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# Spreading dynamics and sedimentary process of the Southwest Sub-basin, South China Sea: Constraints from multi-channel seismic data and IODP Expedition 349



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# ABSTRACT

Neotectonic and sedimentary processes in the South China Sea abyssal basin are still debated because of the lack of drilling evidence to test competing models. In this study, we interpreted four multi-channel seismic profiles across the Southwest Sub-basin (SWSB) and achieved stratigraphic correlation with new drilling data from Integrated Ocean Discovery Program (IODP) Expedition 349. Neogene sediments are divided into four stratigraphic units, each with distinctive seismic character. Sedimentation rate and lithology variations suggest climate-controlled sedimentation. In the late Miocene winter monsoon strength and increased aridity in the limited accumulation rates in the SWSB. Since the Pliocene summer monsoons and a variable glacial-interglacial climate since have enhanced accumulation rates. Terrigeneous sediments in the SWSB are most likely derived from the southwest.

Three basement domains are classified with different sedimentary architectures and basement structures, including hyper-stretched crust, exhumed subcontinental mantle, and steady state oceanic crust. The SWSB has an asymmetric geometry and experienced detachment faulting in the final stage of continental rifting and exhumation of continental mantle lithosphere. Mantle lithospheric breakup post-dates crustal separation, delaying the establishment of oceanic spreading and steady state crust production. © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

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# 1. Introduction

Despite great progress in understanding how tectonic and sedimentary processes interact as a result of the study of high resolution multi-channel seismic profiles tied to scientific and commercial drilling wells on the north and south continental margins of the South China Sea (Holloway, 1982; Ru and Pigott, 1986; Zhou et al., 1995; Schlueter et al., 1996; Shipboard Scientific Party, 2000; Clift and Lin, 2001; Qiu et al., 2001; Yan and Liu, 2004; Hayes and Nissen, 2005; Clift et al., 2008; Sun et al., 2009; Cullen et al., 2010; Ding et al., 2012, 2013, 2014; Franke 2012; Franke et al., 2011, 2014; Savva et al., 2014), a precisely constrained seismic stratigraphic and sedimentary framework for the oceanic basin is lacking. Precisely dated seismic interpretations have never been possible because of the lack of wells in the deep basin, which limits our understanding of sequence boundary dates, as well as the lithology of the different sedimentary units, and the timing of tectonic activities. In 2014, International Ocean Discovery Program

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(IODP 349) Expedition (South China Sea Tectonics) drilled five sites in the basin, three of which penetrated into basalt (Expedition 349 Scientists, 2014). Sedimentary units above the oceanic crust now can be divided based on detailed lithological information, while microfossils in the sediment provide accurate depositional ages for the different units. Integrating core, downhole geophysical logging, and seismic data now make a seismic stratigraphy study of the deep basin possible, and provide the opportunity to reconstruct the spreading history.

The South China Sea basin is divided into three sub-basins based on structural variations: the East Sub-basin (ESB), the Southwest Sub-basin (SWSB), and the Northwest Sub-basin (NWSB) (Fig. 1a). The SWSB is a V-shaped oceanic basin typical of a propagating rift (Briais et al., 1993; Huchon et al., 2001; Li et al., 2012) (Fig. 1b). In relation to the geodynamics of the South China Sea, the SWSB provides information about how continental extension occurred and how this transitioned to oceanic seafloor spreading during break-up.

In this study, we present a seismo-stratigraphic analysis, and place constraints on understanding spreading dynamics as well as the sedimentary processes of the basin. This includes identification and dating of sequence boundaries, calculation of

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**Fig. 1.** (a) Major tectonic units and sedimentary basins in the South China Sea. Dashed square shows the study area; (b) Morphological features of the SW Sub-Basin and adjacent regions. Red broken lines show the locations of example seismic sections discussed in this paper. Drilling sites drilled during ODP 184 Expedition and IODP Expedition 349 are indicated by yellow circles. Red circles are the dredge sites from Yan et al. (2014). Blue broken line shows the boundary between the ESB and the SWSB (referred from Franke et al., 2014).

sedimentation rates, and recognition of major structures formed during different stages of oceanic basement formation. Seismic, logging/coring, and bathymetric geophysical data are combined to constrain further the SWSB tectonic history.

# 2. Geologic setting

## 2.1. South China Sea spreading

The South China Sea is situated at the junction of the Eurasian, Pacific, and Indo-Australian plates, and most scientists agree it is an oceanic basin developed by latest Cretaceous to Paleogene magma-poor rifting that transitioned to subsequent seafloor spreading in the Oligocene (Taylor and Hayes, 1980, 1983; Briais et al., 1993; Hall, 2002; Barckhausen and Roeser, 2004; Sun et al., 2009; Cullen et al., 2010; Li et al., 2012; Franke et al., 2014; Barckhausen et al., 2014; Expedition 349 Scientists, 2014). The fundamental elements of the Wilson cycle, including continental rifting, seafloor spreading, a subsequent collision with Borneo to the south, and subduction under the Luzon Arc to the east (Briais et al., 1993; Hayes and Nissen, 2005; Cullen et al., 2010; Arfai et al., 2011; McIntosh et al., 2013), have been documented for

the South China Sea region, providing compelling insights into the processes operating during initial rifting and seafloor spreading.

Early attempts on dating the spreading history were concluded from heat flow and bathymetry data (Ru and Pigott, 1986), they suggested the oceanic crust in the SWSB is considerably older (55 Ma) than that in the ESB (32 Ma). But the heat flow values reported by Ru and Pigott (1986) are too high for the suggested ages when standard cooling models (Stein and Stein, 1992) are applied. The opening scenario proposed by Taylor and Hayes (1980, 1983) and Briais et al. (1993), which based on interpretation of magnetic anomalies, has generally accepted, i.e., seafloor spreading occurred from 32 to 16 Ma (magnetic anomalies 11-5C). Refinement of the earlier model has been proposed based on more recent ship-borne magnetic data (Barckhausen and Roeser, 2004; Barckhausen et al., 2014), with a revised timing of seafloor spreading in the central South China Sea at 31–20.5 Ma (anomaly of 11-6A1). Constrained by deep tow magnetic data and IODP Expedition 349 drilling results, Li et al. (2014) proposed an onset age of 33 Ma in the northeastern South China Sea, a terminal age of  $\sim$ 15 Ma in the ESB, and  $\sim$ 16 Ma in the SWSB. Although there are 3-4 Myr differences on the cessation time, most of the scientists agreed that the seafloor spreading occurred in the ESB firstly, which was complicated by a southward ridge jump and a re-orientation of the spreading geometry from westward to southwestward ridge propagation (Briais et al., 1993; Barckhausen and Roeser, 2004; Hayes and Nissen, 2005; Li et al., 2008; Sun et al., 2009; Cullen et al., 2010; Franke et al., 2014; Barckhausen et al., 2014; Expedition 349 Scientists, 2014; Li et al., 2015). A rigid block of continental crust, which now forms the Macclesfield Bank and Reed Bank, hindered the propagation of seafloor spreading into the southwestern part of the South China Sea basin until around 25 Ma.

# 2.2. The Southwest Sub-basin

The SWSB is a V-shaped triangular sub-basin opening to the northeast (Fig. 1b). It is 600 km long with an area of 115,000 km<sup>2</sup> and water depths between 3000 m and 4300 m. It is bounded by several tectonic units: the Paracel Islands and the Macclesfield Bank, as well as the Vietnam continental margin to the northwest, with the Reed Bank and Dangerous Grounds to the southeast, and the ESB to the east (Fig. 1b). The Zhongnan Fracture Zone separates the SWSB from the ESB.

The SWSB is roughly outlined by the 3000-m isobath. The bathymetric map shows several big seamounts in the east and two remarkable linear basement highs in the center (Fig. 1b). Seismic data define these linear basement structures as mid-ocean-rift shoulders dominated by parallel fault scarps, with a northeast-oriented central rifted graben between (Li et al., 2012). This depression differentiates the SWSB from the ESB, where the topographic remnants of the spreading ridge are masked by a seamount chain. Further to the southwest in the SWSB the seafloor flattens, and is marked with a few isolated seamounts or linear structures. The seamounts, with alkali basalts dated as 13.9 Ma to 3.8 Ma, represent post-spreading magmatism (Yan et al., 2014) and is also dated at Late Miocene-Pliocene within the Vietnamese continental margin at the tip of the SWSB (Li et al., 2013).

#### 2.3. Continental margin

Both the northern and southern continental margins of the SWSB, and the whole South China Sea, were in an Andean-type convergent setting from the Middle Jurassic to Middle Cretaceous, with a basement of mainly meta-sedimentary rocks correlated from the Caledonian fold belt in the west and the Hercynian fold belt in the east (Taylor and Hayes, 1983; Zhou et al., 1995). During

the Late Cretaceous, episodic rifting with uplifting shoulders and erosion occurred as a result of subduction slab rollback (Hall, 2002; Zhu et al., 2012). Detailed geological interpretation of seismic profiles suggested that rifting propagated from north to south and from east to west (Li et al., 2012; Ding et al., 2013; Franke et al., 2014; Savva et al., 2014). Previous wide-angle refraction seismic studies concluded that the South China Sea continental margin developed by a magma-poor rifting (Qiu et al., 2001; Yan et al., 2001; Ding et al., 2012), contrasting with earlier suggestions of widespread magmatic underplating linked to break-up (Nissen et al., 1995). Numerous sedimentary basins developed, including the Pearl River Mouth Basin and the Qiongdongnan Basin in the northern margin, and the sedimentary basins of the Dangerous Grounds. The Dangerous Grounds, together with the Reed Bank area, collided with Borneo starting in the Middle Miocene (Hutchison et al., 2000; Clift et al., 2008; Cullen et al., 2010; Hutchison, 2010).

## 3. Seismic and cores: data and methods

Five multichannel seismic profiles were interpreted in this study, and four of them were analyzed in detail. Seismic profiles N3, N7, N10 and N16 were obtained during the national ocean project cruise of the Second Institute of Oceanography, State Oceanic Administration, in 2004. Seismic profile NH973-1 was obtained during the "Cruise for Project South China Sea continental margin geodynamics" in 2009. Seismic profiles N3 and NH973-1 are oriented in a northwest-southeast direction, and profile N16 crosses them, trending northeast-southwest (Fig. 1b). The acquisition parameters are listed in Table 1.

Pre-stack processing of these seismic data included amplitude compensation, static correction, gain and mute analysis, predictive deconvolution, multiple attenuation, velocity analysis, residual static corrections, and frequency filtering. Post-stack deconvolution, band-pass, and coherency filtering were then applied to the stacked data, followed by a finite-difference migration.

IODP Expedition 349 drilled and cored two sites in the SWSB that reached the igneous oceanic crust, Sites U1433 and U1434 (Fig. 1b). Seismic profile N3 runs through these two sites. Site U1434 was drilled on a basement high with thin sedimentary cover. Site U1433 was drilled in a depression nearly 50 km away from the relict spreading ridge and was positioned to document the post-South China Sea spreading sedimentary record. We used this drilling site to interpret seismic sequences and define regional lithos-tratigraphic units (Figs. 2 and 3, see Fig. 1 for locations). Age control of the sequence boundaries is mostly provided by biostratigraphic analysis (Expedition 349 Scientists, 2014). These ages were transferred to the seismic profiles after converting drilling depth to two-way travel time using P-wave velocities derived from the log-ging data at Site U1433. Seismic profile N16 provided a tie cross line for correlation of dated horizons between profiles N3 and NH973-1.

Sedimentation rates were calculated for Profiles NH973-1 and N3. These involved time-depth conversions of the interpreted

Table 1Acquisition parameters for seismic lines used in this study.

Profile	N3, N7, N10, N16	NH973-1
R/V	TANBAO	TANBAO
Acquisition date	2004	2009
Streamer channel	480	480
Record length (s)	12.0	12.0
Sampling rate (ms)	2	2
Shot interval (m)	50	50
Airgun volume (L)	83.3	83.3



Fig. 2. Seismic section (left) and interpretation (right) crossing site U1433. The interpreted boundaries are calibrated from recovered lithostratigraphy. Natural gamma radiation and P-wave velocity along the well are shown in depth. Site U1433 has penetrated into the oceanic basement and recovered complete Neogene deposits. Vertical exaggeration is five times. See location in Fig. 4.

Age	Per	iod	Sedimentary Lithology		Seismic facies	Lithology description
	Pleistoc	ene-now		U1	Continuous and parallel, high amplitude and medium frequency in the upper part, low amplitude and medium-high frequency in the lower part	The upper is dark greenish gray clay with interbedded, very thin, clayey silt. The lower part is clay with thin carbonate interbeds
5 Ma <sup>-</sup>	– Pli	ocene		U2	Continuous and parallel, low amplitude and medium-high frequency, locally transparent	Dark greenish gray clay with interbedded thin carbonates
10 Ma -		Late		U3	Parallel and highly continuous, low frequency and high amplitude	Dark greenish gray claystone with thick to very thick (>1 m) greenish gray nannofossil chalk interbeds.
15 Ma-	- Miocene	Middle		U4	Chaotic, locally subparallel, low-medium continuous, low frequency, medium-high amplitude in both sides of the basin, transform into parallel, continuous, medium-high amplitude near the relict ridge	Massive reddish and yellowish brown claystone and claystone with silt, with little coarser material present, occasional, thin, silty turbidites, and common dark staining associated with bioturbation.
	]	Early	2 7 <del>7</del> 7 N 1 2 7 N 7 N 1 7 N	۸ ۲	Hyperbolic to chaotic, low frequency and high amplitude	Basalt

Fig. 3. Recovered lithostratigraphy at site U1433 (Expedition 349 Scientists, 2014) and seismic facies of different sediment units.

seismic sections, and a decompaction process to restore each dated unit to its original thickness. A full suite of geophysical logging was carried out at Site U1433, which allowed us to make a more accurate time-depth conversion. With core-log-seismic integration, Li et al. (2015) built a time-depth conversion from P-wave velocity measurements: Here t stands for the two-way travel time (in milliseconds) starting from the seafloor, and Z is the depth in meters below the seafloor.

# 4. Seismic stratigraphy analysis

Geological interpretations of seismic profiles N3, N7, N10 and NH973-1 are presented in Figs. 4–7, respectively. Five distinct

 $Z = 0.000152626 t^2 + 0.714658 t,$ 

seismic units are seen in the sediments from the bottom up, i.e., U5: Paleogene; U4: Early to Middle Miocene, U3: Upper Miocene, U2: Pliocene, and U1: Pleistocene. Each unit is characterized by particular reflection patterns and internal structures.

# 4.1. U5 (Paleogene, >25 Ma)

U5 represents the syn-rift unit, which is widespread in the continental margin and fills fault-bounded sags with a wedge-shaped stratigraphy. In our seismic profiles this unit only exits on the continental slope (Figs. 8 and 9), and is characterized by chaotic (locally subparallel) and discontinuous-moderately continuous reflectors with low frequency and variable intensities (Fig. 3), indicating syn-sedimentary deformation. A thin interval moderate-tostrong amplitudes and continuous reflectors seal this unit, which is locally truncated at its base and onlapped on the top (Figs. 8 and 9). Based on previous work on the surrounding continental margin (Franke et al., 2014; Ding et al., 2014; Savva et al., 2014), we interpret this surface as the break-up unconformity marking either an inter-rift status or the onset of seafloor spreading in the SWSB at about 25 Ma. Although most authors agreed that continental rifting started in the early Cenozoic Era (Schlueter et al., 1996; Yan and Liu, 2004; Hutchison and Vijayan, 2010), the age of the base of this unit is diachronous. U5 was deposited much later in the slope area than in the shelf region.

## 4.2. U4 (Middle Miocene and older, $\sim$ 25–11.6 Ma)

This unit spans the time of seafloor spreading and the oldest sediments deposited after the end of spreading. A basal unconformity featuring moderate- to high-amplitude, continuous reflections separates it from the oceanic crust. Seismic interpretations show that this unit is mainly confined to grabens or half-grabens in the oceanic basin, and that the seismic reflectors differ spatially and temporally (Figs. 4–7). This unit can be separated into subunits U4a and U4b. Subunit U4b appears to be syn-tectonic, forming syndepositional structures (Figs. 8-10). This subunit is characterized by chaotic (locally subparallel), discontinuous, or moderately continuous reflectors with low internal frequencies, indicating a high-energy sedimentary environment. Subunit U4b is distributed on both sides of the basin, especially in the slope-foot area (e.g., the thickness near the Macclesfield Bank is 300 ms two-way travel time [TWT], or  $\sim$ 400 m, Fig. 4). The thickness decreases oceanward and be absent in the distal part. The younger Subunit U4a appears stratified and shows reflectors of subparallel, medium, continuous and moderate-high amplitude. This sub-unit is generally undeformed, indicating a distal, sedimentary environment. Subunit U4a downlaps on to the underlying Subunit U4b and the oceanic basement near the relict spreading ridge. The subunit also onlaps on uplifted basement blocks (Fig. 9). Lithological study of Site U1433 indicates that Unit U4 is composed of reddish brown or yellowish brown massive sediments with common burrowing stained black by diagenetic alteration (Fig. 3). Since only 48 m of sediments was recovered at Site U1433 (about 48 m), the lithology of the Lower Miocene and older sediments away from the spreading ridge is not well constrained. We suggest these might be composed of terrigenous clastic and carbonate sediments from the continental margins, especially in the slope-foot area. It is hard to date this sedimentary unit, especially Subunit U4b. The lower part of this unit is characterized by an age progression relating to the formation of new oceanic basement. Magnetic anomaly 6C was identified close to the Macclesfiedl Bank by Briais et al. (1993) and Li et al. (2014), suggesting the lowest part of the succession may date to the Late Oligocene ( $\sim$ 25 Ma) near the slope foot area.

Further to the southwest of the SWSB, as indicated in seismic profiles NH973-1 and N10 (Figs. 6 and 7), Unit U4 is generally thicker than seen in seismic profiles N3 and N7. The thickest sediment in the oceanic basin generally occurs in the central valley, where it can reach to 350 ms (TWT), or 470 m in NH973-1 (Fig. 6), and increases to 490 ms (TWT), or 660 m in N10 southwest further (Fig. 7). There is no apparent difference in the seismic reflectors either near the continental slope or in the central valley. Reflectors are typically chaotic, discontinuous, and locally subparallel, with variable frequencies, and highly variable amplitudes, indicating a high-energy sedimentary environment during the time of seafloor spreading.

#### 4.3. U3 (Upper Miocene, 11.6 Ma to 5.3 Ma)

The internal reflectors of this unit are parallel layered, highly continuous, low frequency, and high amplitude. They are locally transparent (Fig. 2). At Site U1433 this unit is dominated by dark greenish-gray clay with frequent graded carbonate interbeds (Fig. 3). These carbonate layers are sometimes up to several meters thick and well consolidated, with high velocity, which causes the remarkably strong seismic reflectivity across the whole basin. This unit conformably overlies the unit below and generally has uniform 100–150 ms (TWT) (120–180 m) thickness, except in the central valley, as shown in Fig. 6, where the thickness can reach 630 ms (TWT) (750 m). Multiple irregularly stacked, buried channels are identified in this unit, indicating active mass transport since the Middle Miocene and a composite cut-and-fill history in the central valley. Similar buried channels are seen in profile N10, but not as well developed as those in NH973-1.



Fig. 4. Multichannel seismic profile N3 running from the south of Macclesfield Bank, across the SWSB in a southeastern direction. Locations of t IODP Site U1433 and U1434 are shown. Top: Original seismic profile, bottom: a geological interpretation. Colorful broken lines show distribution of different basement domains. The locations of the enlarged seismic sections shown in Figs. 2, 8, 13 and 15 are indicated. Vertical exaggeration is nearly three.



**Fig. 5.** Multichannel seismic profile N7 running from the east of Zhongjian Massif, across the SWSB in a southeastern direction, and to the north of Zhenghe Massif. Top: Original seismic profile, bottom: a geological interpretation. Colorful broken lines show distribution of different basement domains. The locations of the enlarged seismic sections shown in Fig. 10 are indicated. Vertical exaggeration is nearly 3.



**Fig. 6.** Multichannel seismic profile NH973-1 running from the south of Zhongjian Massif, across the SWSB in a southeastern direction, and into the north of Dangerous Grounds. Top: Original seismic profile, bottom: a geological interpretation. Colorful broken lines show distribution of different basement domains. The locations of the enlarged seismic sections shown in Figs. 9 and 14 are indicated. Vertical exaggeration is 3.



**Fig. 7.** Multichannel seismic profile N10 running from the south of Phu Khanh Basin, across the SWSB in a southeastern direction, and into the north of Dangerous Grounds. Top: Original seismic profile, bottom: a geological interpretation. Colorful broken lines show distribution of different basement domains. Vertical exaggeration is 3.

4.4. U2 (Pliocene, 5.3–1.8 Ma)

In contrast to the Upper Miocene unit, the Pliocene shows rather transparent parallel seismic reflectors with high continuity, medium to high intensities, and low amplitudes. Coring at Site U1433 demonstrated that this unit is similar to the Upper Miocene in being dominated by dark greenish-gray clay with carbonate interbeds (Fig. 3). However, the carbonate beds are generally thinner, usually <50 cm, making the reflectivity much weaker. This unit shows a descending trend from southwest to northeast, with



**Fig. 8.** Enlarged seismic section (top) and interpretation (bottom) of seismic profile N3 (north margin) shows the transfer from basement domain 1 to domain 2. The occurrence of a igneous body (?) marks the termination of U5 and faulted-sags controlled landward dipping faults, as well as the beginning of new-formed basement with deformed U4b. Thick grey line shows a landward dipping reflector, interpreted as Moho, which raises oceanward and seems to merge into the top basement of domain 2. Mantle exhumation may have occurred. Vertical exaggeration is nearly 2. See Fig. 4 for location.

thicknesses between 300 and 460 ms TWT in profiles N10 and NH973-1, and between 200 and 350 ms TWT in N7 and N3. Buried channels are also identified in this unit (Fig. 6), indicating continuous mass transport and cut-and-fill history.

### 4.5. U1 (Pleistocene, <1.8 Ma)

The internal seismic reflectors of the Pleistocene change up-section and are separated by a strong continuous reflector (Fig. 2), which can be traced into the central basin and used as a benchmark of the Pliocene–Pleistocene boundary. The lower part has similar features to the Pliocene, characterized by low amplitude, medium–high frequency reflectors. In Fig. 2 it appears to downlap from the two sides of the bounding highs. However, the upper part features strong seismic reflectivity and low-medium frequency. Site U1433 core reveals that the upper part is dark greenish-gray clay, silty clay, and clay with nannofossils (Fig. 3). The clay is interbedded with small volumes of generally thin, graded quartzose silt and nannofossil ooze, both interpreted as turbidite deposits. The lower part is dominated by dark greenish-gray clay with thin carbonate interbeds. The whole unit is usually 400–600 ms (TWT) thick across the region. It thins or pinches out over pre-existing highs and thickens in the center. These ponded sediments may represent turbidites carried by oceanbottom currents.

# 5. Sedimentation rate

Ten artificial wells in profile NH973 and 13 artificial wells in N3 were constructed to calculate sedimentation rates for every major



Fig. 9. Enlarged seismic section (top) and interpretation (bottom) of seismic profile NH973-1 in the continental – oceanic transition (COT) area of the Dangerous Grounds. A half-graben with a remarkable detachment structure exists in the slope area of the Dangerous Grounds. Numerous normal faults developed in the hanging wall. This listric detachment faults flattens and joins the supposedly Moho reflector. Arrays of oceanward normal faults separate the domain 1 (hyper-stretched crust) from the domain 2 (exhumed subcontinental mantle) marking the end of U5. Vertical exaggeration is nearly 2. See Fig. 6 for location.

depression from the slope foot area to the relict spreading center (Fig. 11). Because the age of the oceanic basement differs with location, the duration of the U4 (Middle Miocene and older) also changes.

The calculated sedimentation rates for each seismic profile are shown in Fig. 12a and b. Both seismic profiles show similar trends for sedimentation rates, which are generally between 20 m/my and 80 m/my during the early and middle Miocene, decrease slightly during the late Miocene (between 20 m/my and 60 m/my), followed by an increase during the Pliocene (generally between 50 m/my and 100 m/my), and then increase sharply again in the Pleistocene (between 80 m/my and 200 m/my). Exceptions appear in Line 5 of profile NH973, and Lines 6 and 7 of seismic profile N3. Line 5 features a much higher sedimentation rate than the others, which is 220 m/my in the middle Miocene, decreases to 140 m/my during the late Miocene and Pliocene, and increases to 200 m/my in the Pleistocene. Lines 6 and 7, as seen in Fig. 12b, are characterized by extremely low sedimentation rates (<10 m/my) during the middle Miocene, which were in the depressions close to the relict spreading center. Site U1433 yielded only 48 m of middle Miocene sediments.

## 6. Structure of the basement

We divide the basement into domains 1, 2 and 3. Our identification of the different basement domains is based on four

seismic profiles in this paper (Figs. 4–7). Generally Domain 1 distributes in the continental slope area, and is characterized by fault-controlled sags and wedged-shaped unit U5. Further oceanward is the Domain 2 featured with well-developed extensional structures, syn-depositional subunit U4b, and absence of Unit U5. Domain 3 lies exclusively in the northeast part of the SWSB with absence of subunit U4b. In the following we describe the structures of these basement domains together with sedimentary units, since there is a tie link between sediments and deformation related to the creation of new oceanic basement. Some detailed interpretations in selected small regions are shown to highlight key observations.

## 6.1. Basement Domain 1

Domain 1 is limited in the continental slope area. Seismic profile N3 lies in the northeastern part of the basin (Fig. 4). Several faulted-sags developed in the left controlled by landwarddipping faults (Fig. 8). A basement high separates the abyssal basin and the continental slope. Wedge-shaped Unit U5 terminates against this basement high and is not recognized oceanward. The fault on the right side of the basement high thus clearly developed after deposition of Unit U5. The nature of this basement high is not clear. Chaotic and discontinuous internal reflectors within the basement might indicate a magmatic origin. Fragmentary, but occasionally strong internal reflectors can be identified in the base-



**Fig. 10.** Enlarged seismic section (top) and interpretation (bottom) of seismic profile N3 shows faults affecting the U4b sedimentary unit and the basement domain 2. Fragmentary but distinct reflector elements within the basement can be identified. By aligning the individual reflector elements a detachment system may be inferred. The sedimentary unit U4a seals this detachment system without deformation. Vertical exaggeration is nearly 2. See Fig. 4 for location.



Fig. 11. Time-depth conversion of the seismic profiles NH973-1 (top) and N3 (bottom). Colorful triangles are the locations of artificial wells constructed to calculate the sediment rates of major depressions in the oceanic basin.

ment. We interpret this landward dipping reflector as the Moho, which is  $\sim$ 8 s (TWT) in the slope area and quickly shallows oceanward.

Similar structure can also be observed in the southern margin (Dangerous Grounds). Fig. 9 shows the part of profile NH973-1, extending from the Dangerous Grounds for nearly 10 km into the



Fig. 12. An overview of the sediment rate curves of the seismic profiles NH973-1 (a) and N3 (b). Both experienced a decrease from the middle Miocene to early Miocene, a slight increase during the Pliocene, and a sharp increase since the Pleistocene.

SWSB. Fragmentary reflectors in the acoustic basement can be identified at about 8 s (TWT) at the NE end, and bends down in a SE direction beneath the NW edge of the Dangerous Grounds, representing the Moho. A half-graben, with a remarkable clear detachment structure, is located in the slope foot area. A prominent detachment fault is developed along the SE margin of this halfgraben. This listric fault flattens and joins the apparent Moho. Numerous normal faults developed in the hanging wall, with similar dipping direction, which were mainly active during the Paleogene. All these faults cut Unit U5 into many narrow sub-blocks that step down to the oceanic basin. The uppermost part of Unit U5 shows clear indications of erosion, implying a hiatus as the origin for the break-up unconformity of the SWSB ( $\sim$ 25 Ma). Unit U4 drapes over the detachment structure and thickened toward the abyssal basin. The lower layer of Unit U4, or Subunit U4b, is affected by normal faults. In contrast the upper layer (U4a) and younger units are marked by continuous and parallel reflectors.

# 6.2. Basement Domain 2

According to our interpretation the basement Domain 2 is characterized by (1) complex and chaotic internal structures with high amplitude reflectors; (2) no clear Moho reflections; and (3) the presence of deformation structures, such as faulted-sags and rift basins, affecting both the basement and the overlying sedimentary units (Figs. 4 and 5).

Fig. 8 shows the transfer from Domain 1 to 2. Further oceanward Unit U5 disappears, and Unit U4 lies directly on the oceanic basement. Faulted sags also developed and were generally controlled by oceanward-dipping faults. Unit U4 is locally affected by normal faults with large offset. The lower part of Unit U4 (Subunit U4b), is syn-depositional with growth structure, and Subunit U4a generally seals the faults that affect Subunit U4b, as well as the deformed structures in this sequence.

The presence of intense faulting and tilted blocks is remarkable in this domain. We even noted some isolated rifted basins. Fig. 10 shows a typical example in Domain 2 along seismic profile N7. The basement features tilted faulted blocks cut by antithetic faults. Fragmentary but partly strong internal reflectors can be identified inside this basement connecting to the major basin-bounding normal faults. An alignment of these reflectors results in listric normal faults that ramp down to a common surface that we interpret as a detachment. Within the basin Subunit U4b appears to be syntectonic, forming growth structures. Subunit U4a is generally not perturbed by deformation and seals the fault-bounded tilted blocks. Further to the southeast, this unit directly onlaps on to a basement high. Subunit U4b is not observed further oceanward.

Large regular tilted blocks are also discovered on the Dangerous Grounds side. A domino-type structure is shown in Fig. 13 (see Fig. 6 for location, between CDP 29000 and 32000). These rotated blocks are controlled by complex systems of faults that face oceanward. The tops of the blocks have moved farther away from the ridge axis than the bottoms, and a displacement contrast exists between the different rheological layers. Syn-tectonic Subunit U4b is limited in the deepest part of the faulted-sag, and disappears in the faulted-sag located in the northwest part of this profile. Subunit U4a is more stratified than U4b, and is not perturbed by deformation, but directly overlies basement.

Further southwest of the SWSB, as indicated on profiles NH973-1 and N10 (Figs. 6 and 7) the oceanic basement is generally dominated by this domain which is marked with numerous extensional faults, well-developed tilted fault blocks, rugged basement, and wedge-shaped sedimentary units, even in the fossil spreading center. The spreading center now is an asymmetrical rift valley bordered by two large rift shoulders between which the thickest deposits have accumulated and which reach 2.3 s (TWT) (2640 m) (Fig. 14). Several step-down normal faults developed in the inner north rift shoulders. Only two normal faults developed along the inner south rift shoulder. Unit U4 is controlled by normal faulting and forms a typical wedge shape. Unit U3 is not fault controlled, but is still slightly wedge shaped. After the Miocene, sediments form sheets with cyclic reflectors. Several normal faults with little throw were identified within the valley. The two rift shoulders formed linear seamount chains in a NE45-55° orientation (Fig. 1b).

## 6.3. Basement Domain 3

The transition between Domains 2 and 3 is marked by the absence of Subunit U4b. Subunit U4a lies directly on the younger basement (Fig. 13). This basement domain is roughly flat, and the sediments are generally not affected by tectonic deformation. Fig. 15 shows the generally flat oceanic basement without normal faulting, overlain with sediment sheets containing parallel and nearly horizontal internal reflectors. An igneous high stands in the south, capped with flat-lying Pliocene and younger sediments. Punctuated igneous bodies are more common in the northeast part of the SWSB than the southwest, and even form a huge seamount standing in the fossil spreading center (CDP 18000–21000, Fig. 4). Dates for rocks dredged from this seamount indicate that they



**Fig. 13.** Enlarged seismic section (top) and interpretation (bottom) of the seismic profile N7 shows the titled blocks in the SWSB. These titled blocks are controlled by listric faults facing inward and experienced clockwise rotation. Deformed sedimentary unit U4b distributes in the right half graben but disappears in the left one, marking a transition from domain 2 to domain 3. Vertical exaggeration is two times. See location in Fig. 5.



**Fig. 14.** Enlarged seismic section (left) and interpretation (right) of the seismic profile NH973-1 showing a huge rifted valley in the spreading center. This rifted valley is bordered by two rift shoulders, and is asymmetric with thicker U4 sedimentary unit in the left side. Several secondary faults developed inside the valley. Numerous buried channels could be identified in units U3 and U2, indicating intense turbidite activities. Vertical exaggeration is two times. See location in Fig. 6.



**Fig. 15.** Seismic section (top) and interpretation (bottom) of seismic profile N3 shows a fairly flat oceanic basement in the SW Sub-basin. A small igneous body exists in the right. Vertical exaggeration is two times. See location in Fig. 6.

formed by magmatism after the cessation of seafloor spreading ( $\sim$ 9 Ma, Yan et al., 2014). Igneous bodies with chaotic and disturbed internal reflectors are also observed in seismic profile N7 (CDP 14700 and 16700, Fig. 5), but are less frequent compared to those seen in profile N3.

The width of basement Domain 3 is  $\sim$ 250 km in profile N3 (Fig. 4), and decreases to  $\sim$ 100 km in N7 (Fig. 5). Further to the southwest the entire oceanic basement shows the features of Domain 2 (Figs. 6 and 7). Domain 3 is limited to the northeast part of the SWSB.

## 7. Discussion

#### 7.1. Sedimentary process and controlling factors

#### 7.1.1. Early-Middle Miocene

During the opening of the SWSB in the early Miocene, sediments were generally deposited in a high energy, syn-tectonic environment. Since 16 Ma, the SWSB ceased seafloor spreading and began thermal subsidence, which in turn increased the space for large accumulations of terrigenous sediments. The source of the sediment accumulating at this time is a matter of debate because various possible sources could have contributed. In theory, clastic material could flow to the region from mainland Borneo, but to do this, the sediment would have to cross the rough bathymetry of the Dangerous Grounds, which is marked by many ridges and deep basins that are efficient sediment traps (Yan and Liu, 2004; Hutchison and Vijayan, 2010; Ding et al., 2013). An increasing sedimentation rate from southwest to northeast suggests most of the clastics were transported from the southwest, or from the Indochina peninsula and/or Sunda Shelf. Studies of the sedimentary budget of the continental margins of Southeast Asia indicate high accumulation rates in the Early and Middle Miocene, which might have resulted from the rapid denudation of the Tibetan Plateau during this time, coupled with intensification of the summer monsoon (Clift et al., 2004; Murray and Dorobek, 2004; Clift, 2006; Li et al., 2013). The central rift valley could have acted as an important conduit, as well as a depo-center. The chaotic and high amplitude reflectors imply a distal turbidite origin. Studies of surface currents in the South China Sea also favor transportation from southwest to northeast (Wang et al., 2006).

In other places, especially in the northeast, turbidite deposits are rare and the sedimentary environment is relatively quiet. Bioturbation of the Middle Miocene recovered at Site U1433 is consistent with sedimentation at lower bathyal to abyssal water depths.

### 7.1.2. Late Miocene

In the late Miocene, sedimentation rates decreased in both seismic profiles. A similar decrease in sedimentation rate is also found in the sedimentary basins offshore Indochina (Clift et al., 2004; Clift, 2006; Li et al., 2013). Clift (2006) suggested that the low rates of sedimentation and erosion seen in the late Miocene (11 Ma to 5 Ma) may be linked to increased aridity and a stronger winter monsoon across Asia at that time. Chemical weathering in South China was reconstructed from the chemical index of alteration at ODP Site 1148 (Wang et al., 2003). The results indicate decreased humidity after the late Middle Miocene. This arid climate reduced erosion rates in terrestrial drainage basins, and resulted in low sed-imentation rates both at the continental margin and in the deep sea.

The only exception to this pattern is in the central rift valley where the sedimentation rate is four to five times higher than in other places at this time (Fig. 12a), although the rate was lower compared with that in the Middle Miocene. The wide and deep central valley was not only the depo-center, but also acted as a conduit for terrigeneous sediment transport. These well-developed buried channels indicate an active cyclic cut-fill history. Abundant turbidity deposits are found in Site U1433 cored during IODP Expedition 349, including a large volume of terrestrial clastics (Expedition 349 Scientists, 2014), which indicates active turbidity current.

The frequent carbonate interbeds might have originated from the Macclesfield Bank in the north and the Reed Bank and Dangerous Grounds in the south, where widespread Late Oligocene–Early Miocene carbonate deposits have been discovered from seismic stratigraphic and drilling/dredging works (Schlueter et al., 1996; Franke, 2012; Steuer et al., 2013a; Ding et al., 2013, 2014). Coral reefs continued to develop on the basement highs even into the late Miocene.

#### 7.1.3. Pliocene

In most parts of the oceanic basin, the Pliocene sequence shows totally different reflections from the underlying Miocene and featured with rather homogeneous seismic facies. Site U1433 sees a sharp contrast in lithostratigraphy, changing from interbedded clay and carbonate beneath to primarily clay above. Li et al. (2015) suggested this sharp contrast might indicate a major tectonic event, i.e. the buildup of the Taiwan Orogen, which makes Taiwan be a major provenance for post-Miocene sediments in the South China Sea (Expedition 349 Scientists, 2014). This may be reasonable in the ESB. However the SWSB is far away from the Taiwan Orogen, or the northern continental margin, and the seamounts or seamount chain (such as the Zhongnan Seamount Chain) would have blocked the terrestrial sediments coming from north. Although we can't exclude the possibility that the sharp lithological change is related to the shift from left-lateral to right-lateral strike slip movement along the Red River Fault (e.g., Range et al., 1995; Clift and Sun, 2006), we prefer the opinion that it indicates a change in regional sedimentary environment that occurred around 5 Ma. Since Pliocene most of the shallow carbonate mounds in the Dangerous Grounds were flooded, except some basement highs, such as the Reed Bank (Ding et al., 2014; Steuer et al., 2013b), which caused reduced production and decreasing carbonate flux into the SWSB in the Pliocene (Fig. 3).

Buried channels are still found in the central valley but with decreased frequency. Nonetheless, the sedimentation rate was still higher than that in adjacent areas. We suggest that beginning in the Pliocene there was a decrease in the frequency and volume of turbidity currents, which might be linked to increasing sea level but more likely due to continued subsidence of the continental margins.

Increasing sedimentation rates in the SWSB during Pliocene might result from a strengthened summer monsoon in East Asia inducing a switch to a wetter climate (Wang et al., 2003; Clift et al., 2014). The sedimentary basins under the continental shelf were filled by this time (Murray and Dorobek, 2004; Li et al., 2013; Savva et al., 2013). Onset of the Mekong River delta in its present location may also contribute to the trend.

#### 7.1.4. Pleistocene

The sedimentation rate increased sharply during the Pleistocene and reached a maximum. This increase in sedimentation rate has been recorded in other places as well, such as the European Alps (Kuhlemann et al., 2002), offshore Angola (Lavier et al., 2001), or the offshore Amazon basin (Figueiredo et al., 2009). This supports the idea of the global climate being dominant in controlling continental erosion, as it is unlikely that bedrock uplift in the SE Asia, the Alps, Africa, and South America was synchronous. Zhang et al. (2001) proposed that this worldwide increase in sedimentation rates was driven by the glacial–interglacial climate that changes on time scales of  $\sim$ 100 k.y.

Carbonate turbidites continued to be deposited during the early part of the Pleistocene but then were suddenly truncated. A tectonic subsidence study on the Reed Bank area shows that subsidence rates increased during the Pleistocene (Ding et al., 2014), which might have induced the drowning of carbonate reefs in the Dangerous Grounds, and then reduced the carbonate flux to the abyssal basin. The whole South China Sea began to be dominated by a distal hemipelagic muddy setting with a common, open-ocean siliceous microfossil assemblage and limited influxes of calcareous material. Coring at Site U1433 revealed that the Pleistocene is completely composed of turbidites, with several small turbidite silts stacked on top of one another (Expedition 349 Scientists, 2014).

### 7.2. How were basement domains created?

Until now only two drilling sites (U1433 and U1434) have penetrated into the oceanic basement in the SWSB, and their positions are limited to being near the relict spreading ridge in the northeastern part of the sub-basin. Results from dredging works in the SWSB are not appropriate for determining the nature of the basement, because most of the rock samples were from seamounts. Geochemical analysis of the samples proved they are generally oceanic island basalt (OIB) type with ages between 13.9 Ma and 3.8 Ma (Yan et al., 2014). These were formed after the cessation of seafloor spreading. Thanks to the high-resolution seismic profiles and refraction seismic data, we can now discuss the nature of these basement domains and how they were formed.

#### 7.2.1. Domain 1: hyper-extended continental crust

Seismic interpretations show that basement Domain 1 features (1) well developed faulted sags with thick syn-tectonic sediments; (2) a visible Moho around 8 s (TWT) that shallows oceanward; Refraction seismic data indicate 6 km/s velocities of the upper basement (Ding et al., 2013; Ruan et al., 2011; Qiu et al., 2011). We believe that Domain 1 represents hyperstretched continental crust. Works on the continental margin (Davis and Kusznir, 2004; Ding et al., 2013; Pichot et al., 2014; Savva et al., 2014) and the COB (Franke et al., 2011, 2014) all argued this domain experienced depth-dependent extension. The upper crust undergoes brittle deformation with symmetric crustal blocks bounded by conjugate normal faulting, underlain by ductile necking of the lower crust. Observation from seismic profiles shows the normal faults affecting Unit U5 do not create large basement offsets (Fig. 8), suggesting these faulting are not the main thinning mechanism leading to hyper-stretched continental crust. The necking of lower crust is inferred be the major cause. Non-uniform extension of hyperstretched continental crust is often invoked in magma-poor passive margins, such as the Iberia-Newfoundland rifted margins (Davis and Kusznir, 2004: Manatschal, 2004: Crosby et al., 2011). and the Australian-Antarctic rifted margins (Gillard et al., 2015).

#### 7.2.2. Domain 2: exhumed subcontinental mantle

The transition between Domains 2 and 1 is marked by a basement high (Fig. 8) or arrays of seaward dipping normal faults (Fig. 9). The Moho reflector shallows and joins with the basement reflection in Domain 2. Fig. 8 shows a fragmentary but distinct reflector that rise from depths of >8 s (TWT) to 7 s (TWT) where it apparently merges with the top basement reflection. A similar rising Moho was also observed in the COB further to the southwest, where this reflector shallows over a distance of nearly 30 km (Fig. 7). Domain 2 is not compatible with the occurrence of a steady state oceanic crust because of (1) the presence of major deformation structures, including tilted blocks and detachments, affecting both basement and overlying sediments, and (2) the absence of Moho reflections. 2-D velocity model of the crustal structure and upper mantle derived from a wide-angle refraction seismic profile across the SWSB, with its location close to Profile NH973-1, indicates a <6 km/s upper basement velocity (Pichot et al., 2014), which is lower than that of a typical steady-state oceanic crust (6-7 km/s, Salisbury and Christensen, 1978; Guerin et al., 2008; Gillard et al., 2015). Domain 2 are more comparable and compatible with observation of landward-dipping reflections at the COB and mantle lithosphere exhumation are common at many magma-poor passive margins, including the Iberia-Newfoundland (Hopper et al., 2007; Lau et al., 2006; Péron-Pinvidic and Manatschal, 2009; van Avendonk et al., 2009), Australian-Antarctic (Gillard et al., 2015), and Morocco (Maillard et al., 2006). Several Ocean Drilling Program (ODP) sites (Beslier et al., 1994; Manatschal et al., 2011; Péron-Pinvidic et al., 2013) and dredging sites (Gillard et al., 2015) have discovered serpentinized peridotites in these areas, which appear to be mainly of subcontinental origin (Trommsdorff et al., 1993; Rampone et al., 1995, 1998) and often contain gabbroic intrusions and basaltic dykes (Boillot and Froitzheim, 2001; deMartin et al., 2007).

Thus we interpret Domain 2 to be exhumed subcontinental mantle. The exhumation of mantle material has also been reported in the COB of the NWSB (Franke et al., 2014) and offshore NW Palawan (Franke et al., 2011), which can extend over >50 km between the first clear seafloor spreading anomaly and the interpreted seaward limit of continental crust.

Generally seafloor spreading is dominated more by extensional detachment faulting rather than magmatism when magma budgets are low (Purddy et al., 1992; Morgan and Chen, 1993; Dick et al., 2003). Although magmatism is limited in Domain 2, several igneous bodies still can be identified (Figs. 4 and 15). Locally a highly reflective top basement might also indicate the present of sparse extrusive magmatic rocks above the exhumed subcontinental mantle.

#### 7.2.3. Domain 3: steady-state oceanic crust

Seismic interpretations show that Domain 3 occupies the central area of the northeast SWSB. The transition between Domains 2 and 3 is generally marked by arrays of tilted blocks controlled by seaward-dipping reflectors at the end of Domain 2 (Figs. 4, 5 and 13). This domain is constrained by (1) termination of the syntectonic Unit U4b, and Subunit U4a lying directly on this basement domain without deformation; (2) shallowing of the top basement with a generally flat geometry. High basement velocities are observed (6–7.2 km/s; Zhang et al., 2015), based on 3D wideangle refraction seismic survey in the fossil spreading center in the northeastern SWSB. All these features imply that this domain is oceanic crust formed in a steady state spreading with a high magma budget. Geochemical analysis of the basalt sampled at Sites U1433 and 1434 indicated a typical mid ocean ridge origin (Expedition 349 Scientists, 2014).

## 7.3. Mode of spreading

Here we adopt a conceptual model to describe the general evolution of SWSB seafloor spreading.

Franke et al. (2014) proposed continental rifting of conjugate magma-poor margins. They argued that the continental margin

experienced largely symmetric non-uniform extension controlled by lateral flow in ductile mid-crustal layers, consistent with recent finite element modeling (Clift et al., 2015). Structures in Domain 1 in this study are consistent with this model. The upper crust undergoes brittle deformation with symmetric crustal blocks bounded by conjugate normal faulting, underlain by ductile necking of the lower crust. During the latest extension phase the continental crust became brittle as it thinned and this process is probably linked to the onset of asymmetric extension resembling simple shear characterized by maximum thinning of the crust and the detachment faulting (Fig. 16A).

Faults at the rim of crustal blocks cut through the entire crust and enable a coupling with the mantle, which marks the continental crust boundary and the onset of the continental mantle process (Hayes et al., 1995). Asymmetry became dominant in this stage (Fig. 16B). A propagating spreading model has been generally accepted for the opening of the SWSB that was the result of westward propagation toward the western continental margin (Briais et al., 1993; Huchon et al., 2001; Savva et al., 2014). In the SWSB continental breakup and exhumation of mantle occurred in the northeast while the system still was in the stretching mode in the southwest. We agree with Franke et al. (2014) that the mode of rifting as observed in the SWSB did not result in typical margin-wide simple-shear architecture. Propagating rifting and anisotropy of the continental margin would have alternated the upper or lower plate of detachment system along strike. The upper or lower plate margin may have alternated within tens of kilometers depending on which of the normal faults in the individual rift basins enabled the coupling conceptually developed by Lister et al. (1986).

The extension of the lithosphere continued and lead to the deformation in the exhumed continental margin (Fig. 16C). Extensional detachment faults occurred, resulting in tilted blocks and the deformation of the overlying sediments. Some faults may have served as magma feeders, extruding pillow basalts at the seafloor. The spreading center was not yet localized at that time.

The continental mantle lithosphere finally broke up with the ongoing rise of the asthenosphere, which increased the thermal gradient and caused large-scale melt infiltration into the overlying lithospheric mantle (Fig. 16D). The oceanic spreading was steady state, forming normal oceanic crust. Sediment was deposited directly on the new-formed basement without deformation.

Huismans and Beaumont (2011) proposed two types of end member models of passive margin formation to explain depthdependent extension using numerical modeling experiments. Our observations and interpretations show the spreading of the SWSB fits their Type I model very well. This type usually features (1) a narrow transitional region of crustal thinning; (2) asymmetric geometries with detachment faulting; (3) breakup of crust before the mantle lithosphere; (4) exhumation of continental mantle lithosphere; (5) limited magmatism during rifting, leading to a magma-poor continental margin; and (6) delayed establishment of an oceanic spreading center and normal crust production. Seismic evidence indicates offshore Vietnam, at the southwest tip of the SWSB, the crust is hyper-stretched and the lower crust is missing in some places (Li et al., 2013). The upper crust rests directly onto the exhumed subcontinental mantle (Savva et al., 2013). This is also strong that in the SWSB that breakup of continental crust occurred before the lithospheric mantle.

The magma budget of the SWSB decreases from northeast to southwest appears to be the primary explanation for the observed tectonic variations. Even after the cessation of seafloor spreading there were still plenty of magmatism in the northeast part and the formation of huge seamounts. It is noted that the South China Sea is not a "free-to-go" spreading basin. Its evolution was controlled by the movement of adjacent continental blocks. During



**Fig. 16.** Conceptional model showing the final rifting stages and onset of seafloor spreading in the SWSB, South China Sea (not to scale). (A) The continental margin of South China Sea experienced depth-dependent stretching since the late Cretaceous. In the final stage of continental rifting detachment fault occurred and cut through the entire brittle crust, enabling a coupling with mantle. (B) Continental mantle exhumation along a detachment fault that develops from the previous crustal-scale fault at the rim of crustal blocks. (C) Continued lithospheric extension lead to the presence of major deformation structures affecting both basement and overlying sediments. (D) Breakup of the lithosphere, the asthenospheric mantle reaches the surface. A steady state seafloor spreading begins with accretions of normal oceanic crust and post-rift volcanism.

the Middle Miocene the southern continental margin, including the Reed Bank and Dangerous Grounds, collided with Borneo and ceased the opening of the basin. The southwestern SWSB stopped spreading before it had achieved steady state. This may explain why the extent of Domain 3 formed during steady state spreading decreases from northeast to southwest, and is absent in the southwest part of the SWSB.

# 8. Conclusions

We interpreted four multi-channel seismic profiles from the SWSB to study spreading dynamics and sedimentary processes through calibration with recently conducted drilling at IODP Sites U1433 and U1434. Four sedimentary units were identified with different reflectors and lithologies, i.e., Pleistocene, Pliocene, Upper Miocene, and Middle Miocene and older. Two abrupt changes in seismic facies were identified. One is along the Miocene–Pliocene boundary at about 5 Ma. The other is very close to the Pliocene–Pleistocene boundary.

Reconstruction of the sedimentation rates shows low rates during the late Miocene (11.6–5.4 Ma), followed by increasing rates in the Pliocene, and reaching maximum rates in the Pleistocene. Increased aridity and a stronger winter monsoon across Asia in the late Miocene limited continental erosion, as well as accumulation on the continental margin and abyssal basin. Since the Pliocene, the summer monsoon dominated Asia again and the glacial-interglacial climate controlled continental erosion, inducing increased accumulation rates in our study area. Onset of the Mekong River delta in its present location may also contribute to the trend.

Comparison of sedimentation rates in different places implies the possibility that the terrestrial sediments originated from the southwest, i.e., the Indochina peninsula and Sunda Islands. The source of the carbonate interbeds is most likely within the Dangerous Grounds and the Reed Bank area to the south, or the Macclesfield Bank in the north. The central spreading valley of the SWSB acted as both the main conduit and depocenter. Future petrological and geochemical analysis of recovered sediments from Sites U1433 and U1434 should provide more detail about the provenance of the sediments.

Geophysical observations from the basement structure and overlying sediments identify three types of basement, i.e. Domain 1: hyper-stretched continental crust, Domain 2: exhumed subcontinental mantle, and Domain 3: steady state oceanic basement. A model of spreading has been proposed that the SWSB has experienced depth-dependent stretching in the final stage of continental rifting, resulting in hyper-stretched continental crust and detachment faulting penetrating down to the Moho enabling a coupling with the mantle. As the extension continued, mantle exhumation occurred with well-developed tilted blocks, normal/detachment faulting and deformation of the overlying sediments. Finally the lithosphere broke up with the ongoing rising asthenosphere, and stable, sustainable oceanic accretion formed the oceanic Domain 3. The fact that this steady state oceanic domain only exists in the northeastern SWSB may imply a higher magma budget in that part and a propagation of rifting to the southwest. The southwest-ern SWSB was still dominated by subcontinental mantle exhumation before the cessation of seafloor spreading.

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