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The geophysical characteristics and evolution of northern and southern margins of the South China Sea

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Abstract: Data of about 40,000 km gravity and magnetic measurements, 10,000 km multichannel seismic lines, 20 sonobuoy refraction seismic stations, and 5 heatflow stations have been obtained by our institute in the South China Sea (SCS) during the passed ten years. Based on these and other data, the present paper discusses the tectono-geophysical characteristics and evolution of SCS and put forward some new ideas.

On the northern margin of SCS, five parallel structure zones have been recognized and named as, from the north to the south, the Littoral Fault Zone, Northern Depression Zone, Central Uplift Zone, Southern Depression Zone, and Slope Fault Zone. The basement of the margin is the extension of that inland Southeast China and consists of the Hercynian fold belt in the east and the Caledonian fold belt in the west. Both belts were extensively disturbed by Yanshanian magmatic emplacements. Based on gravity data, the crustal thickness is 25-26 km for the Northern Depression Zone, greater than 29 km for the Central Uplift zone, and 20-22 km for the Southern Depression Zone. A gradient belt of Moho surface is observed along the Slope Fault Zone.

A belt of high magnetic anomalies is found extending from the Dongsha Uplift NE-ward to the Penghu Islands, and a magnetic quiet zone extending along the lower slope. The former is interpreted as the manifestation of a basalt belt of 1-3 km in depth. These were intraplate eruptions and indicate the Cenozoic extension.

The Slope Fault Zone is represented by a northward dipping lithospheric fault that penetrates the basement down to the Moho. We prefer the interpretation of the fault as a segment of the Mesozoic East Asia subduction zone. The I-type granites (76-130 Ma) and associated volcanic rocks in the basement of the continental shelf might be the associated magmatic arc, while the thickened crust in the Central Uplift Zone might be the accretional wedge. The magnetic quiet zone might indicate the remains of the Paleo-Pacific oceanic crust.

In the southern margin of SCS three seismic sequences have been identified. In particular, a thick Paleogene sequence consists of neritic clastics with clear stratification and widespread distribution. This sequence was strongly deformed into asymmetric folds and eroded in the western Nansha Block. Based on the correlation with limited and distant wells, this compressional event, called as the Nansha Movement, is tentatively dated as Late Eocene, which was contemporaneous with the first phase of the Zhu-Qong movement in the northern margin of SCS, but under totally different stress regime.

Unconformably overlying Neogene sequence is thin and mainly as fillings of small and discrete half grabens in the Dangerous Grounds, but thick and continuous on the Liyue Bank and the NW Palawan shelf (1.5 to over 2 km), and even thicker in the Zengmu Basin (the Great Sarawak Basin) and to the west. This indicates that the Dangerous Grounds have stayed mainly in the uplift state since the Nansha Movement, different from the shelf area to the east, south, and southwest.

In light of the above-mentioned findings, we suggest that this block collided with Paleo-Borneo and uplifted in Late Eocene time, long before the start of the opening of SCS. Before the collision, most areas of the Nansha block was the shallow sea bordering the Paleo South China continent, where marginal rifting had been continuing since the Late Cretaceous. Not until the Late Oligocene the extension extended southward to the Nansha Block and became strong enough to open the SCS. Later in the Early Miocene, Borneo rotated counterclockwisely, probably about a pole near the center of Borneo rather than to the west. The narrow Nansha Trough Basin was formed by the elastic downwarp under the load of the NW-ward overthrusting Sabah nappe, while the Zengmu Basin was formed by the extension west of the pole of rotation.

INTRODUCTION

In 1982-1983, the South China Sea Institute of Oceanology (SCSIO), Academic Sinica, cooperating with the Nanhai West Oil Corp. of China National Offshore Oil Corp. (CNOOC), integrated geophysical data and studied the basement structure of the Pearl River Mouth Basin (PRMB) in the northern South China Sea (SCS). In 1984, cooperating with the Nanhai East Oil Corp. of CNOOC, the SCSIO deployed two parallel geophysical survey lines of 800 km in total length from the western side of the Dongsha Uplift in the PRMB through the continental slope to the northern edge of the deep-sea basin of the SCS, across several oil wells. In 1986-1988, we carried out a geophysical survey in the northeastern SCS with about 1,600 km lines, among which a transect of 735 km was made through the Bashi Strait to the West Philippine Sea. Since 1987, comprehensive geophysical surveys have been conducted in different sea areas of the Nansha Islands of the southern SCS.

This paper summarizes major geophysical and structural features in the SCS based on data from these investigations, including about 40,000 km gravity and magnetic measurements, 10,000 km multichannel seismic lines, 20 sonobuoy refraction seismic stations, and 5 heatflow stations (Fig. 1). Some problems pertaining to the evolution of SCS are also addressed.

DOMINANTLY EXTENSIONAL NORTHERN CONTINENTAL MARGIN

The northern margin of the SCS is dominated by extensional structures since the Late Cretaceous time. Major structural elements and geophysical features are discussed in the follows.

The Littoral Fault Belt

It is a NE-striking fault belt roughly parallel to the coastal line of Southeast China. Several strong historical earthquakes (M>7) took place in Quanzhou (Fujian) and Nan'ao (Guangdong) along this belt. In Line 1 (Fig. 2), 400-450 nT positive magnetic anomalies appears above a fault between the Wanshan Uplift and the Zhu-1 Depression in PRMB. This is one of the major faults in the Littoral Fault Belt. The high positive magnetic anomaly reflects probably the basaltic extrusion. The fault belt may be traced far to the west but with less distinct gravity-magnetic anomalies, partially due to the inefficiency of conventional marine geophysical methods in very shallow sea areas.

The Littoral Fault Belt is clearly seen in the deep seismic section from Changle (Fujian) to Nan'ao (Liao *et al.*, 1988). A crust-mantle mixolimnion exists in the lower crust along the belt. The fault belt cuts down to Moho and may be recognized in the 35 km upward continuation of gravity data. It represents the boundary between continental and transitional crusts. The South China mainland to the north is underlain by continental crust with a thickness of 30 km in Fuzhou-Quanzhou, 27-28 km in Xiamen-Santou, and 27-29 km in the northern Hainan Island. The vertical crustal velocity structure generally fits the 3-layer model. The mean velocity of P_n wave is 6.3-6.4 km/s in the crust, slightly higher than that in other areas of China, the P_n wave of Moho is 8.00-8.10 km/s. In the low crust there is a layer of low velocity (5.5-5.9 km/s), 3-5 km in thickness and 15-20 km in depth.

South of the fault belt the continental shelf is underlain by thinned crust (mainly 22-27 km). The Pearl River Mouth Basin (PRMB) is a large rift basin with Cenozoic sediments up to more than 10 km.

The Northern and Southern Depression zones

The Northern Depression Zone includes the Zhu-1 and Zhu-3 depressions in PRMB, while the South Depression Zone includes the Zhu-2, Shenhu, and North Xisha depressions (Figs. 1, 3, 4 and 5). The NEE- or NE-trending rift depressions are major oil bearing areas of PRMB. So far, high oil-producing reservoirs are found in the western Zhu-1 depression and northwest margin of Dongsha Uplift, and a few on the uplift.

Studies of more than 40 wells (Li, 1989) revealed that the basement is composed of partially metamorphosed sedimentary rocks of Hercynian Fold belt in the east and Caledonian Fold Belt in the west. This basement was intensively disturbed by granitic intrusions with K-Ar ages of 76-130 Ma, belonging to the 4th and 5th episodes of the Yanshanian movement. These may be I-type granites, similar to the widespread Yangshanian granites along the South China coast. The granites and associated volcanic rocks comprised a magmatic arc associated with the Mesozoic active continental margin along East Asia.

Our gravity data show that the crustal thickness is 25-26 km for the Zhu-1 and Zhu-3 depressions and 22 km for the Zhu-2 Depression (Fig. 7). The "mirror relationship" between the depression and the Moho surface is seen in Figs. 3-5. In the eastern and western segments the Moho surface is basically NEE oriented, while in the central segment of PRMB (the Panyu Low Uplift and the Zhu-2 Depression) the Moho is highest (22 km in depth) and nearly E-W or NWW oriented, and the depression is the

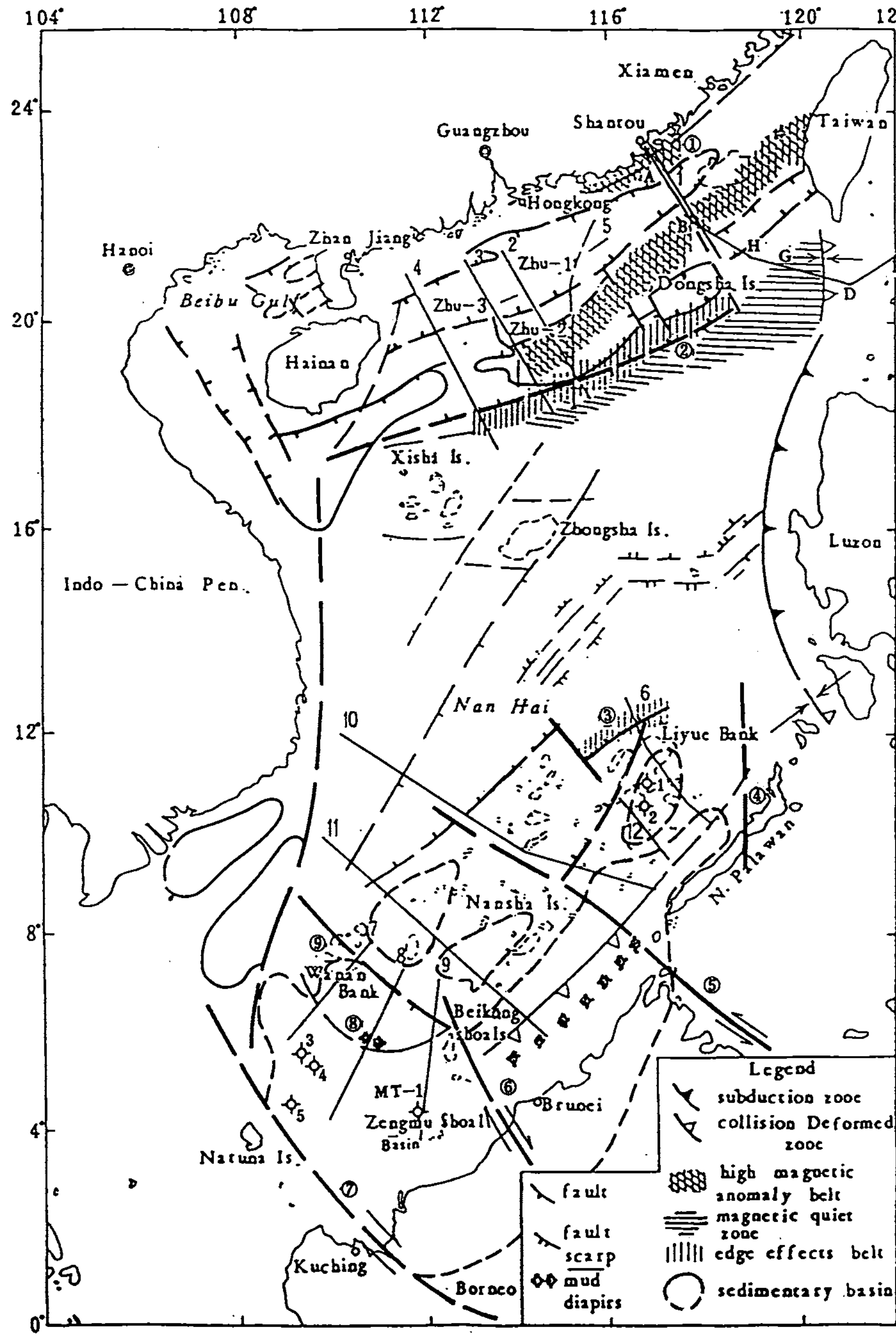

Figure 1. Simplified map showing survey lines and geological structures. The code for wells are A-1 (1), Sampaguita-1 (2), AP-1 (3), AL-1x (4), the well on the Paus-Ranas Uplift (5).

deepest (> 10 km) (Fig. 3). The clockwise contortion of the Moho isobaths (Fig. 7) suggests the existence of two NW strike-slip faults along the western and eastern borders of the central segment. These faults played an important role in the "E-W segmentation" of PRMB.

The Central Uplift Zone.

This NE-striking uplift zone, lying in between the Northern and Southern Depression zones, consists of the Dongsha Uplift and the Shenhu Uplift. To the northeast it connects the Taiwan Shoal and the Penghu Uplift, forming a large uplifted zone in the northern continental margin of SCS (Fig. 1). Some exploration wells in the Dongsha Uplift encountered Early Paleozoic migmatite and metamorphic rocks with metamorphic age of 70-90 Ma (Li, 1989). Gravity data show that the crust thickness in this uplift zone is generally greater than 29 km, thicker than that in the depression zone to the north and the south.

A belt of high magnetic anomalies appears in

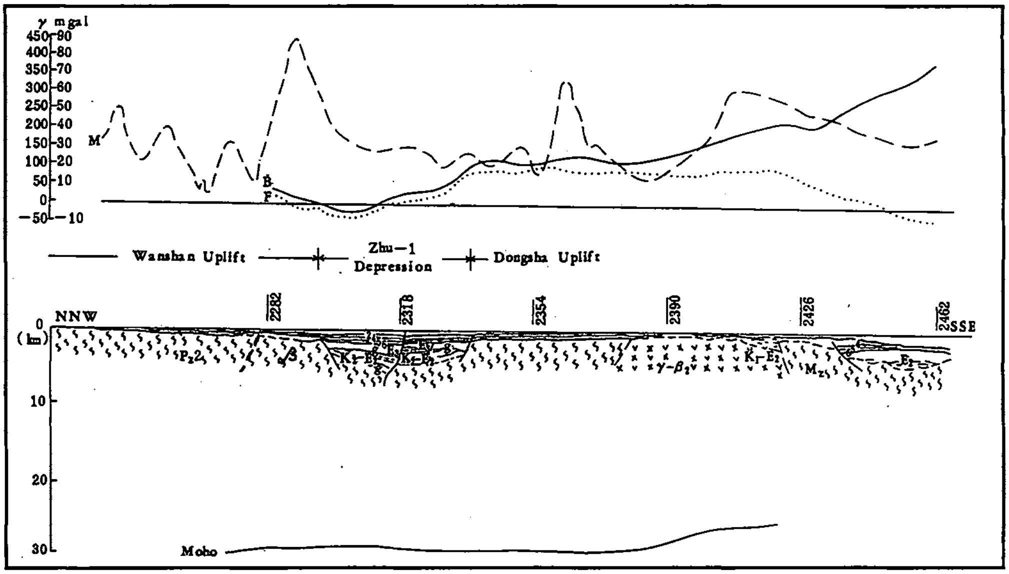

Figure 2. The geological and geophysical explanation of Line 1.

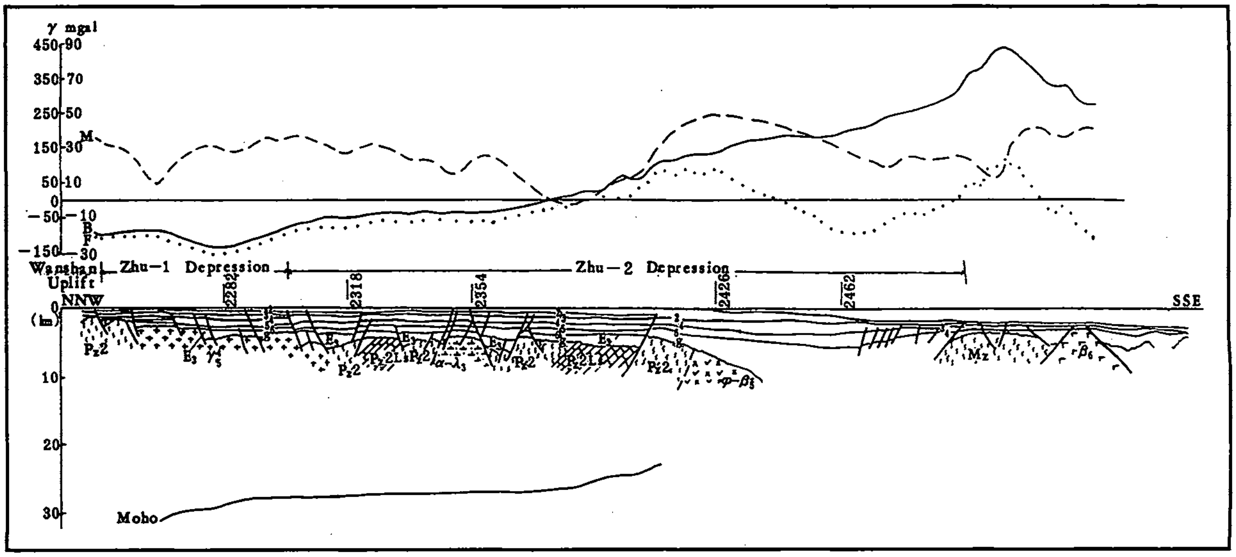

Figure 3. The geological and geophysical explanation of line 2.

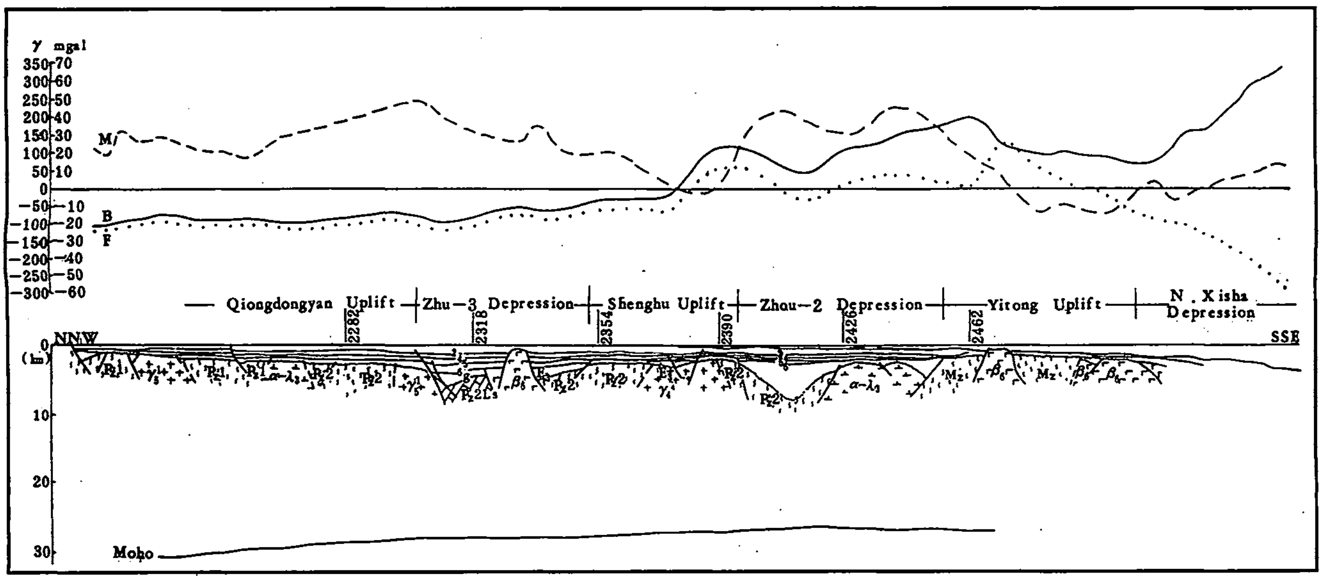

Figure 4. The geological and geophysical explanation of line 3.

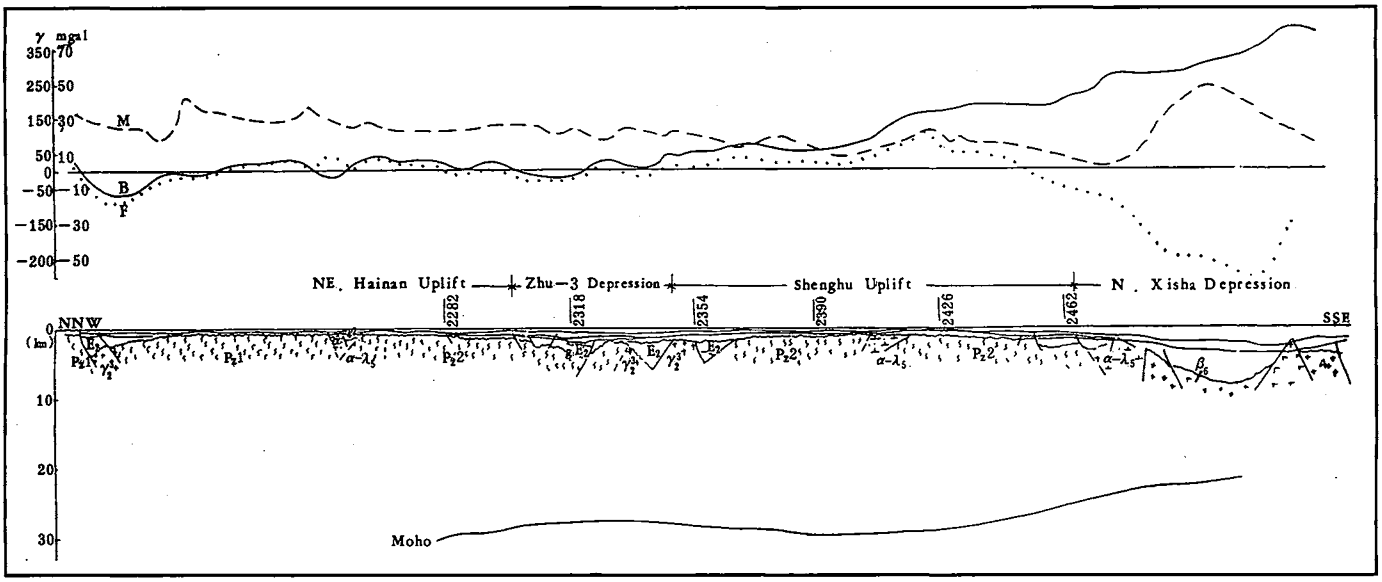

Figure 5. The geological and geophysical explanation of line 4.

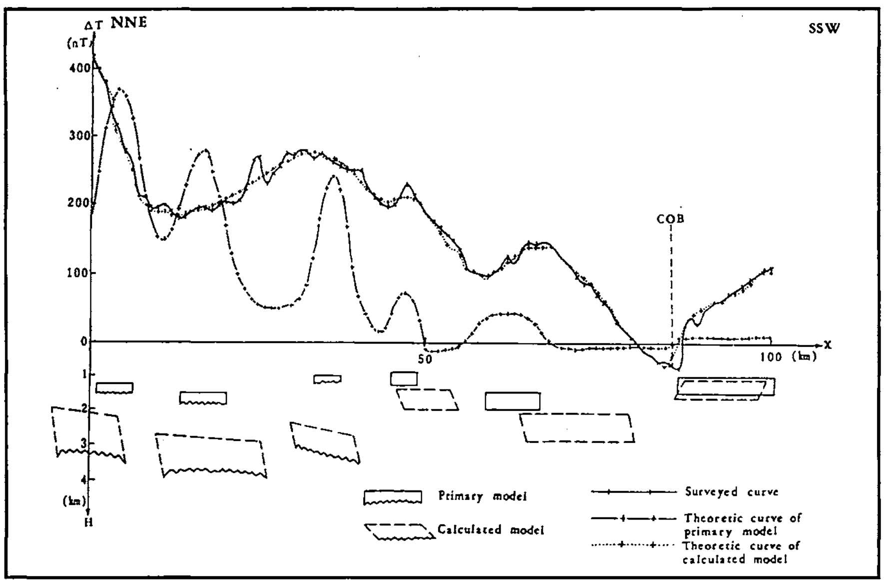

Figure 6. The inverse curve of the magnetic anomaly (ΔT) of the southern segment of line 5 southwest of the Dongsha Islands (Zhang, pers. comm.).

the Dongsha Uplift and the Zhu-2 Depression, and continues westwards to the Shenhu Uplift. The whole anomaly zone is approximate 450 km in length and 50-70 km in width. The zone bends at 115°50'E, with a NE strike to the east and a NEE strike to the west. In the eastern and central portions, anomalies are high with a maximum over 350 nT and averaging approximately 300 nT. In the western portion the anomalies are slightly lower, generally less than 200 nT, with a maximum of 250 nT. The shape of anomalies are similar to that in the east. These high magnetic anomalies are the indication of basic rocks. Inverse calculations suggest that the rock bodies are thin and horizontally finite plates (Fig. 6), different from the vertically infinite ones in the central basin of SCS. The depth is generally 1-2 km in uplift areas to the east and 2-3 km in depression areas. Four wells in the Dongsha Uplift penetrated alkali basalt of 45.1-17.1 Ma in age (Liang and Li, 1992). In the Penghu Islands, alkali tholeiitic basalt and alkali basalt of 16.2-8.2 Ma age are observed (Juang and Chen, 1992). These were intraplate eruptions and indicate that the northern margin of the SCS was an extensional passive margin in the Cenozoic era.

The Slope Fault Belt

A major finding of the Sino-US expanding seismic profiles in the northern SCS is a great north-dipping lithospheric fault extending along

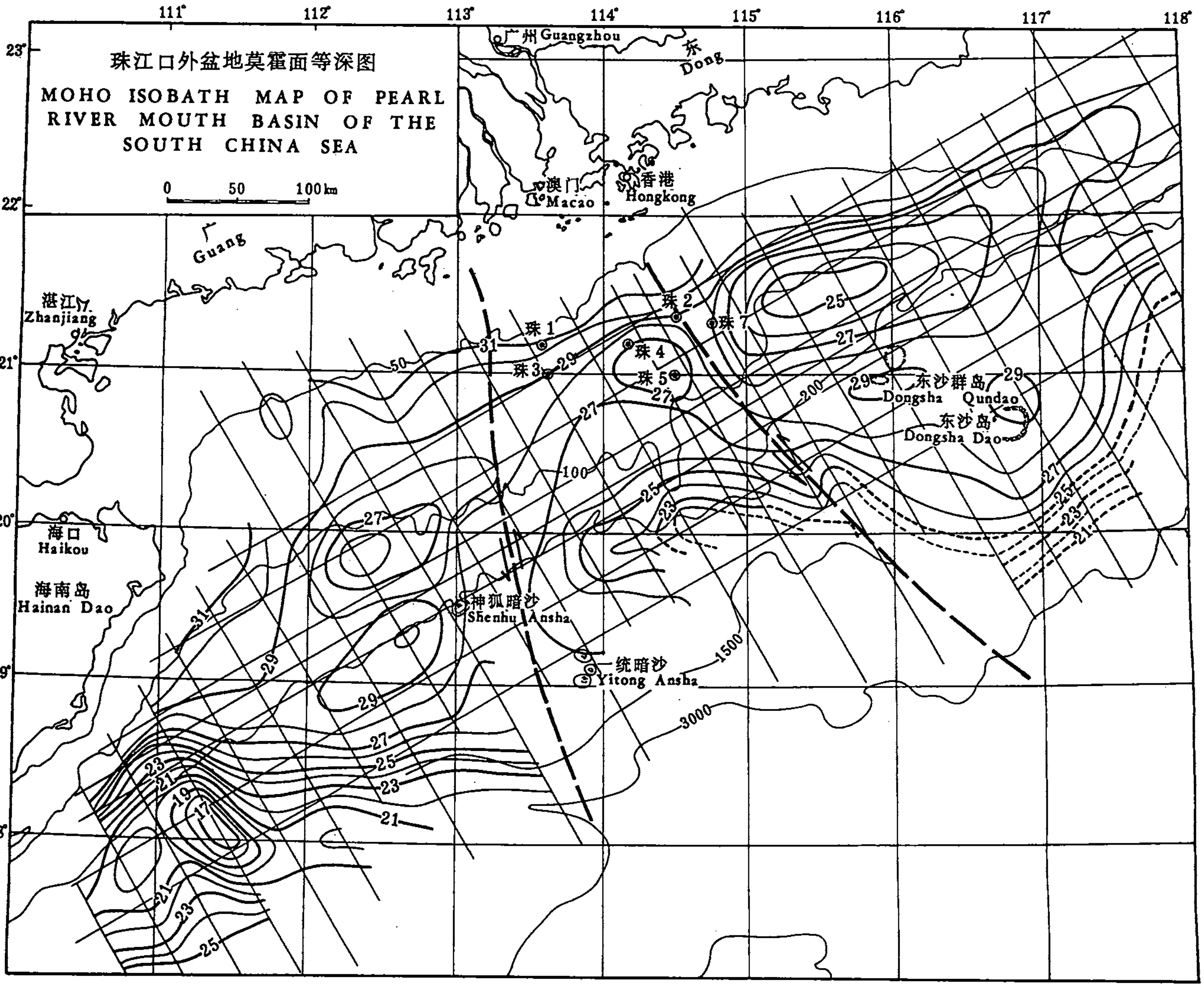

Figure 7. The Moho isobath map of the Pearl River Mouth Basin.

the lower continental slope (Yao, pers. commun.). This fault cuts through the basement to the Moho surface, but did not involve the Tertiary sediment cover. The lower part of a Moho gradient belt identified on our gravity data (Fig. 7) coincides with the fault. Some small and shallow earthquakes occurred in the eastern portion of the fault. This fault may extend further westward but this cannot be confirmed due to lack of deep seismic data (Fig. 8).

The Magnetic Quiet Zone

South of the lower slope of the northern SCS there is a zone of low amplitude and low gradient magnetic anomalies (Figs. 1, 9 and 10), in significant contrast to the strong and linear anomalies in the Central Basin of SCS. This magnetic quiet zone is about 60-80 km in width south of the Dongsha Uplift and widens NE-wards to about 195 km near the northward continuation of the Manila Trench at 120°20'E and 21°20'N. Figure 11 shows the interpretation of a geophysical profile from offshore East Guangdong to the Bashi Strait. The magnetic quiet zone appears in between the foot of the continental slope and the collision thrust belt at the northward continuation of the Manila Trench. Free-air gravity anomalies are low and negative in this belt. In the seismic profile, the basement has disordered reflections unlike the reflections of the sediment strata (Fig. 12).

DOMINANTLY COMPRESSIONAL SOUTHERN CONTINENTAL MARGIN

The southern continental margin of the SCS includes the Nansha Islands (the Reed Bank and the Dangerous Ground), the Nansha Trough, and the northwestern continental shelf of Sarawak, Sabah and Palawan. Major structural elements from the north to the south are as follows (Fig. 1):

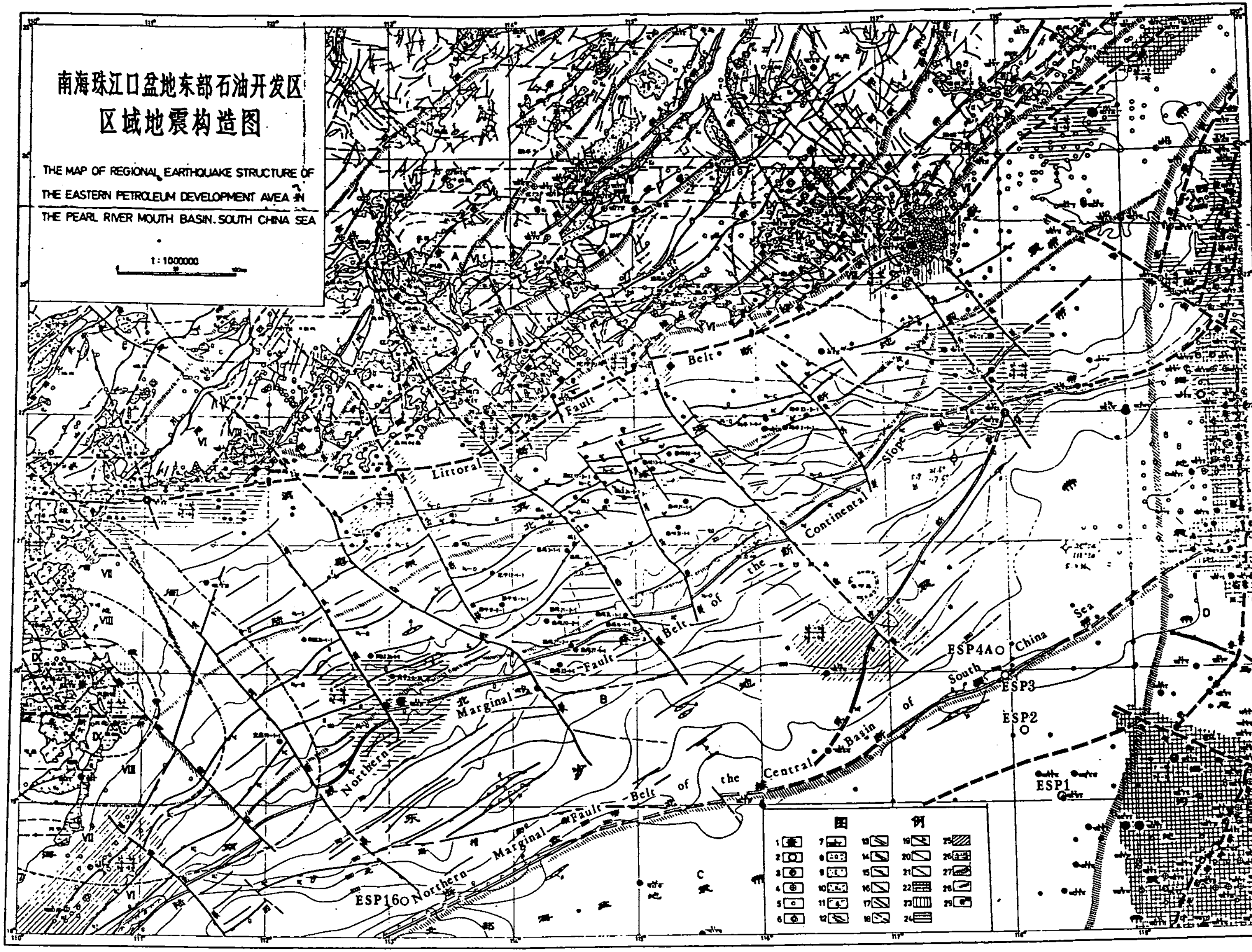

Figure 8. The map of regional earthquake structure of the eastern petroleum development area in the Pearl River Mouth Basin, South China Sea. Note the Northern Marginal Fault Belt of the Central Basin of South China Sea. Its eastern segment is close to the great north-dipping lithospheric fault, which crosses between ESP4A and ESP3, and its western segment coincide with the lithosphere fault (south of ESP16).

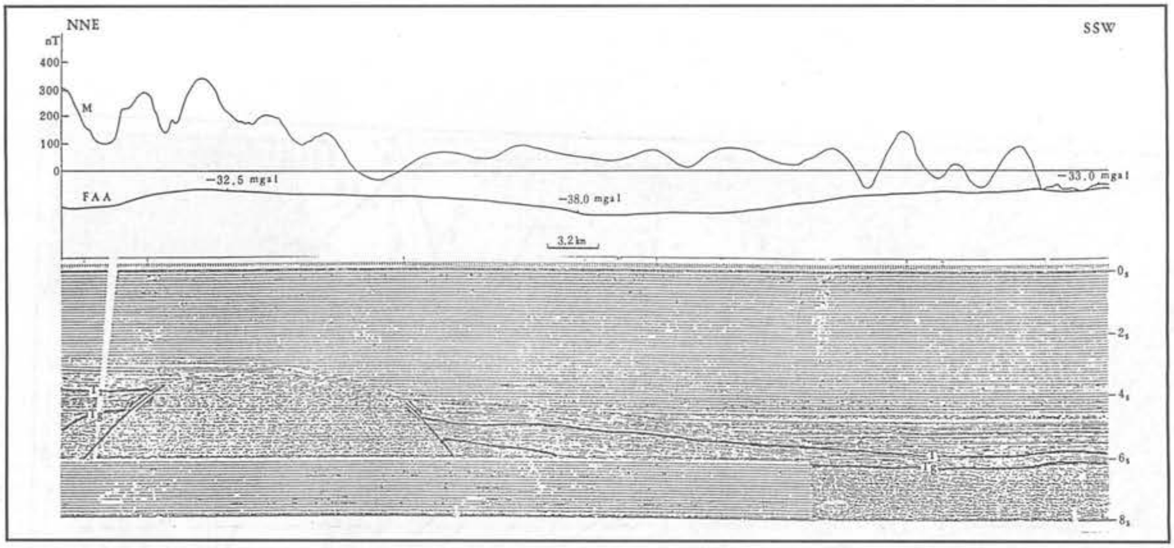

Figure 9. The comprehensive profile of Line 5, showing the magnetic quiet zone in the northern SCS.

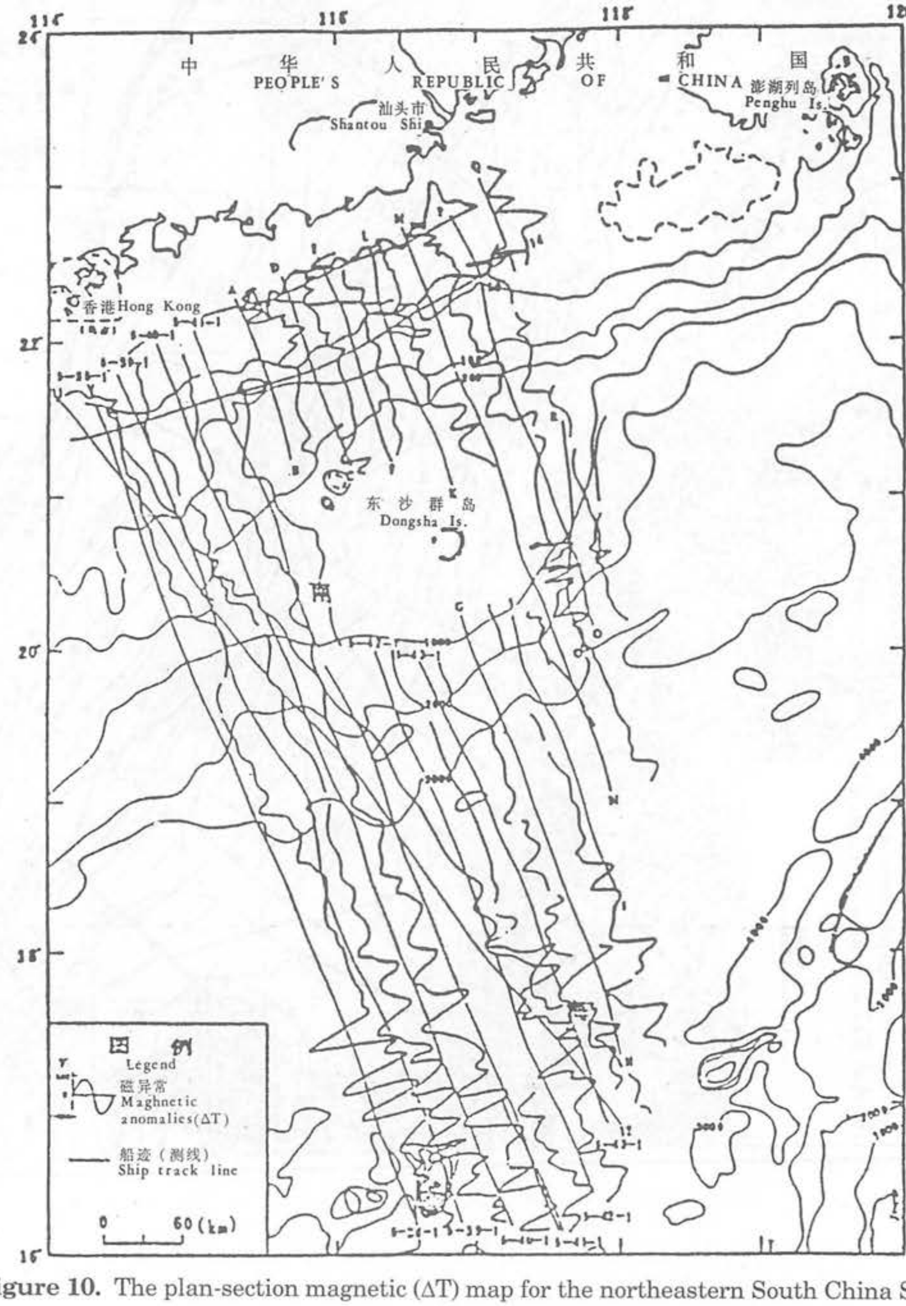

Figure 10. The plan-section magnetic (ΔT) map for the northeastern South China Sea.

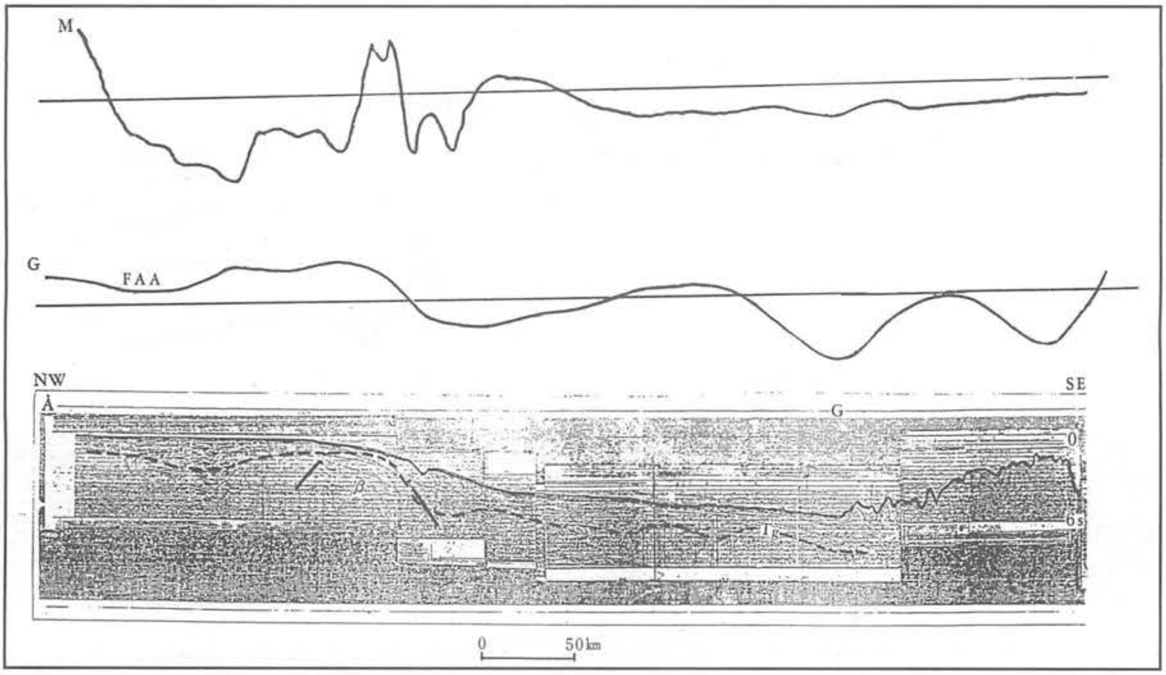

Figure 11. The interpretation of the comprehensive geophysical profile from Shatou to the Bashi Strait to the western Philippines (the A-B-H-G-D-E-F profile in Fig. 1).

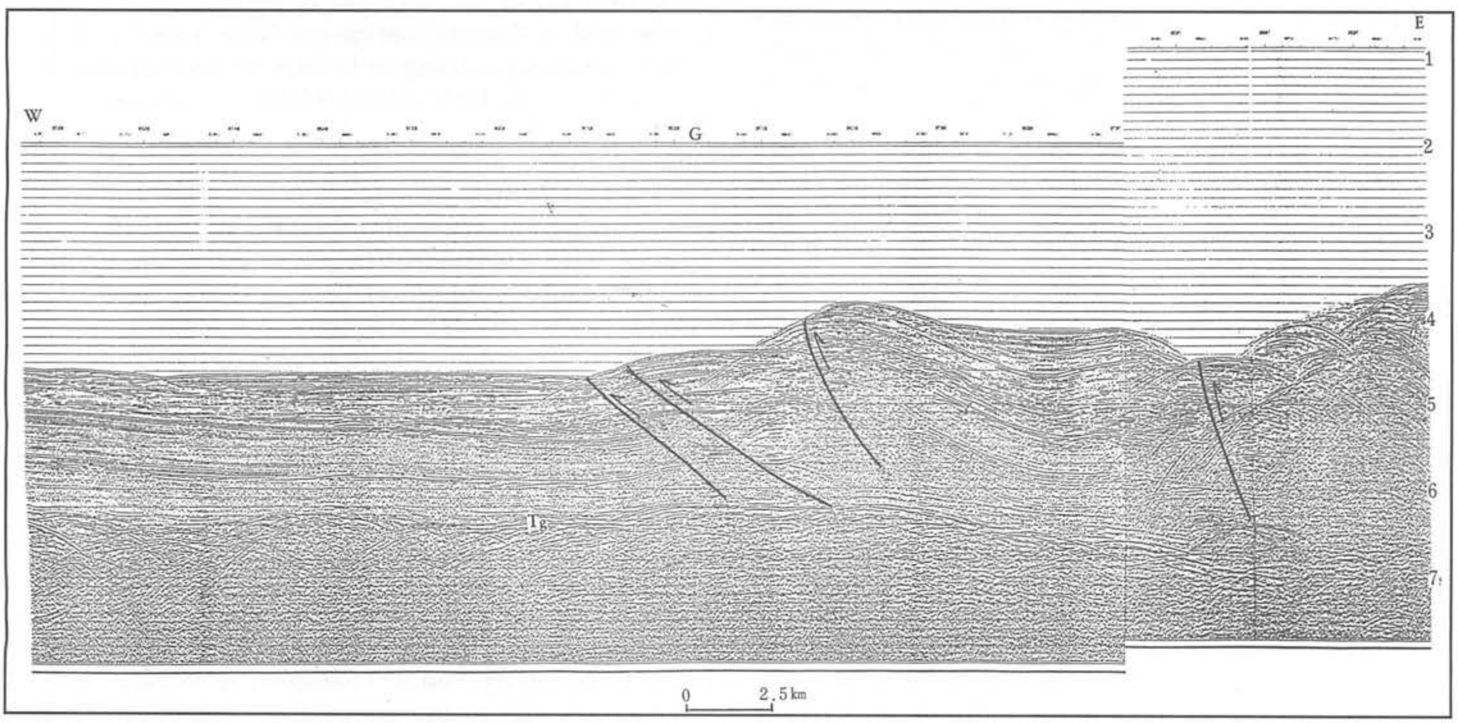

Figure 12. The collision structures seen at the segment G of Figure 11.

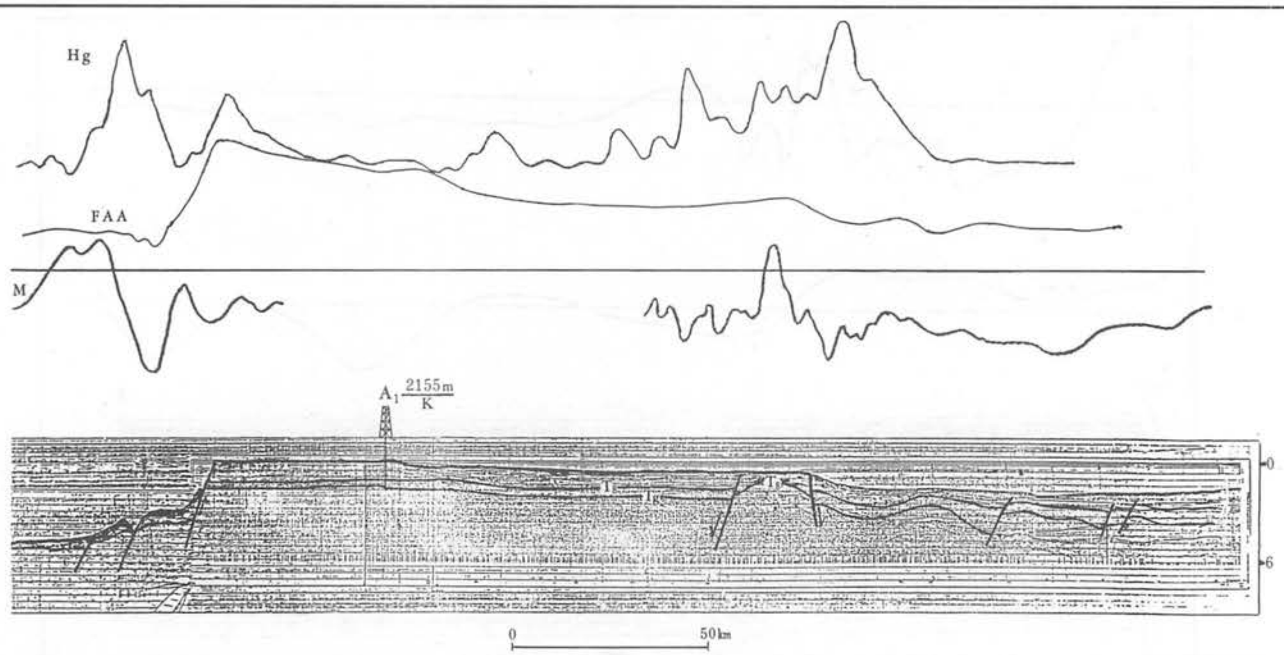

Figure 13. The comprehensive profile of Line 6 across the Northern Fault Belt of the southern continental margin of SCS.

The Northern Fault Belt

It is a NE-striking fault belt that separates the oceanic crust of the central basin of SCS with the continental crust of the Nansha block (Fig. 1 (3)). This fault is clearly shown by a combination of positive and negative free-air gravity anomalies respectively on the continental side and the oceanic side (Fig. 13), and is referred to the "edge effect" (Su and Huang, 1987). Compared with the northern margin of the SCS, the southern margin has more significant "edge effect". The gravity anomaly varies as much as 110 mgal in the distance of only 18 km. Computer simulation shows that the fault plane between oceanic and continental crusts is almost upright and more steep than that of the northern boundary. No magnetic quiet zone is found between the two types of crust, and the magnetic lineations in the oceanic crust are very clear.

The Nansha Block

This is a micro-continental block composed of about 400,000 km^2 underwater plateau with over 190 islands, reefs, and shoals. The block is surrounded by faults. It is separated from the deep-sea basin of the SCS to the north and northwest by the Northern Fault Belt, from the Sarawak-Sabah Block to the south by the Crocker Thrust Belt, from the Palawan-Calamian Block to the northeast by the Ulugan Fault (Fig. 1 (4)), and from the Sunda Shelf to the southwest by the Lupar Fault (Fig. 1 (7)). Simulation based on free air gravity anomaly map (Fig. 14) indicate that the Nansha Block has a transitional crust with thickness about 20-25 km (Su *et al.*, unpubl.).

On our multichannel seismic profiles three significant structural layers (mega-sequences) are identified (Jiang and Zhou, 1993). The Upper Structural Layer is composed of shallow marine clastic and carbonate sediments with relatively uniform thickness, strong and continuous reflectors, and a velocity mostly less than 3.0 km/s. This layer is tentatively dated as Late Oligocene to Quaternary.

The Middle Structural Layer is widespread and consists of 1-3 km, generally over 2 km thick, neritic clastics with clear stratification, intermediate seismic frequency, amplitude and continuity, and a velocity generally 3.8-4.5 km/s. According to correlations in seismic reflection characteristics and with limited and distant wells, the Middle Structural Layer is tentatively dated as Paleogene. The Eocene clastic rock encountered by the TM-1 well at 285 km, 3°59'45"N and 11°08'44"E (Soeparjadi, 1985), may represent its upper portion (Fig. 23).

The Lower Structural Layer is the acoustic basement with discrete, weak, and low-frequency reflections, and a velocity usually greater than 5.0 km/s. It is interpreted as composed of Mesozoic sedimentary and metamorphic rocks complicated by acid to basic extrusions and eruptions, similar to the basement for the northern margin of the SCS. The oldest basement rocks so far found are the Late Triassic to Early Jurassic shale and sandstone dredged east of the Meiji Reef southwest of the

Liyue Bank (the Reed Bank) (Kudrass *et al.*, 1985). This rock may be correlated with the outcrop of radiolaria-bearing rocks of lower Mid-Triassic sequence in Calamian. Fontaine *et al.* (1983) proposed a Jurassic Tethys in Southeast Asia according to stratigraphic data. Early Jurassic marine sequence dominantly distributes in South China and Indochina Peninsula, and the Late Jurassic one mainly in the south, such as Sarawak, Mindoro, Calamian, North Palawan, and Sumatra. The Jurassic marine strata drilled offshore west of North Palawan (Fontaine *et al.*, 1983) is inferred to exist in the Nansha block. The Sampaguita-1 well in the Liyue Bank encountered over 700 m of Lower Cretaceous inner marine sequence (Taylor and Hayes, 1980). Its lithological feature indicates a terrigenous source. The structure and stratigraphy of the Liyue Bank are similar to those of Mindoro, Calamian, and North Palawan. They originated from the continental margin of South China.

The Nansha Block may be further divided into four major units, the Zhenghe, Yunqin, Liyue, and NW Sabah-Palawan provinces (Fig. 1). Locations of their boundaries are basically conjectural at present.

The Zhenghe province, or called the Zhenghe Uplift, lies in the north-central portion of the Nansha Block. This is an area of extended uplifting (Fig. 15, the central segment). In the uplift, the Upper Structural Layer is relatively thin (usually about 1 km or less); the Middle Structural Layer absent or very thin. Even in small and discrete half grabens the Tertiary infill hardly exceeds 2.5 km. The basement was often metamorphosed, such as the Upper Jurassic amphibolite and the Lower Cretaceous schist dredged northwest of the Liyue Bank, and the Lower Cretaceous paragneiss dredged north of the Meiji Reef (Kudrass *et al.*, 1985). Vague stratification in the basement can be seen in some portions of the seismic profiles.

In the Yunqin province to the west, the Upper Structural Layer is also thin, but the Middle Structural Layer is rather thick. A distinct feature of this sub-block is the widespread deformation of the Middle Structural Layer into asymmetric folds (Fig. 17). The unconformity above this deformed layer is tentatively dated as Late Eocene. The corresponding compressional event is called the Nansha Movement, which was contemporaneous with the first phase of the Zhu-Qong Movement in the northern margin of SCS, but under a totally different stress regime.

A common feature for the Zhenghe and Yunqin provinces is the relatively strong Quaternary deformation which is, at least partially, responsible for the rough topography in these areas. The Upper Structural Layer is gently undulated and locally even totally eroded away. Seamounts of very young basalt are often seen.

The Liyue province is located east of the Zhenghe Uplift. It differs from the other two sub-blocks by having a relatively thick (1.5 km to more than 2 km) and undeformed Upper Structural Layer, and a thick and tilted Middle Structural Layer (Fig. 19). The Late Eocene compression and Quaternary undulation has little effect in this region. The basement was not or only slightly metamorphosed, such as the Upper Triassic to Lower Jurassic deltaic sandstones and siltstones dredged east of the Meiji Reef (Kudrass *et al.*, 1985) or those encountered by the Sampaguita-1 well (Taylor and Hayes, 1980).

The NW Sabah-Palawan province includes the Nansha Trough Basin and the NW Palawan Basin. These are mainly foreland basins associated with the NW-ward thrusting of the Sabah-Palawan block (Hinz and Schluter, 1985), but the Middle Structural Layer under the NW flank of the NW Palawan basin was subjected to strong tilting.

The Zengmu Basin (the Great Sarawak Basin)

This Tertiary basin lies southwest of the Nansha Block. The basin is confined by NW-SE strike-slip structures, including on the west side the dextral Lupar Fault, Fig. 1 (7), on the east side the sinistral Sabah shear zone, Fig. 1 (5), and in the middle the dextral Beikang-Tinjar Fault, Fig. 1 (6). The northern border is the generally NW-striking Wan'an Fault (Fig. 1 (9)), and the southeastern border is the compressive fault belt northwest of Sarawak and Sabah. The Paleogene Rajang Group constructed a folded basement of the basin. The thickest Cenozoic strata is over 9 km in this important petroliferous basin (Figs. 20 to 23).

The Wan'an-Beikang Fault Belt

It is an arc-shaped fault belt connecting the Wan'an and Beikang banks, about 300 km in length (Fig. 1 (8)). Figs. 20, 21 and 22 show the three profiles across the fault belt. This is a deep feature characterized by a deep Tertiary depression and a Moho rise. This is assumed to be the southwestern boundary of the Nansha Block. To the north, the Pre-Tertiary basement was deformed and faulted. Gravity and magnetic anomalies indicate low density and low magnetic materials. The depth of the magnetic basement, in accordance with the acoustic basement, varies in the range of 4-7 km. According to gravity data, the depth of Moho is estimated as 17-19 km. South of the fault belt, the acoustic basement is deeper with less deformation and faulting. Gravity and magnetic anomalies indicate high density and low magnetism. The

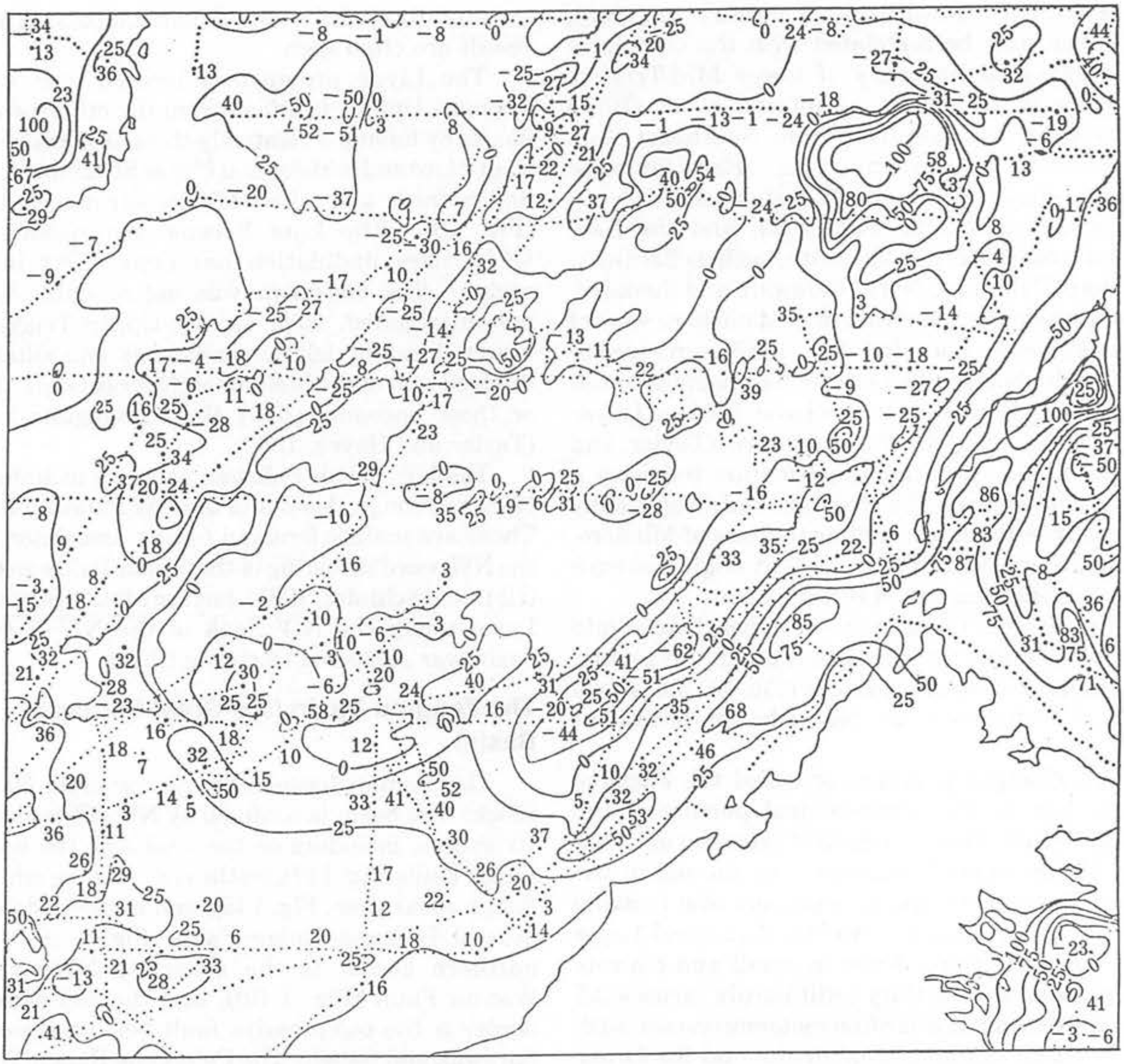

Figure 14. Free-air gravity anomaly map for the Nansha Islands and adjacent sea areas. Dots and adjacent numbers indicate the localities and free-air gravity values of the points used in the compilation. Contours are in mgal (Su *et al.*, unpubl.).

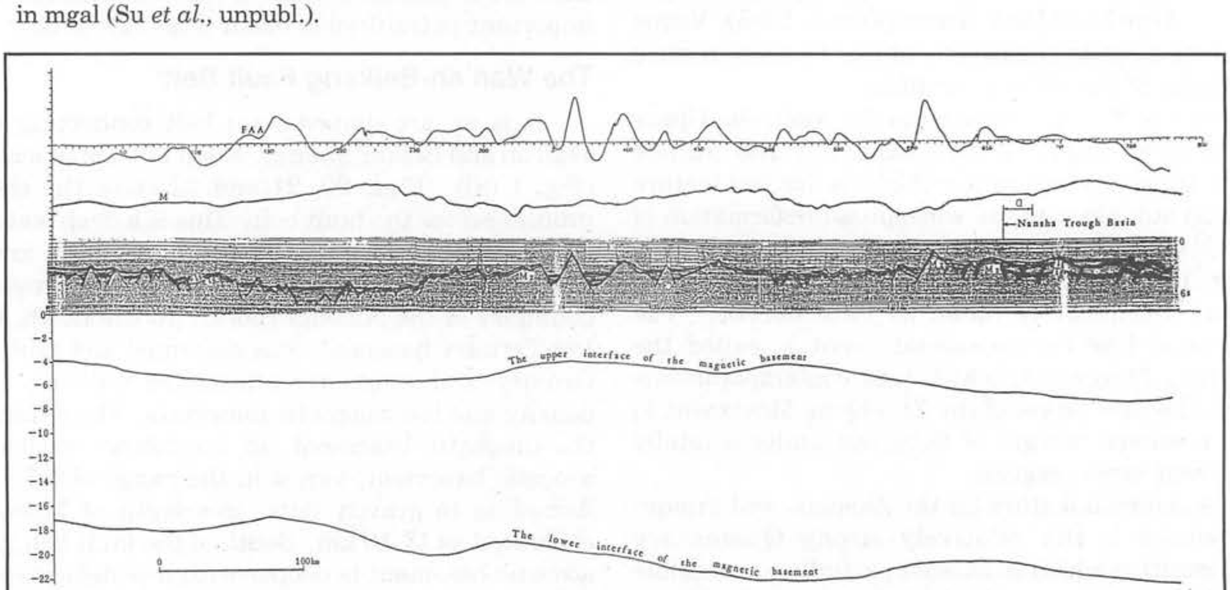

Figure 15. The comprehensive profile of line 10 across the Zhenghe Uplift (for location see Fig. 10).

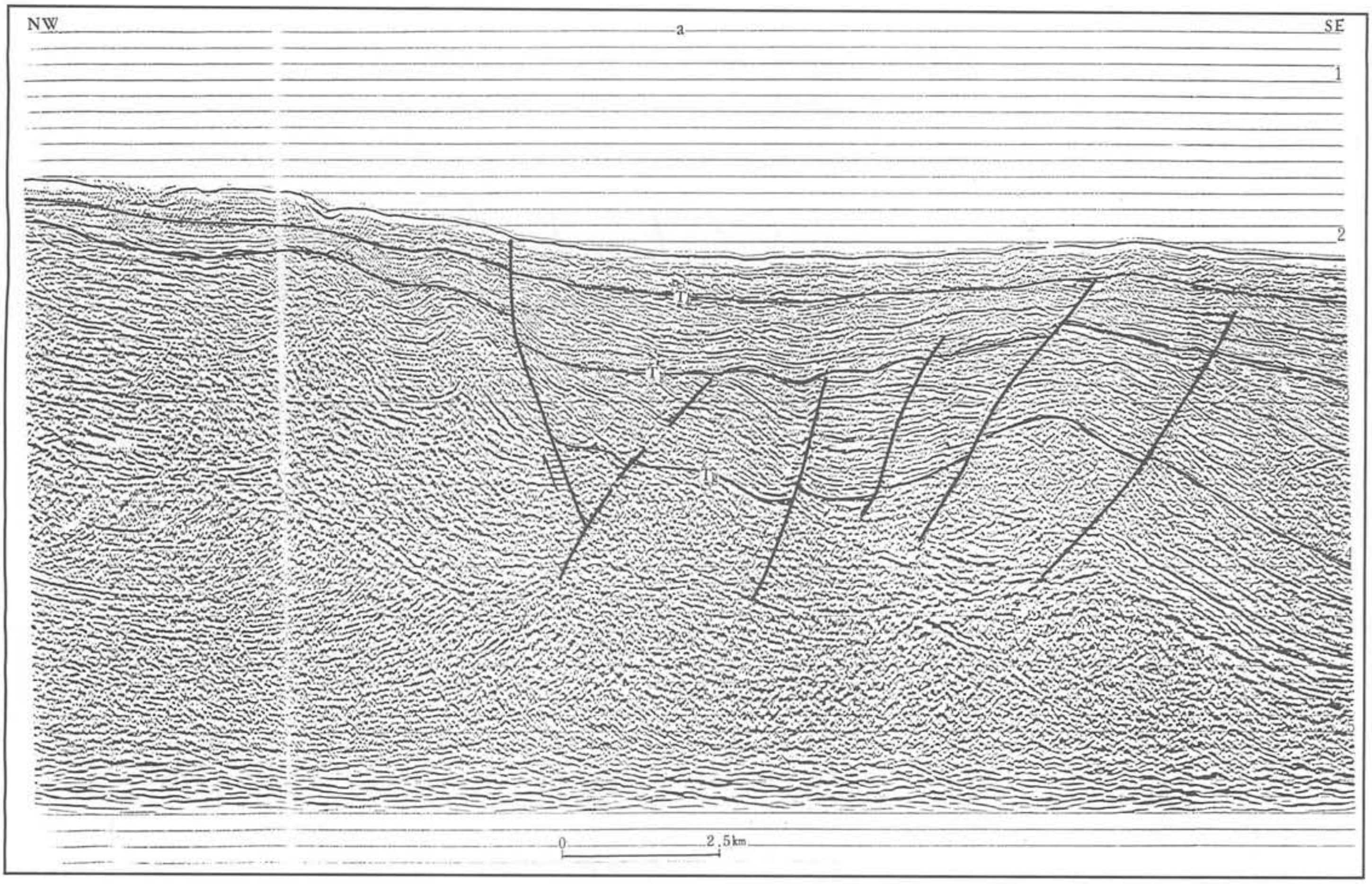

Figure 16. The seismic section of the southeast segment of the line 10 (the segment a in Fig. 15). Note the thick Middle Structural Layer (between T_8 and T_g) and underlying Mesozoic strata in the Nansha Trough Basin.

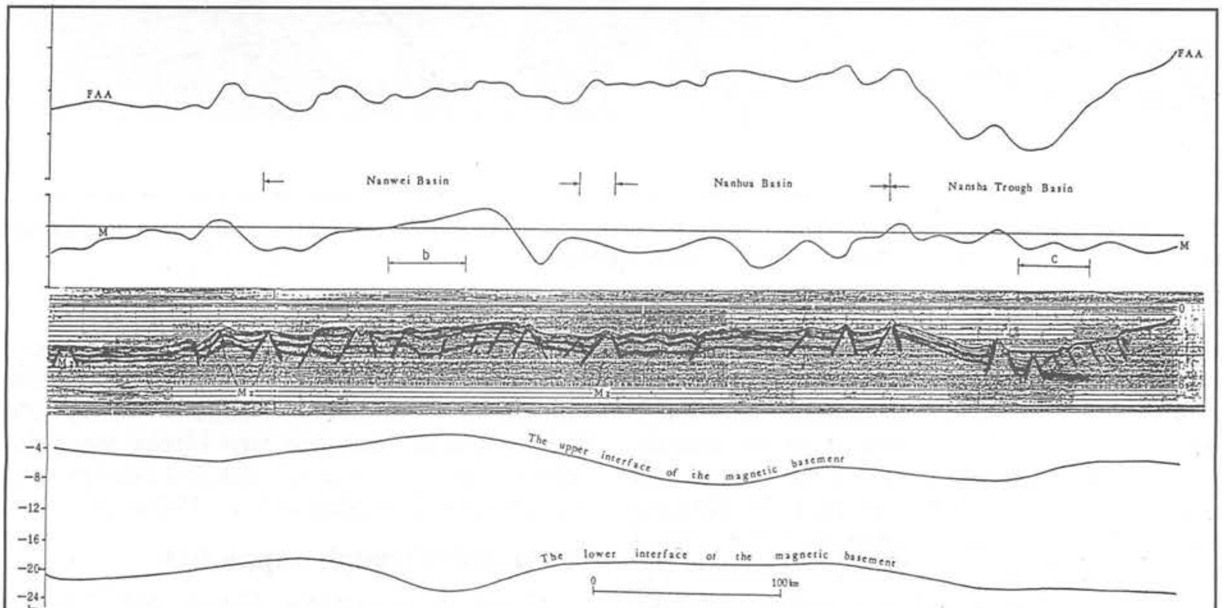

Figure 17. The comprehensive profile of line 11 across the Yunqin Sub-block (for location see Fig. 1), showing the asymmetric folds of the Middle Structural Layer.

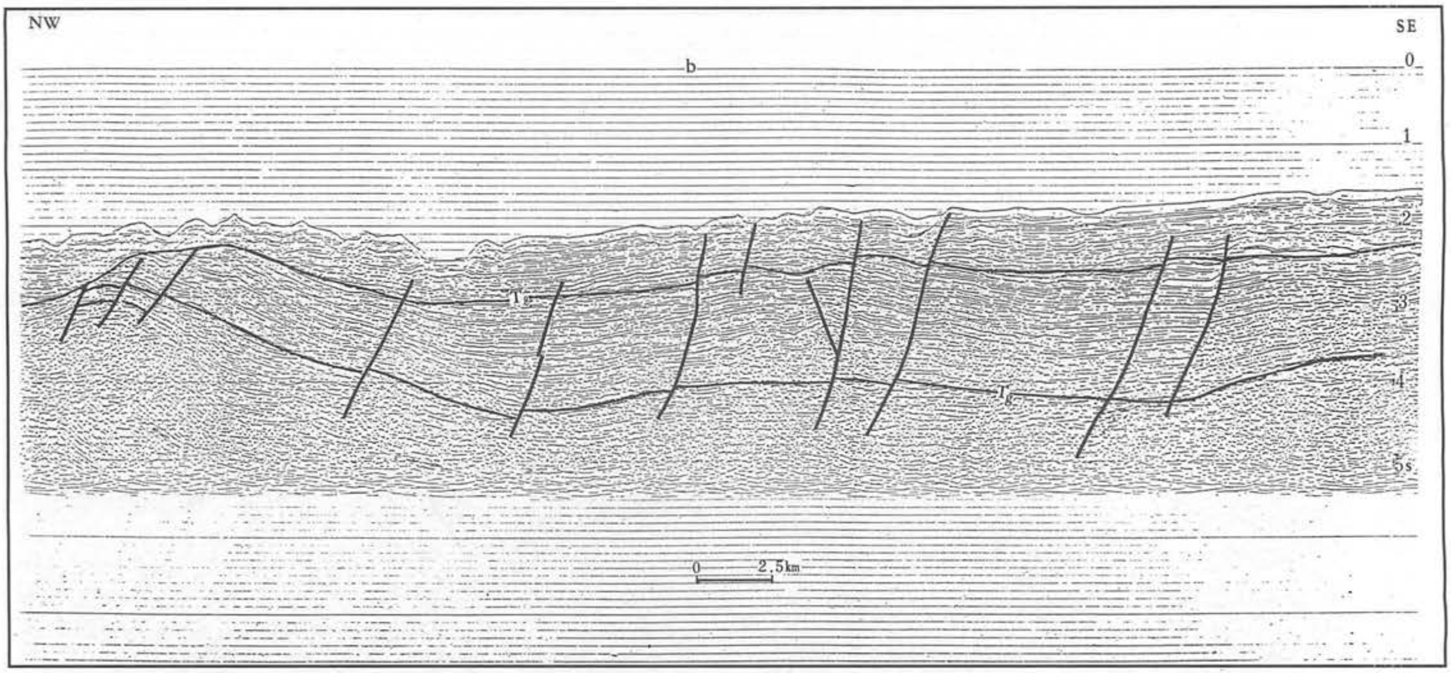

Figure 18. The seismic section of a segment of line 11 (the segment b in Fig. 17), showing the thick Middle Structural Layer and underlying Mesozoic strata in the Nanwei Basin.

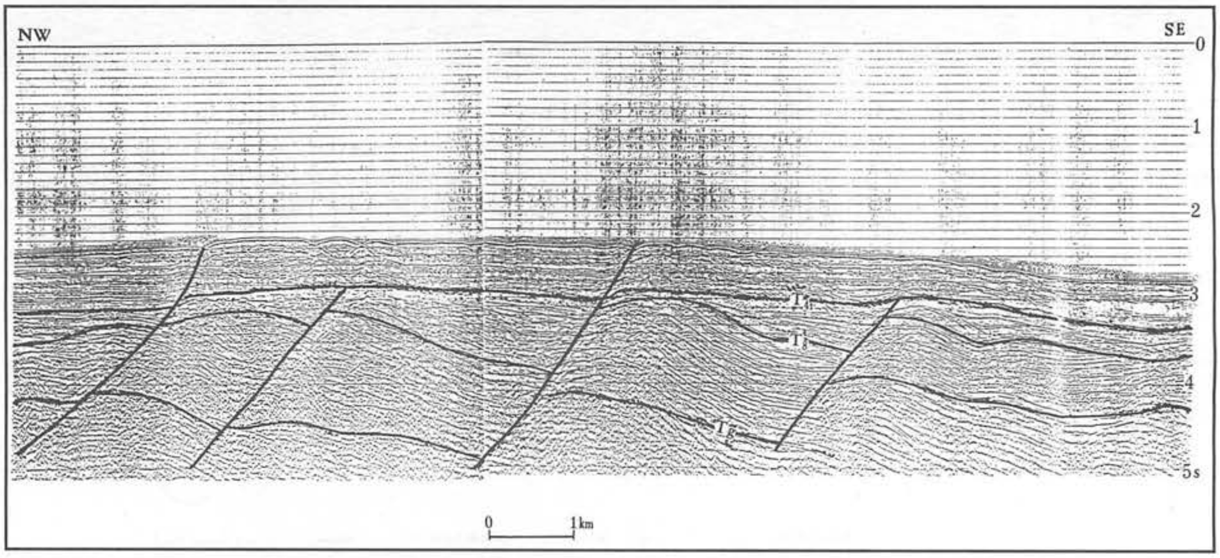

Figure 19. The seismic section 12 (the middle segment of Line 12 in Fig. 1), showing the Middle and Lower structure layers of the Liyue Sub-block (for location see Fig. 1).

gravity anomaly is reversed with the relief of seismic basement, while the magnetic basement is about 4 km deeper than the seismic basement. The depth of Moho is about 20 km according to the gravity data. The different geophysical fields on the two sides of the fault belt indicates that the Nansha Block has different basement features and crustal structure from the Zengmu Basin. In Line 8, the Moho surface rises 4 km and the depth of basement is over 9 km. The rise of Moho indicates a crustal extension. The heat flow is low north of the fault belt (two stations, 1.09 and 1.99 HFU, respectively). Many diapiric structures occur below the unconformity T_2 (between Paleogene and Neogene), which may be mud diapirs related to compression. It is assumed that the two blocks were in an extensional contact earlier, but had a compressional contact later, probably in Late Paleogene time.

The Nansha Trough Nappe Belt

Geophysical surveys offshore NW Sabah and South Palawan showed that the Lower Miocene carbonate platform extends from the Nansha Block SE-wards to beneath the southern Nansha Trough.

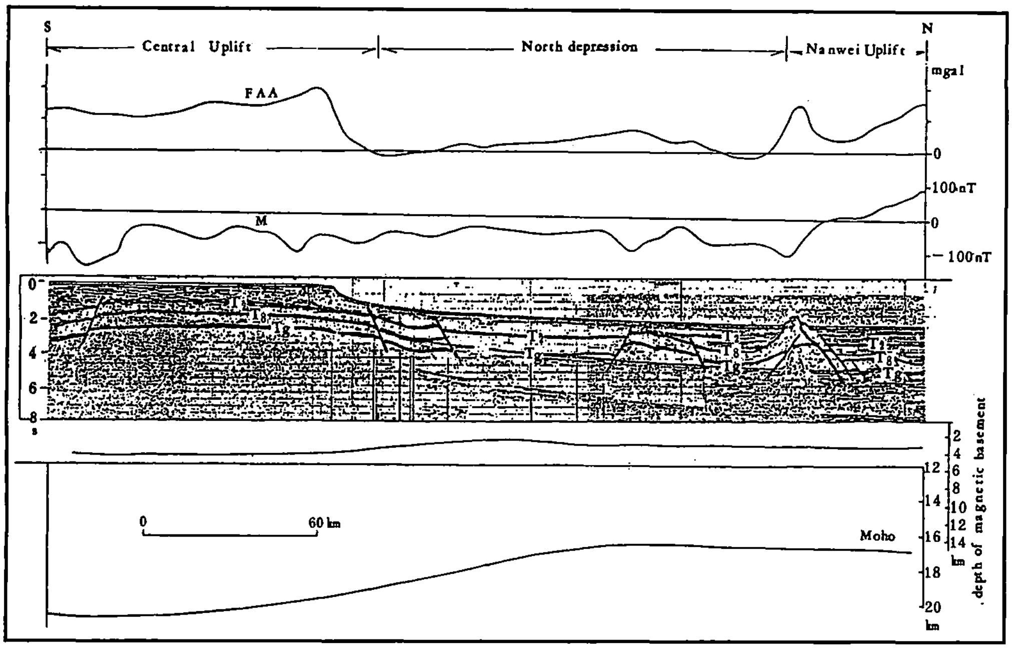

Figure 20. The comprehensive geophysical profile and its explanation of the line 7.

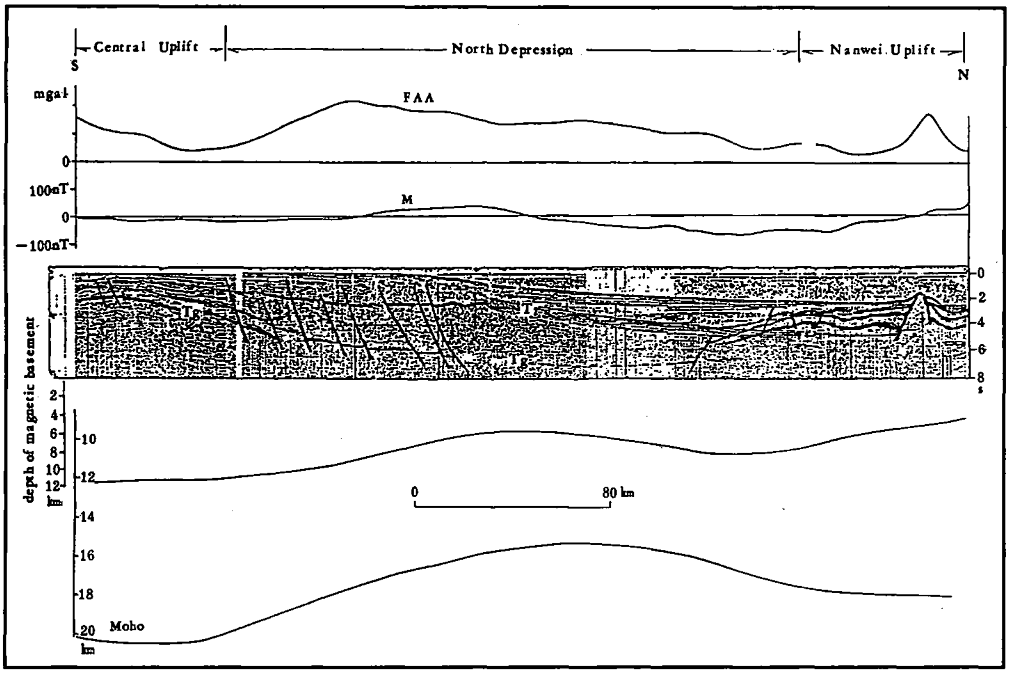

Figure 21. The comprehensive geophysical profile and its explanation of line 8.

Thus the Nansha Trough was not a Tertiary subduction zone, but rather formed as a gravity downwarp associated with the collision nappe in the southern Nansha Trough and NW shelf of Sabah and southern Palawan (Hinz and Schluter, 1985; Hinz *et al.*, 1989). Our seismic profile (Fig. 24) verified this conclusion.

SUMMARY AND DISCUSSIONS

1. The northern continental margin of the SCS is very different from the southern one in geological structures and geophysical fields. In general, the northern margin is a divergent margin, but the southern one is a convergent one. Gravity and magnetic anomalies of northern margin basically reflect the relief of Pre-Tertiary basement, especially the free air anomalies correspond well to the relief of acoustic basement. But for the southern margin, the crust is thinned, the Pre-Tertiary basement is less magnetized and has complicated relationships between gravity and magnetic anomalies and seismic basement. Free air

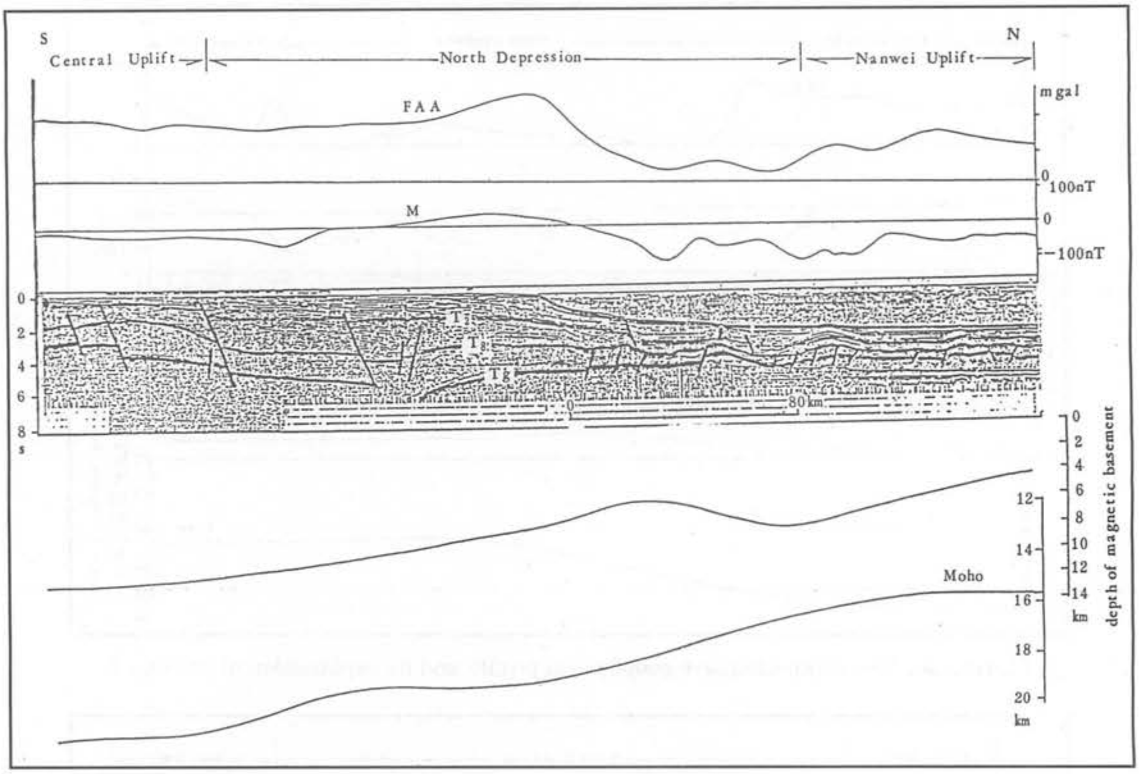

Figure 22. The comprehensive geophysical profile of Line 9 and its interpretation.

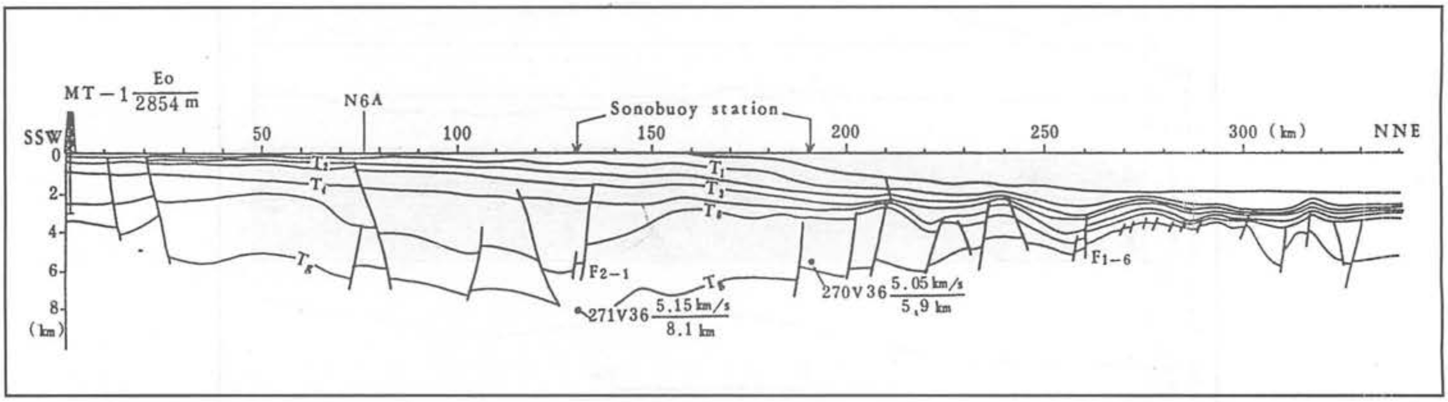

Figure 23. The interpretation of the seismic profiles of line 9. Locations of the TM-1 well (Soeparjadi *et al.*, 1985) and the sonobuoy stations 270V36 and 271V36 (Houtz and Hayes, 1984) are indicated.

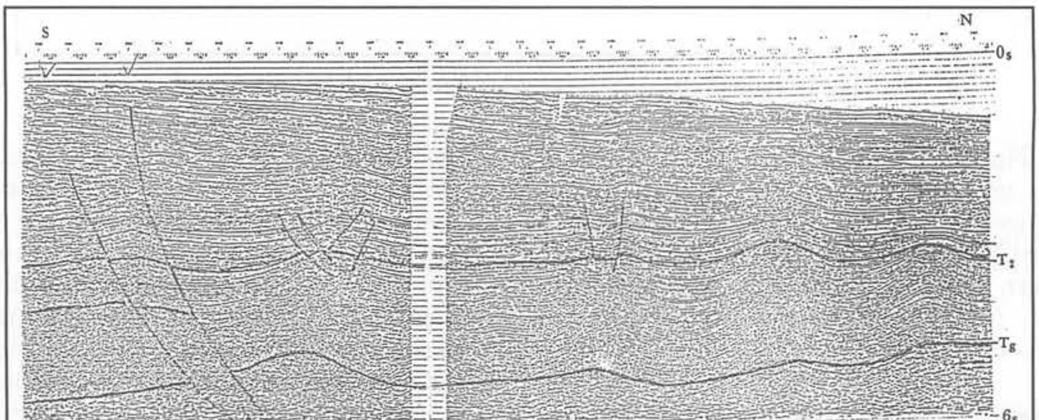

Figure 24. The mud diapir seen in the central segment of Line 8.

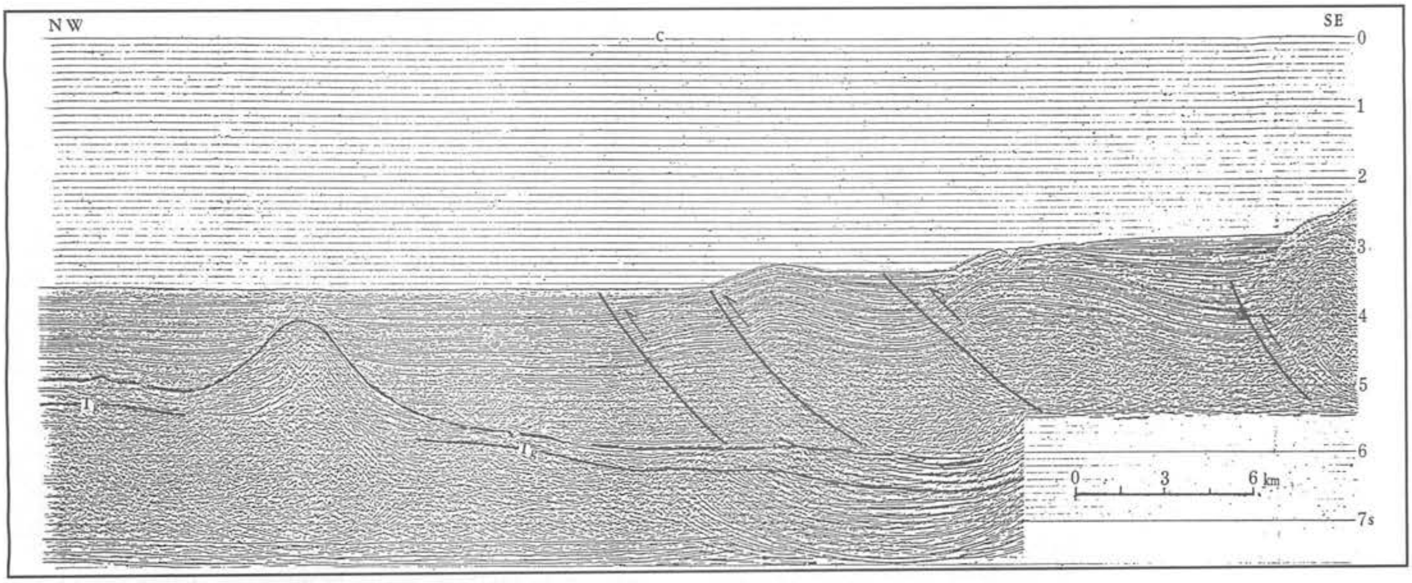

Figure 25. The seismic section of the southeast portion of the line 11 (the segment c in Fig. 1). The thrust structures in the Nansha Trough are clearly revealed.

gravity anomalies mainly show a regional positive high, while magnetic anomalies show a regional negative low. In the northern margin, the Littoral Fault belt demarcates the continental crust inland and the transitional crust offshore. Large earthquakes occurred along this fault belt. In the southern margin no such fault belt is observed. Although a significant convergence is indicated by geological and geophysical evidences along the Nansha Trough Nappe Belt, virtually no earthquakes have been reported there.

2. The northward dipping Slope Fault Belt is an important structural feature in the northern margin of the SCS. It may be a detachment developed during the extension process of the northern margin (Hayes, 1989). But we favour the interpretation of this fault as a portion of a Mesozoic subduction zone along East Asia (Yao, pers. commun.). The Late Yanshanian I-type granites and associated volcanic rocks found in the NE-striking Northern Depression Zone might represent a magmatic arc associated with this subduction zone, while the thicker crust in the Central Uplift Zone (including the Dongsha Uplift) might be formed by accretion along this subduction zone. The Magnetic Quiet Zone south of the Slope Fault Belt might represent the remaining piece of Paleo-Pacific oceanic crust.
3. The dating of the Middle Structural Layer in the Nansha Block and the compressional event affecting the layer has significant geological implications in terms of the evolution of SCS. If the layer is Paleogene and the compressional event occurred in the Late Eocene, as proposed in this paper, most parts of the Nansha Block was a continental shelf or shallow sea bordering the Southeast Asian continent which received relatively stable sedimentation. Only the Zhenghe Uplift was a part of land at that time, possibly adjacent to the Xisha and Zhongsha islands. The Nansha Block collided with Paleo-Borneo and was uplifted in Late Eocene, before the start of the opening of SCS. This collision resulted in a regional folding of the Paleogene strata. Rifting started in the land areas in Late Cretaceous or even earlier. Not until the Late Oligocene did the extension stress extended southward to the longshore areas and became strong enough to open the SCS. Later in the Early Miocene, the Borneo rotated counterclockwisely, probably about a pole near the center of the Borneo rather than west of the Borneo. The narrow Nansha Trough Basin was formed by the elastic downwarp of the Nansha block under the load of NW-ward overthrusting Sabah nappe, while the Zengmu Basin was formed by the extension west of the pole of rotation.

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