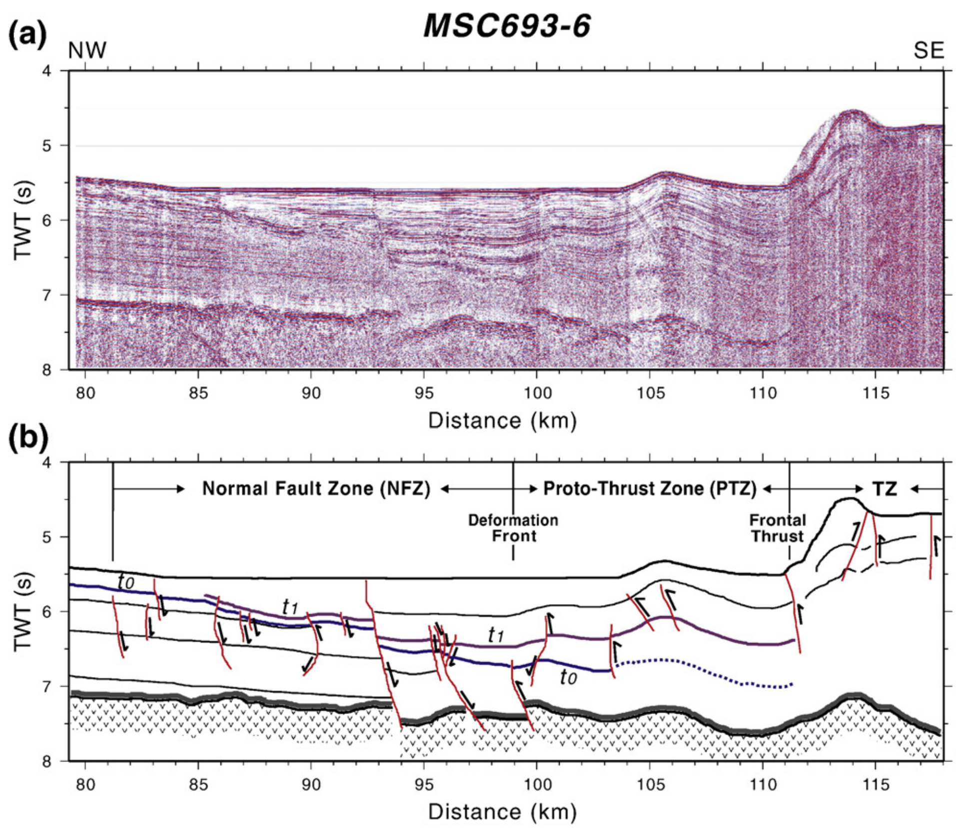

Fig. 8. Detailed structures in the trench area of MCS693-6 profile. Blue line marks the sequence boundary t_0 between hemipelagic and trench-fill sediments. Numerous normal faults exist in the normal fault zone (NFZ). At the distances of 94 km, 97 km and 100 km, the volcanic basement is also faulted. Some blind thrust faults and folds are found in the PTZ.

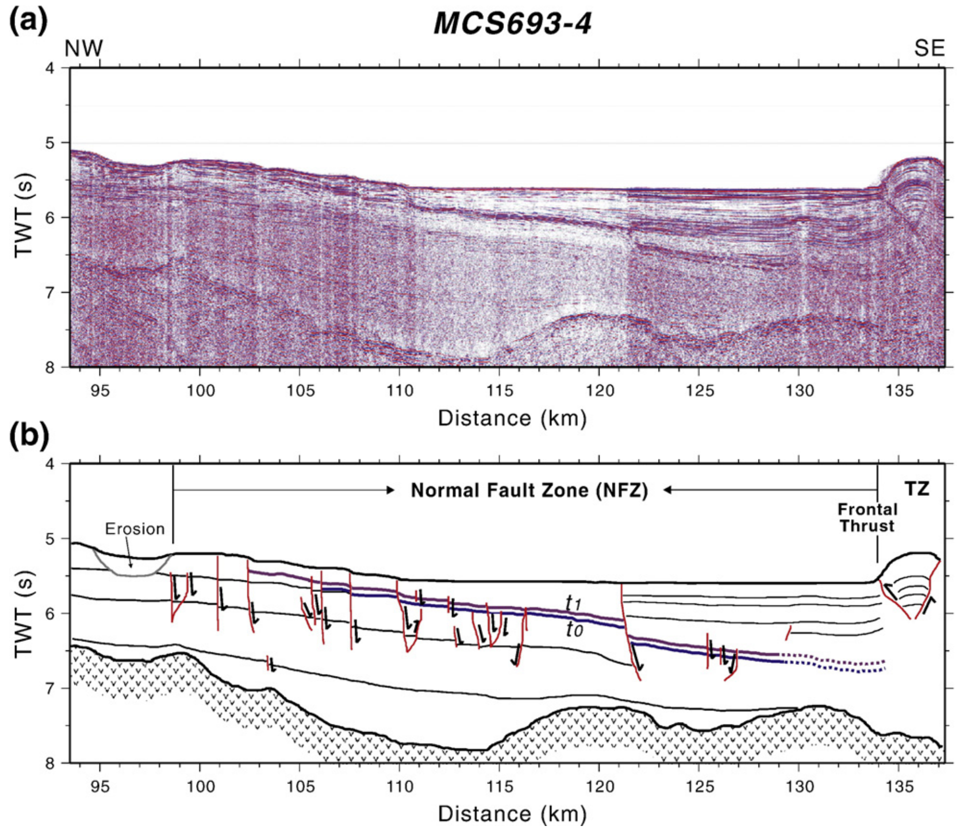

Fig. 9. Detailed structures in the trench area of MCS693-4 profile.

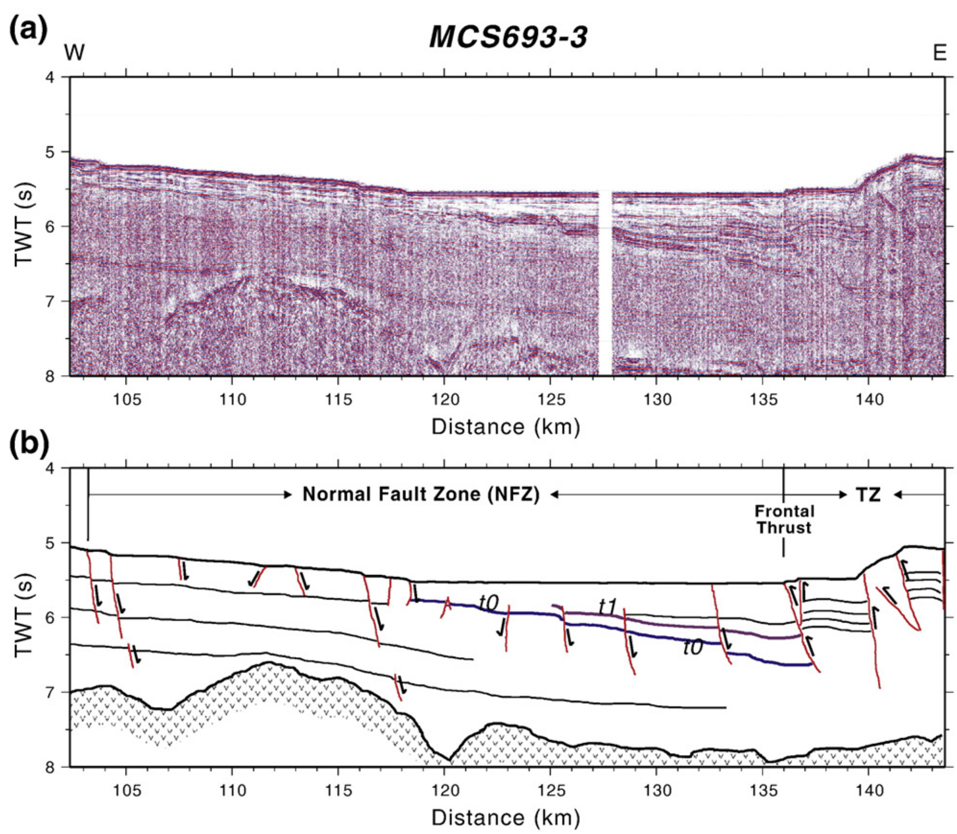

Fig. 10. Detailed structures in the trench area of MCS693-3 profile.

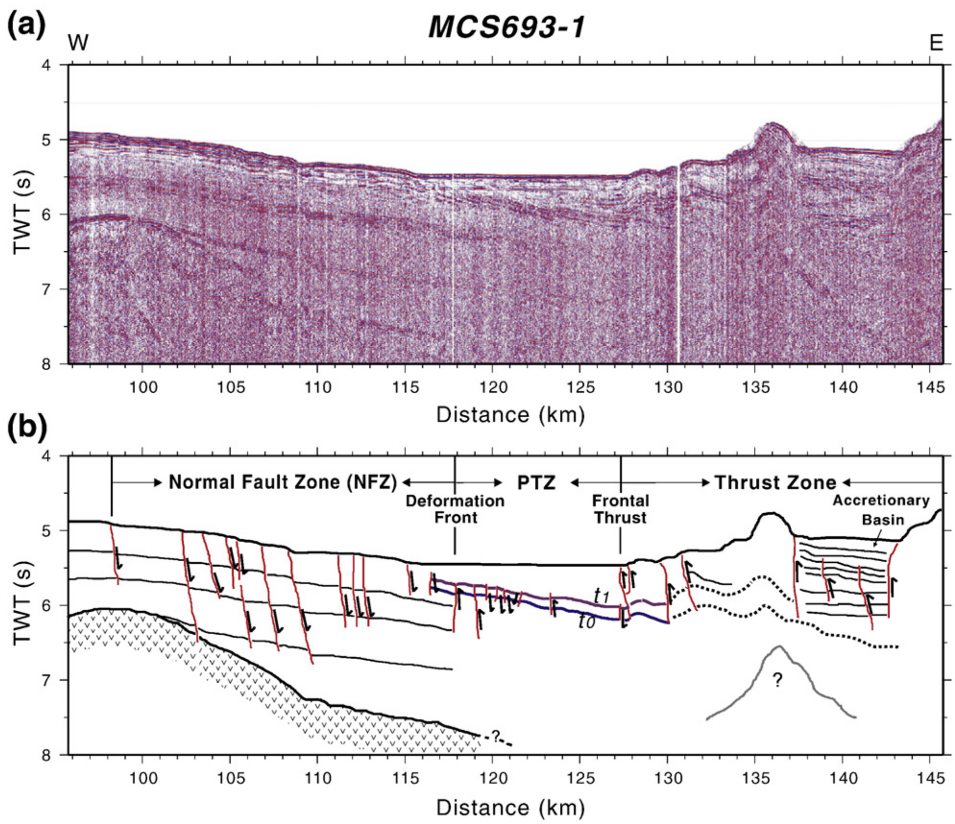

Fig. 11. Detailed structures in the trench area of MCS693-1 profile. Blind normal faults and blind thrust faults can be observed in the PTZ.

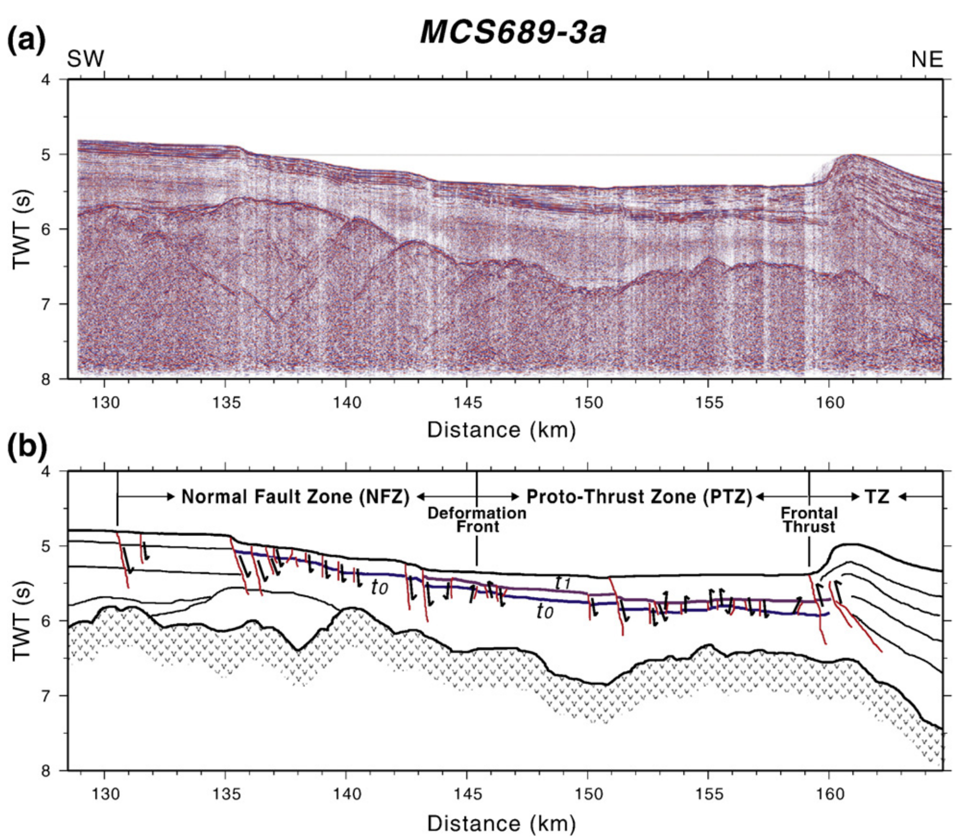

Fig. 12. Detailed structures in the trench area of MCS689-3a profile.

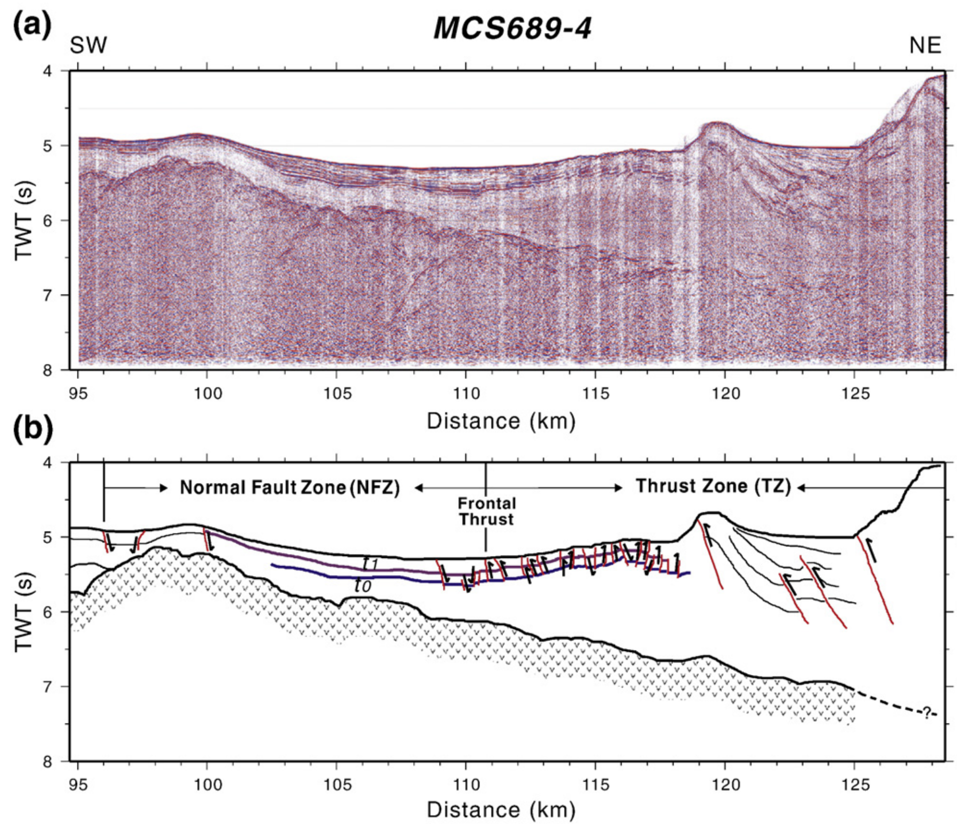

Fig. 13. Detailed structures in the trench area of MCS689-4 profile.

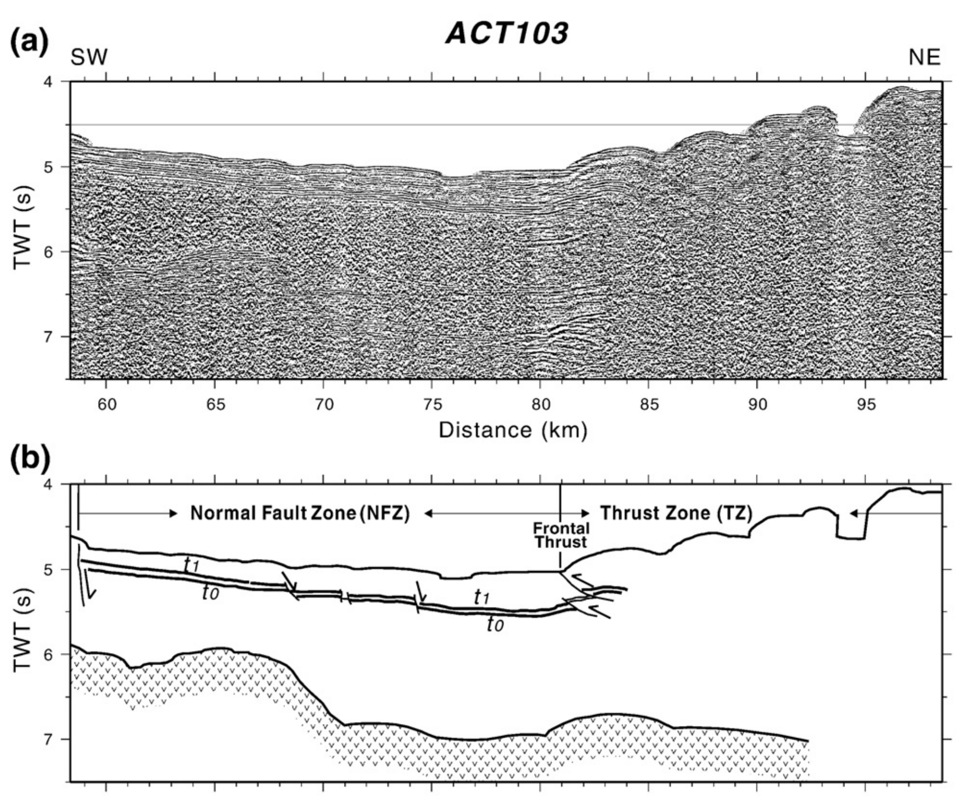

Fig. 14. Detailed structures in the trench area of ACT103 profile.

could be faulted either by the subduction-related bending of the crust or by the westward convergence of Luzon Arc.

3.2. Sequence boundary between hemipelagic and trench-fill sediments

Based on the seismic reflection data between 14°N and 19°N, Hayes and Lewis (1984) have shown a major structural decollement at the Manila Trench area. This decollement or unconformity separates the hemipelagic sediments from the turbidity sediments. The turbidities in Manila Trench between 14°N to 19°N could be transported from either the uplifted collisional zone of Taiwan or from the Palawan area by gravity-controlled processes (Lewis and Hayes, 1984). Deep-sea drilling results from Barbados indicated that the interface between the hemipelagic strata and the overlying turbidites could be due to an abrupt change in clay mineralogy (Moore et al., 1981). Some faults (splay faults) may root in this major decollement between the hemipelagic and turbidity sediments (Hayes and Lewis, 1984).

Similarly, we have also observed two pronounced seismic reflectors in the trench area; the lower and upper sequences are identified as t_0 and t_1 respectively (Figs. 8–14). The transition zone above t_0 and beneath t_1 is likely to be the boundary between hemipelagic and trench-fill sediments as indicated by Hayes and Lewis (1984). Beneath the sequence boundary t_0 or above the boundary t_1, the facies of the hemipelagic (or mixed pelagic) and turbidities sediments are transparent (lower amplitude). By comparison with the results of Hayes and Lewis (1984), the lower boundary t_0 in this study may generally separate the hemipelagic and trench-fill sediments. The dipping angle of the boundary t_0 increases eastwards and southwards. The boundary t_0 has been folded more or less or thrusted toward trench and is onlapped by offscarping trench-fill sediments.

The thickness of trench-fill sediments above the boundary t_0 decreases from south to north. In the northern part near Taiwan, the boundary t_0 apparently have been uplifted (Figs. 7 and 13). The larger capacity of receiving sediments at the southern portion of the trench (e.g. Figs. 2 and 8) indicates that the crust (and the lithosphere) has been bent considerably. This situation implies that westward retreating of the South China Sea subducting slab undergoes much easier in the south than in the north in our study area.

3.3. Normal fault zone and proto-thrust zone at the northern Manila Trench

In terms of structural deformation, the upper crust around the northern Manila Trench can be characterized by three zones: a normal fault zone (NFZ), a proto-thrust zone (PTZ) and a thrust zone (TZ; the Manila accretionary prism).

The NFZ is defined by high concentration of normal faults in the upper sedimentary layers (Figs. 8–15). Some normal faults are covered by trench-fill sediments (Fig. 8). We have delineated the NFZ distribution in the study area (Fig. 16). The NFZ is wider to the south. Several large normal faults even extend

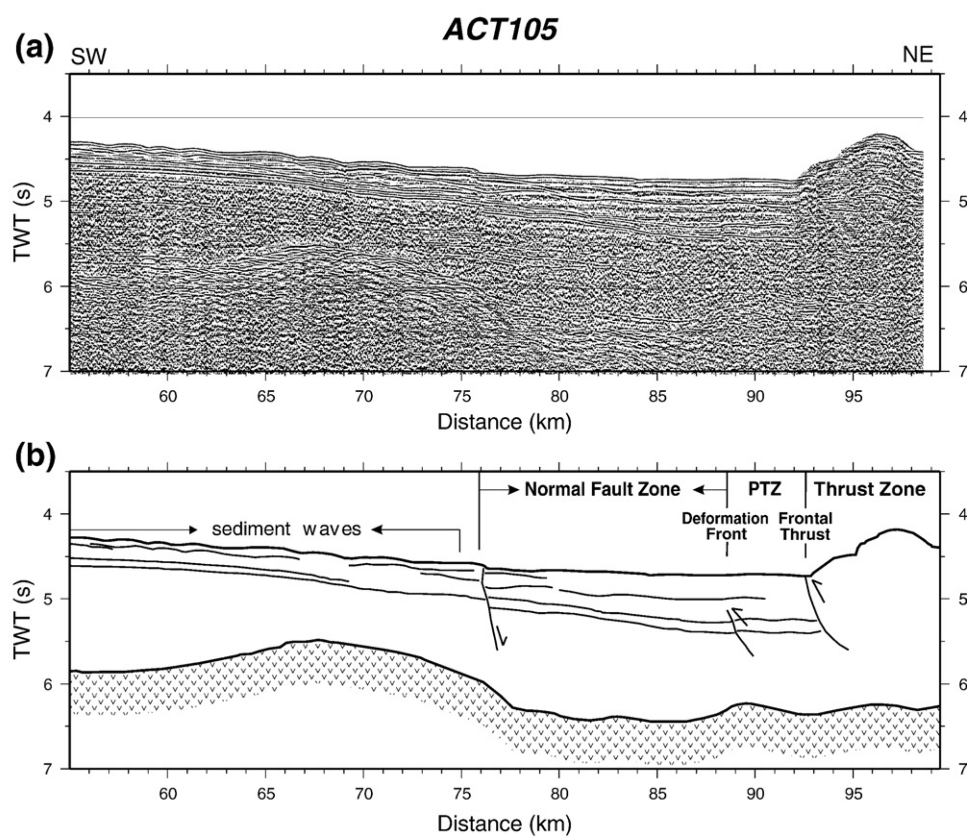

Fig. 15. Detailed structures in the trench area of ACT105 profile.

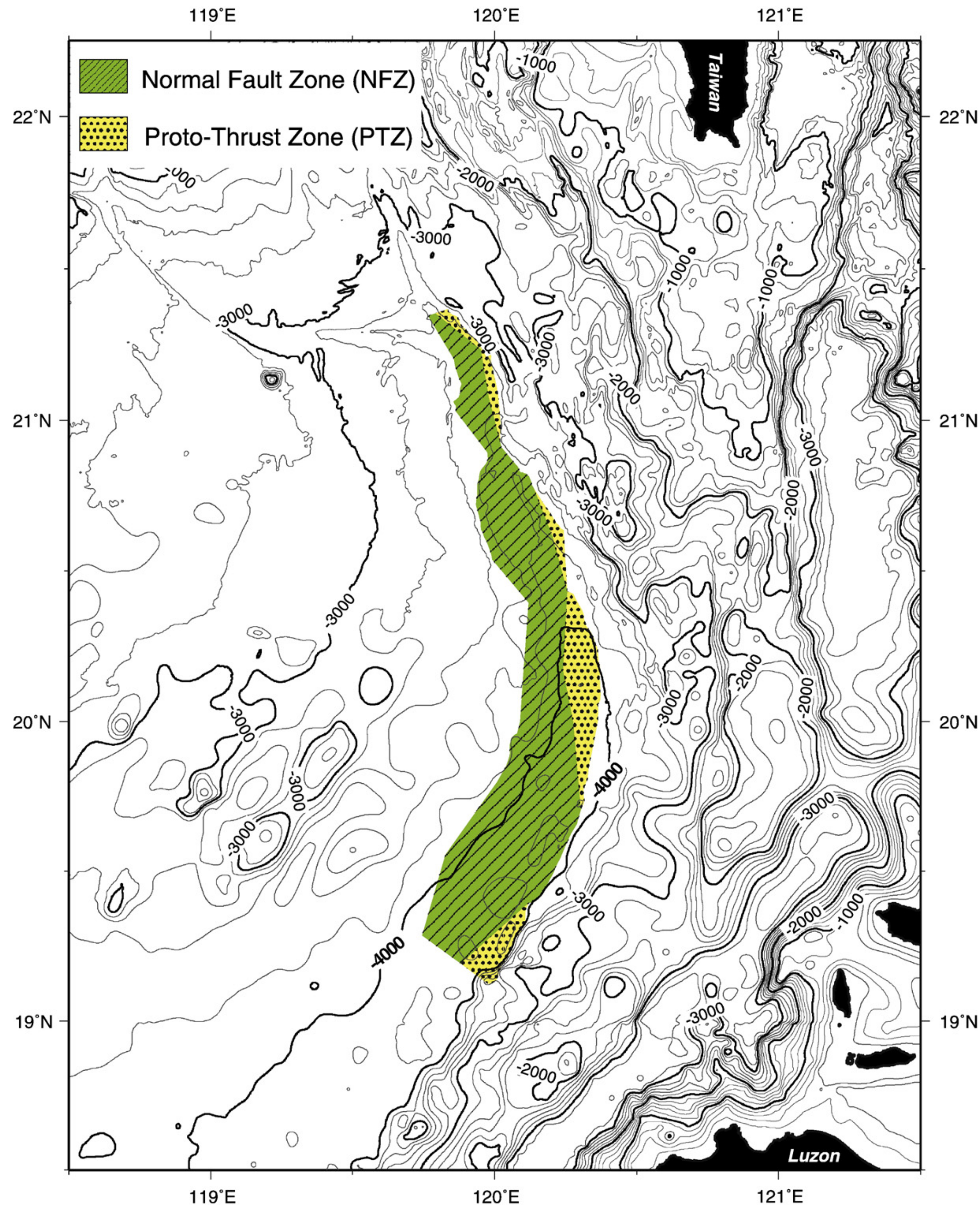

Fig. 16. The NFZ and PTZ distribution in the northern Manila Trench. The green area marks the NFZ, and the yellow area marks the PTZ.

upward to the seafloor. The development of the normal faults at the NFZ is likely to begin when the lithosphere has bent as a result of subduction process. The bending of the lithosphere may cause gravity sliding and faulting of the upper sedimentary layers. The basement has also been faulted as shown in profiles MSC693-6 and MSC693-1 (Figs. 8 and 11).

The frontal thrust is defined as the most seaward thrust fault; this thrust fault can be traced at the seabed. The deformation front is defined as the location of the first seaward blind thrust fault or of the flank where sediments start to fold. However, the latter situation is generally difficult to be delineated. The PTZ is defined as the zone between the deformation front and the frontal thrust (Figs. 8, 11, 12 and 15). In fact, The PTZ represents a transitional zone from extensional (normal faults) to compressional (thrust faults) environments. Thus, normal faults (blind or not) and blind thrust faults may coexist often in this zone. The stratigraphic sequences in the PTZ are usually faulted and folded slightly in the beginning of seaward flank in the PTZ (Fig. 8), and the compression increases towards the accretionary prism. For example, in the profile MCS693-6, sequences have already been uplifted slightly at the distance of 99 km but uplifted significantly at the distance of 104 km (Fig. 8). The observation of the fault system at the northern Manila Trench may suggest two possibilities of structural development near the trench. Normal faults (blind or not) could be reactivated as blind thrust faults and blind thrusts would continue to develop into thrusts at the seafloor later.

As suggested by the development of blind thrust faults to thrust faults at the seabed, it seems that the compressive stress is transmitted upwards and from east to west. However, such a phenomenon could be accounted for by two reasons. Firstly, brittle deformation of blind thrust faults could develop along the pre-existing buried normal faults. Secondly, the upper sedimentary layers may be less compacted and contain more water. Thus, ductile deformation could occur much easier at upper sedimentary layers. Ductile deformation at upper sedimentary layers may gradually become brittle deformation when lateral compaction of sediments increases due to the Luzon Arc convergence.

4. Conclusions

We have analyzed twelve seismic reflection profiles at the northern Manila Trench to understand the crustal structures in a plate convergence zone from normal subduction to the initial collision of the Taiwan mountain building. The volcanic basement of the northern South China Sea basin generally deepens toward the trench. The sedimentary boundary, t_0, is suggested to differentiate the hemipelagic sediments from the trench-fill sediments in almost all the interpreted seismic profiles. Taking t_0 as a benchmark, we can observe a larger volume of trench-fill sediments in the south than in the north, suggesting the transportation of sediments along the trench from the north. The deposited sediments may come from the SE Eurasian margin or from the erosion of the Taiwan mountain belt. In the north, the trench-fill sediments above the boundary t_0 are not only less but also folded and uplifted. This situation reflects the subduction-collision transition of the plate convergence between Philippine Sea Plate and Eurasian Plate. According to the structural features of the upper crust at the northern Manila Trench, we can identify three distinctive zones: a normal fault zone (NFZ), a proto-thrust zone (PTZ) and a thrust zone (TZ). The NFZ is generally narrower toward the north, suggesting that the subduction-related bending effect of the crust (or lithosphere) significantly decreases northward, or the volcanic basement gets closer to the continental margin northward. The PTZ contains blind thrust faults or folds. Due to plate convergence, the blind thrust faults probably take place along the pre-existing buried normal faults. The blind thrust faults may develop to the thrust faults at the seabed if the plate convergence continues. It implies that the PTZ incubates potential thrust faults in the future and may generate earthquake–tsunamis. The upward development from a blind thrust fault to a frontal thrust at seabed could be ascribed to the brittler behavior in the lower sediments which are more compacted and contain less water. The upper sedimentary layers may become brittler on account of an increasing plate convergence.

Acknowledgement

We acknowledge the help from the crew of R/V Ocean Research I during the seismic data collection. We are grateful to Drs. J.-C. Sibuet, Y.-C. Yeh and A.T. Lin for their fruitful discussions. We also thank Prof. Char-Shine Liu and one anonymous reviewer for their constructive comments. This study was under the grant of National Science Council, Taiwan. Part of the financial support was provided by the Central Geological Survey of Taiwan under the integrated research project of gas hydrates study.

References

Angelier, J., 1986. Preface to the special issue on Geodynamics of the Eurasian–Philippine Sea Plate Boundary. Tectonophysics 125, IX–X.

Bowin, C., Lu, R.S., Lee, C.-S., Schouten, H., 1978. Plate convergence and accretion in Taiwan–Luzon region. American Association of Petroleum Geologist Bulletin 62, 1654–1672.

Hayes, D.E., Lewis, S.D., 1984. A geophysical study of the Manila Trench, Luzon, Philippines 1. Crustal structure, gravity, and regional tectonic evolution. Journal of Geophysical Research 89, 9171–9195.

Hsu, S.-K., Liu, C.-S., Shyu, C.-T., Sibuet, J.-C., Lallemand, S., Wang, C., Reed, D., 1998. New gravity and magnetic anomaly maps in the Taiwan–Luzon region and their preliminary interpretation. TAO 9, 509–532.

Hsu, S.-K., Yeh, Y.-C., Doo, W.-B., Tsai, C.-H., 2004. New bathymetry and magnetic lineations identification in the northernmost South China Sea and their tectonic implications. Marine Geophysical Researches 25, 29–44.

Kao, H., Huang, G.-C., Liu, C.-S., 2000. Transition from oblique subduction to collision in the northern Luzon arc-Taiwan region: constraints from bathymetry and seismic observations. Journal of Geophysical Research 105, 3059–3079.

Lallemand, S., et al., 1997. Swath bathymetry reveals active arc–continent collision near Taiwan. Eos, Transactions of the American Geophysical Union 78, 175–178.

Lewis, S.D., Hayes, D.E., 1984. A geophysical study of the Manila Trench, Luzon, Philippines, 2. Fore arc basin structural and stratigraphic evolution. Journal of Geophysical Research 89, 9196–9214.

Liu, C.-S., Liu, S.-Y., Lallemand, S.E., Lundberg, N., Reed, D., 1998. Digital elevation model offshore Taiwan and its tectonic implications. TAO 9, 705–738.

Moore, J.C., Biju-Duval, B., et al., 1981. Near Barbados Ridge, scraping off, subduction scrutinized. Geotimes 26, 24–26.

Sibuet, J.-C., Hsu, S.-K., 2004. How was Taiwan created? Tectonophysics 379, 159–181.

Sibuet, J.-C., Hsu, S.-K., Debayle, E., 2004. Geodynamic context of the Taiwan orogen. In: Clift, P., Wang, W., Hayes, D.E. (Eds.), Ocean–Continent Interactions within East Asian Marginal Seas. Geophysical Monograph, vol. 149. AGU, Washington, D. C., pp. 127–158.

Teng, L.-S., 1990. Geotectonic evolution of late Cenozoic arc–continental collision in Taiwan. Tectonophysics 183, 57–76.

Yeh, Y.-C., Hsu, S.-K., 2004. Crustal structures of the northernmost South China Sea: seismic reflection and gravity modeling. Marine Geophysical Researches 25, 45–61.