Cenozoic tectono-sedimentary characteristics and extension model of the Northwest Sub-basin, South China Sea

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Abstract Based on the interpretations of three seismic profiles and one wide-angle seismic profile across the Northwest Sub-basin, South China Sea, stratigraphic sequences, deformation characteristics and an extension model for this sub-basin have been worked out. Three tectonic-stratigraphic units are determined. Detailed analyses of extension show that the event occurred mainly during the Paleogene and resulted in the formation of half-grabens or grabens distributed symmetrically around the spreading center. Sediments are characterized by chaotic and discontinuous reflectors, indicating clastic sediments. Farther to the southwest, the sub-basin features mainly continental rifting instead of sea-floor spreading. The rifting would have been controlled by the shape of the massif and developed just along the northern edge of the Zhongsha-Xisha Block, rather than joined the Xisha Trough. After 25 Ma, a southward ridge jump triggered the opening of the Southwest Sub-basin. The NW-directed stress caused by the sea-floor spreading of the Northwest Sub-basin may have prevented the continuous opening of the sub-basin. After that the Northwest Sub-basin experienced thermal cooling and exhibited broad subsidence. The deep crustal structure shown by the velocity model from a wide-angle seismic profile is also symmetrical.
1. Introduction

The Northwest Sub-basin (NWSB) is one of three sub-basins of the South China Sea (SCS); the other two are East Sub-basin (ESB) and Southwest Sub-basin (SWSB) (see Fig. 1 for locations). The NWSB is the smallest one with a NE-SW orientation similar to a horn opening to the NE. The sea-floor dips from the SW to the NE with an average gradient of $(0.3-0.4) \times 10^{-3}$ degree, and water depth between 3000 and 3800 m. The NE-elongated Shuangfeng Seamount lies in the center of the NWSB with 2407 m of water depth above its top. The relative height above the surrounding sea-floor is over 1100 m. To the north is the northern continental margin of the South China Sea (SCS). The Zhongsha and Xisha Islands border its south and southwest. The Xisha Trough (XT) lies in the west and the ESB connects with the NWSB directly in the east. Episodes of continental rifting, volcanism and sea-floor spreading have co-shaped the NWSB into its current tectonic configuration. What’s more, the narrow size of the marginal rift basin and the close continental margins make this area an ideal natural geological laboratory to investigate continental rifting.

There is some disagreement about the spreading age of the NWSB. The scenario of the SCS opening proposed by Taylor and Hayes (1983) and Briais et al. (1993) has been generally accepted, i.e., sea-floor spreading took place from 30 to 16 Ma (anomalies 11–5c, the age according to the revised geomagnetic polarity timescale by Cande and Kent, 1995), complicated by two southward ridge jumps and a southwestward ridge propagation event. The NWSB started its sea-floor spreading between 30 and 29 Ma in a NW-SE direction, similar to the ESB. Between 29 and 25 Ma the sea-floor spreading ceased in the NWSB, while it still continued in the ESB with the direction changing to N-S. Another interpretation has it that the SCS opened in two stages, an early opening of the NWSB and SWSB at 40–33 Ma, and a later one of the ESB during 30–16 Ma (Yao et al., 1994; Li et al., 2007). Yao (1999a) identified one more sequence layer in the NWSB by correlating seismic profiles in the ESB and the NWSB, which made him consider that the NWSB geological age should be older than the ESB, and so a 42–35 Ma spreading age for the NWSB was proposed. A much earlier spreading age was argued by Wessmann et al. (1996), who thought that the NWSB opening might have started from the early Eocene or even the late Mesozoic, according to their interpretation of multi-channel seismic profiles across the NWSB, together with biostratigraphic assessment of the middle to late Oligocene foraminifera and mid-Eocene nannofossils (NP16–NP25) discovered in bathyal mud sampled from the south slope of the XT.

Besides the discrepancies of the spreading age, other key issues that are also enigmatic include the type of passive margin, e.g., is it either a volcanic or non-volcanic passive margin; and the

![Figure 1](image_url)  
Figure 1  Map showing the general topography in the mid-north of the South China Sea (Black lines are the seismic profiles. Red broken line is the wide-angle seismic profile). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
extension model, e.g., being a pure shear (McKenzie, 1978), a simple-shear (Wernicke, 1981), or an intermediate model (Lister et al., 1986).

This paper presents a seismic-stratigraphic analysis of the NWSB. Using 2D multi-channel seismic profiles acquired in this area (A joint Sino-Germany SO49 survey, 1987–1989), emphasis is given to place constraints on our understanding of the Cenozoic tectono-sedimentary evolution and dynamics of the NWSB and adjacent region. Efforts also contributed to the understanding of crustal structures and the basin extension model provided by a wide-angle seismic profile (OBS2006-1) carried out in 2006 by the Second Institute of Oceanography, SOA (See Fig. 1 for location). A joint analysis of these data improves our understanding of the rifting processes, including the degree of symmetry of rift structures, and thus address fundamental questions concerning the mechanism of rifting.

2. Geological setting

In the middle Jurassic, the southeast margin was an Andean type convergent margin with a basement of mainly meta-sediments of the Caledonian fold belt in the west and the Hercynian fold belt in the east (Taylor and Hayes, 1983; Zhou et al., 1995). The volcanism ceased by approximately 85 Ma (Clift and Lin, 2001). Since the paleo-stress field changed from compression to extension in the late Cretaceous or Paleogene (Taylor and Hayes, 1980; Zhou et al., 1995; Sun et al., 2009), episodic rifting with uplifting shoulders and erosion probably began in both the northern and southern continental margins of the SCS. The rifting propagated from north to south and from east to west, finally leading to sea-floor spreading of the SCS (30–16 Ma). The southern movement of the Zhongsha-Xisha Block (ZXB), which acted as the south margin, triggered the opening of the NWSB behind it. Cenozoic sediments in the ZXB are not thick. Well Xiyong-1 penetrated cratonized Proterozoic metamorphic rocks directly below the Miocene, which is similar to the Yangtze Block (Qiu et al., 2001). This suggests that the ZXB was once a part of the Yangtze Block.

The Free-air gravity anomalies of the NWSB are generally in an NE direction, while they change to an E–W direction to the east of 115°E (Fig. 2a). NW–SE-trending gravity anomalies also exist in the upper-left of the study area. Three gravity anomaly belts can be classified from north to south, i.e., the NEE-trending negative belt in the north (0 to −40 mGal); the NE–NEE orientation positive belt in the middle (0−40 mGal); and the negative belt in the south (0 to −30 mGal). The middle positive gravity anomaly belt corresponds with the Shuangfeng Seamount. The change of gravity anomalies from north to south shows the existence of high-density materials in the center of the NWSB, which might have been caused by mantle intrusion after the sea-floor spreading (Ding et al., 2002). The Zhongsha Islands have positive gravity anomalies generally over 30 mGal.

The orientation of the magnetic anomalies in the NWSB is also in a NE–ENE direction (Fig. 2b). These anomalies are stripped with long-wave lengths. Four magnetic anomaly belts can be noted from north to south, i.e., the NE-trending positive belt in the north (50 to 200 nT); the ENE-trending negative belt in the center (0 to 150 nT); the ENE-trending positive belt in the south (50 to 150 nT); and the ENE-trending negative belt on the southern edge (0 to −100 nT). This positive-negative array shows that the NWSB was formed by sea-floor spreading.

3. Seismic stratigraphy

Seismic sequence analysis includes identification of sequence boundaries and interpretation of the inner reflection of sequences, of which the former is the basis for establishing the sequence stratigraphic framework (Weimer, 1990). Three seismic profiles were analyzed during our research, comprising from west to east SO49-25, SO49-18 and SO49-17 (See Fig. 1 for locations). Data from key wells in the north continental margin, including wells BY7-1-1, PY33-1, LH10-1-1 and ODP 1148 were used to interpret seismic sequences against regional litho-stratigraphic units. The sequence boundaries in the sea basin are mostly identified based on borehole data and the seismographic characteristics, including reflection frequency, amplitude and continuity; and reflection termination (onlap, downlap and truncation). In general, a boundary can be traced and correlated in a certain area, and its type is determined by interpreting system tracts with reflection properties below and above the boundary. Because of the absence of well data, the ages of boundaries in the NWSB were dated according to the contrast with the northern continental margin (Gao and Bai, 2000; Li et al., 2002, 2005; Pang et al., 2007; Briais et al., 1993).

Results show that the NWSB is composed mainly of Neogene sediments, with a relatively thin Paleogene section. Three principle seismic units are recognized in the NWSB featuring particular reflection patterns, geological age, and internal structure (Table 1).
Subdivision of these units has not been attempted because of the lack of adequate sedimentary indicators in the seismic profiles.

### 3.1. Unit I (Paleogene)

The basal seismic-stratigraphic unit covering the NWSB has been termed Unit I. The bottom boundary is coincident with a high-amplitude surface and is locally diffractive, marking the top of the acoustic basement of the NWSB. The Paleogene (mainly Oligocene) is characterized by chaotic and discontinuous reflectors with low frequency and various intensities, indicating an energetic and disturbed sedimentary environment during sea-floor spreading. The sediments might be volcanic debris, terrestrial clastics, or derived from lava flows. The interval velocity is between 3.4 and 3.6 km/s. The thickness is between 600 and 1000 m. The Paleogene sequences are topped by an unconformity that can be traced over the whole area. Downlaps and truncations can be observed along this unconformity.

### 3.2. Unit II (Early Miocene)

Seismic reflections in this unit are distinct from the underlying basal unit, and show parallel-subparallel, high-moderate frequency, and continuous reflectors, showing a quiet sedimentary environment and thermal subsidence after the cessation of sea-floor spreading. The sequences are generally horizontal except for areas close to the continental slope or affected by igneous bodies, indicative of typical deep marine facies. This unit can be traced across the whole basin except for the seamount. Li et al. (2005) reported the existence of a deep fan formed between 16.5 and 10.5 Ma in the foot of the north continental slope. This deep fan is lenticular in shape and onlaps above the sequence boundary. The interior is characterized by low intensity or is transparent. The top of this unit is a conformity in the basin but an unconformity at the continental margins. The interval velocity is between 1.7 and 2.3 km/s, and the thickness is between 1160 and 1620 m.

### 3.3. Unit III (middle Miocene — present)

With different intensities Unit III varies from the top downward: the upper part is characterized by continuous parallel reflectors with moderate-high intensity; the middle part has low intensity and is generally transparent; the lower one is characterized by continuous and high intensity again. The sequences are generally horizontal except for areas near to the continental slope or affected by igneous bodies, indicative of typical deep marine facies. This unit can be traced across the whole basin except for the seamount. Li et al. (2005) reported the existence of a deep fan formed between 16.5 and 10.5 Ma in the foot of the north continental slope. This deep fan is lenticular in shape and onlaps above the sequence boundary. The interior is characterized by low intensity or is transparent. The top of this unit is a conformity in the basin but an unconformity at the continental margins. The interval velocity is between 1.7 and 2.3 km/s, and the thickness is between 1160 and 1620 m.

### 4. Cenozoic deformation

Profile SO49-17 lies on the easternmost side of the study area (Fig. 1). Interpretation of the interpretation shows grabens or half-grabens with numerous extensional faults in the continental margin. A basement high separates the margin and the deep oceanic basin (Fig. 3). Seismic reflectors inside the basement high are chaotic and disturbed, indicating an igneous origin. Several oceanward-dipping normal faults border its southern edge. Inside the NWSB the thickness of Unit I reduces from the slope foot to the central oceanic basin. This sedimentary wedge shows the control of the oceanward-dipping normal faults, or just relates to the distance to the northern terrestrial

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**Table 1** Seismic faces and sequences of the Southwest Sub-basin, South China Sea.

<table>
<thead>
<tr>
<th>Sequence Internal reflection pattern</th>
<th>Frequency</th>
<th>Intensity</th>
<th>Continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit III (N$_1^{2}$-Q)</td>
<td>Parallel</td>
<td>High, uniform</td>
<td>Moderate to low, locally blank</td>
</tr>
<tr>
<td>Unit II (N$_1^{1}$)</td>
<td>Sub-parallel to parallel, locally wavy</td>
<td>High to moderate, slightly variable</td>
<td>Moderate</td>
</tr>
<tr>
<td>Unit I (E)</td>
<td>Sub-parallel, locally chaotic</td>
<td>High variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Basement</td>
<td>Hyperbolic to chaotic</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
sources. Two opposite normal faults exist in the center of the NWSB and cut into the basement. Sedimentation was controlled by the north fault with the thickness changing across this syn-sedimentary fault. Farther to the south, Unit I onlaps above the basement before finally disappearing. In the Neocene the activity of normal faulting was reduced.

Profile SO49-18 also shows that the NWSB is bordered by several inward-dipping normal faulting on both edges (Fig. 4). An igneous body stands in the middle of the basement, and almost reaches the sea floor. The basement is more rugged than it is to the east (see Fig. 3). Many normal faults developed and are almost symmetrical around the igneous body at the basin center; most were active in the Paleogene and controlled the sedimentation. After the Miocene the intensity of the extensional intensity was reduced sharply. The NWSB was buried by a post-rift sequence with minor deformation formed in a quiet deep-water sedimentary environment.

Profile SO49-25 lies at the westernmost edge of the NWSB, crossing both the XT and the NWSB (Fig. 1). The XT is a Cenozoic faulted depression with numerous extensional faults (Fig. 5), the deepest part of which is Paleogene displaying restricted rifting formed by crustal extension. The shallow part exhibits broad subsidence, which has occurred since the Miocene (Fig. 5). A wide continental slope lies between the XT and the NWSB; studies on the crustal structure across this trough show a velocity pattern similar to that of a continental nature on both sides, suggesting this area in underlain by continental crust everywhere (Qiu et al., 2001). The basement of the basin is rugged and dominated by many normal faults mostly active in Paleogene. Two grabens have been identified separated by an igneous body in the center. The Paleogene deposits decrease to the middle from both sides. The Cenozoic structure also shows a symmetrical feature related to a centrally located igneous body. After the Miocene, faults became less active and sedimentation occurred in a quiet deep-water sedimentary environment.

Studies on the above-noted three seismic profiles show that the NWSB is a small oceanic basin formed by sea-floor spreading in NNW-SSE direction. Most the faults in the NWSB were active during the Paleogene and are symmetrical in relation to the central igneous body. Paleogene sediments (Unit I, mainly Oligocene) were controlled by normal faulting and formed wedge-shaped grabens with the thickness decreasing to the center on both sides. Seismic stratigraphy also indicates that the NWSB Paleogene is characterized by chaotic and discontinuous reflectors of various intensities, indicating clastic sediments formed during or shortly after sea-floor spreading. After the Miocene a regional thermal subsidence developed and the NWSB was inundated with sediments of the Miocene to Quaternary age, which covered over the faulted sags.

Differences exist in the structural fabric between the east and west parts of the NWSB. The former is characterized by a flat oceanic basement and few normal faults; in the west, seismic cross-sections reveal a strongly symmetrical graben structure showing intense block faulting. A complex pattern of low- and high-angle normal faults bordering several discrete basins and rotated blocks can be observed. There, extensional tectonics is manifested by seismically active normal faulting with a deformation style having neither purely oceanic nor continental character.
5. Extensional model

Extensive study has been devoted to creating an extensional model for the SCS, whereas less has been dedicated to a comparison of the conjugate passive margins of the SCS because of the lack of wide-angle seismic data on the southern continental margin. Most previous models, including the simple-shear model of Zhou et al. (1995) and Hayes et al. (1995), the pure shear model by Nissen et al. (1995), the intermediate model by Yao (1999b), or the pure shear initially, simple-shear later of Wu et al. (2005), were proposed based on data from just one side of the conjugate margins. In 2006, using explosives and an air-gun array as seismic sources and 14 Ocean Bottom Seismometers (OBS) deployed along a 500 km-long profile (Figs. 1 and 6), wide-angle seismic data was acquired over the NWSB. Profile OBS2006-1 starts from the north continental margin of the NWSB crossing the whole oceanic basins, and ends in the Zhongsha Islands in the south. From a combination of seismic reflection and wide-angle studies, the crustal structures can be constructed together with a comparative interpretation of its conjugate margins.

Fig. 6 shows a velocity model of the crustal structure that is consistent with the seismic-phase analysis and the travel-time modeling of all OBS records. In the structure model, two main interfaces, the basement interface and the Moho interface, divide the section into three parts from the top down, i.e., the Cenozoic sedimentary layer, the pre-Cenozoic crust, and the uppermost mantle. The Cenozoic deposits, which are composed of two or three horizontal sedimentary beds, developed on the top of the crust. Within the layers, there are small velocity gradients and velocity differences of 0.5–1.0 km/s over the interfaces. Beneath the Cenozoic, the upper basement has a velocity of 5.5–5.6 km/s, which is relatively low and suggests strong weathering before subsidence. The velocity of the crust changes from 5.6 km/s to 6.8 km/s. The crustal thickness of the continental margin is over 22 km. No High-Velocity Body (HVB) ($v_p > 7.0$ km/s), which is a typical marker of volcanic margins, has been observed under the pre-Cenozoic crust. The crustal thickness decreases abruptly, from 21.5 km to about 11.7 km, over a lateral distance of less than 60 km before entering the oceanic basin, showing the transition to oceanic crust. In the center of the basin the crustal thickness is deeper than the sides (about 12.2 km), corresponding to a central igneous body. The Moho depth under the Zhongsha Islands is about 18.1 km, and the velocities range from 5.5 to 6.9 km/s, which indicate continental crust. The nearby borehole (Well Xiyong-1) penetrated the basement at depths of 1251 m encountering Cretaceous granites and metavolcanic rocks, which confirmed the continental origin. The similar velocity structure of the continental nature on both sides of the NWSB suggests a continuous pre-rift continental crust.

Both the Cenozoic deformation structure reflected by the seismic profiles and the crustal structure conducted by the wide-angle seismic profile imply symmetrical structures on both sides of the rift zone composed of rotated fault blocks bounded by normal

![Figure 5](image_url) Seismic profile SO49-25 and its interpretation.

![Figure 6](image_url) Velocity model of the wide-angle seismic profile OBS2006-1.
faults. Because such symmetry is characteristic of pure shear continental rifting, we suggest that the Cenozoic rifting in the NWSB might follow a pure shear model.

6. Cenozoic tectono-sedimentary evolution

As a part of the SCS, the structural development of the NWSB was generally controlled by three major plates, the Eurasian, Pacific, and the Indo-Australian plates. Before the opening of the SCS, the Zhongsha-Xisha Block and the Nansha Block were all connected with the Yangzi Block, and a proto-SCS lay to the south.

After the late Cretaceous the convergent rate of the Pacific-Eurasia plates decreased. The subducting slab of the Pacific experienced rollback (Hollway, 1982; Northrup et al., 1995). The stepping out or eastward retreat of the West Pacific subduction zone triggered the onset of large-scale rifting along the northern margin of the proto-SCS (Lüdmann and Wong, 1999). Rifted basins controlled by NE–ENE normal faults developed (Fig. 7a).

During the mid-Eocene, the northern margin of the proto-SCS was dominated by the influence of the collision and northward impinging of the Indian Block on Tibet. Hypothesized eastward mantle extrusion caused by the Tethyan Sea closure (Flower et al., 2001), and the extrusion tectonics from the India-Eurasian collision (Tapponnier et al., 1982), could have produced southeastward mantle flow. The proto-SCS began its subduction beneath the Borneo (Hamilton, 1979; Williams et al., 1988). The extension stress in the northern margin of the proto-SCS experienced a clockwise rotation and was in a N–S direction. Faults changed direction from the NE to nearly an E–W-direction thereafter. The southward subduction of the proto-SCS may have jointly produced the N–S slab pull force to drive the extension.

At around 30 Ma, continental breakup occurred first at the ESB. Sea-floor spreading began in the NWSB at roughly the same time as along the northern rift of the ZXB. North and south of the spreading area, rifting continued due to regional extension. Although the NWSB is heavily sedimented, the seismic data reveal horst and graben structures that parallel the axis of the V-shaped domain. The tectonic fabric in the NWSB differs from east to west. Continental and oceanic rifts suggest that extension did not occur synchronously along strike. More complicated rift structure developed in the western part indicates that the sea-floor spreading occurred later than in the eastern part, which has formed mature oceanic basin with fewer faulted blocks of oceanic basement. Extension did not occur synchronously along the strike, but propagated from east to west. The proto-SCS continued its subduction beneath Borneo with the southward movement of the Zhongsha-Xisha and Nansha blocks (Fig. 7b).

Earlier geological studies argued that the XT is a remnant rift of the NWSB with an advancing degree of rifting from west to east (Taylor and Hayes, 1983; Shi et al., 2002). However, Fig. 1 shows that the extensional axis of the western part of the NWSB is in an ENE–WSW direction. It extends to the northwest of the ZXB before it finally disappears, instead of connecting to the XT. Seismic profile SO49-25 also shows the co-existence of the XT and the NWSB. The thicker Paleogene in the XT indicates a longer sedimentary history than the NWSB (Fig. 6). 3D analog modeling proved that the existence of a rigid massif in the extensional area could make its edges, which are vertical to the extensional stress, then thin rapidly and favor the formation of a deep through (Sun et al., 2009). The ZXB is just such a rigid massif that experienced rare deformation in the Cretaceous and weak rifting in the Cenozoic. During continental rifting and the sea-floor spreading thereafter, the extension in the NWSB would have been controlled by the shape of the massif and just developed along the northern edge of the ZXB, rather than joined to the XT.

At 25 Ma the spreading rates increased and the spreading ridge jumped to the south (Li, 2005); the reason for the southward migration is not yet known. Controlled by southeastward stretching, the spreading ridge propagated southwestward rapidly and formed the SWSB. The spreading of the Southwest Sub-basin could have brought northward stress to the ZXB. The NWSB and the marginal basins (the Beibu Gulf Basin, the Qiongdongnan Basin) located north and northwest of the spreading ridge stopped spreading or rifting and passed into a thermal subsiding stage (Fig. 7c).

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**Figure 7** Rifting model of the Southwest Sub-basin, South China Sea.
7. Conclusions

Three tectono-stratigraphic units have been recognized from three multi-channel seismic profiles acquired in the NWSB, in the SCS. Detailed analyses showed that the NWSB was deformed by strong Cenozoic extensional tectonics with the formation of half-grabens, which formed synthetic combinations in either series, parallel, or en-echelon styles. The Cenozoic deformation structures of the continental margins are generally symmetrical, but differ from west to east. The opening of the NWSB started from the east and propagated to the southwest before it finally ceased, which allowed the western part of the NWSB to preserve more geological features of a rifted basin. The tectonic orientation of the NWSB was not only controlled by the extensional stress field, but also by the rigid ZXB in the south. The westward spreading mostly followed the northern edge of the ZXB rather than joining the Xisha Trough. The Paleocene (mainly Oligocene), deposited in the NWSB, characterized by chaotic and discontinuous seismic reflectors, reveals that there was an energetic and disturbed sedimentary environment during the initial phase of sea-floor spreading. The NW stress caused by the spreading of the SWSB after 25 Ma prevented the continuous opening of the NWSB. A thermal subsidence dominated the study area with a quiet sedimentary environment after that.

The crustal structure is similar on both sides of the NWSB and has a N–S symmetry, suggesting that the two sides might have belonged to the same block before rifting. No high-velocity body is found near the bottom of the crust of the northern margin, and the Moho interface has a uniformly large velocity contrast. These observations suggest that there was no significant magmatic underplating during rifting. The northern margin of the NWSB is a non-volcanic passive style one. The symmetrical characteristics both in Cenozoic tectonics and deep structures make us consider that a shear model represents the opening of the NWSB.

Acknowledgments

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