Sedimentary budget of the Southwest Sub-basin, South China Sea: Controlling factors and geological implications

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1 INTRODUCTION

The Tibetan Plateau uplift and formation of the West Pacific marginal seas are the two major tectonic events in Eurasian Mesozoic–Cenozoic geologic history (Clark et al., 2005; Clift, Layne, & Blusztajn, 2004; Hall, 2002). These two events induced the largest source-sink system in the world, that is, a huge amount of terrestrial sediment is transported from the Tibetan Plateau to the Indian Ocean and the West Pacific marginal seas. Understanding of this source to sink process needs an integral study on the continent uplifting, weathering and erosional events, evolution of the Asian monsoon, the development of large Asian rivers, and the formation of marginal basins (Wang, Zhao, & Jian, 2003; Yang, 2006; Zheng et al., 2008). As one of the largest marginal sea basins in West Pacific, the South China Sea (SCS) plays a significant role in mass transport and accumulation since the initial continental rifting in the Late Cretaceous. Except partial accumulation in river beds and onshore basins, most terrestrial sediments enter the SCS via different river systems, including the Pearl, the Red, and the Mekong rivers. With only 0.9% of the global sea area, the SCS reserves 5.5% of the global total sediment mass (Wang & Li, 2009).

Sediment budget research in the SCS is the key to understanding the Cenozoic sedimentary processes, which include not only sediments deposited in the continental shelf and slope area but also the abyssal basin. Well-developed rifted basins in the continental margin have

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trapped most of the river-borne terrigenous sediments, therefore most prior researches in the past few decades have focused on the Pearl River Mouth Basin in the northern continental margin (Clift, Wan, & Blusztajn, 2014), the Indo-China Peninsula continental margin in the west (Clift, 2006; Lee, Lee, & Watkins, 2001; Li, Clift, & Nguyen, 2013; Liu, Zhao, Li, & Colin, 2007; Murray & Dorobek, 2004), the Yinggehai Basin in the northwest (Fyhn, Boldreel, & Nielsen, 2009), and the Dangerous Grounds in the south (Hanebuth, Stattegger, & Saito, 2002; Hazebroek & Tan, 1993; Hutchison, 2004, 2010; Schlueter, Hinz, & Block, 1996). However, if the abyssal basin is not considered, sediment budget calculation of the total SCS basin area is incomplete, which hinders our understanding of a full-scale sedimentary process. Because of the shortage of geological and geophysical data in the abyssal basin of the SCS, especially the lack of research about the sedimentary budget using the multichannel seismic and drilling data, knowledge about the lithology and age of the sedimentary units are very limited. Huang and Wang (2006) calculated the total sediment mass of the SCS and the sediment budget in different geologic times. But the lack of drilling constraints in the abyssal basin area decreased the accuracy of the results.

In 2014, International Ocean Discovery Program (IODP) Expedition 349 (South China Sea Tectonics) drilled five sites in the SCS abyssal basin area for the first time, three of which (U1431, U1433, and U1434) penetrated the basaltic basement (Figure 1; Li et al., 2014; Li et al., 2015). Sedimentary units above the oceanic crust now can be divided precisely on the basis of detailed lithological information, and dating of microfossils provides accurate depositional ages for the different units. Integration of drilling, downhole geophysical logging, and seismic data now make a seismic stratigraphy study of the abyssal basin possible and provide an opportunity to reconstruct the Cenozoic sedimentary process. In this study, we calculated the sedimentary budget of the abyssal basin in different geological times. The sedimentary budget of the continental margin of Vietnam, including the Mekong River continental shelf and slope area; estimated the sediment budget at different stages; and analysed the sediment sources for the whole basin. This study will improve our understanding of the sediment budget of the study area.
budget changes of the Southwest Sub-basin (SWSB) and its controlling factors, such as changes in East Asia tectonic settings, climate, continental margin river systems, and the evolution of the East Asia monsoon.

2 | GEOLOGICAL SETTING

Most scientists agree that the SCS was a part of the South China margin during the Mesozoic and experienced epidotic rifting due to stress field changes resulting from rollback of the Pacific subduction belt since the Late Cretaceous (Hall, 2002; Pubellier & Morley, 2014; Yao, Zeng, & Hayes, 1944; Zhou, Ru, & Chen, 1995). Numerous rifted basins developed in the present northern and southern continental margins of the SCS, including the Pearl River Mouth Basin, the Qiongdongnan Basin, the Yinggehai Basin, and the Reed Bank Basin. Meanwhile, the direction of tensile stress rotated clockwise (Cullen, Reemst, Henstra, Gozzard, & Anandaraoop, 2010; Franke et al., 2014; Sun et al., 2009). With continuing extension, seafloor spreading occurred in the Early Oligocene. The opening scenario proposed by Taylor and Hayes (1980, 1983) and Briais, Patriat, and Tapponnier (1993), based on magnetic anomaly interpretations, has been generally accepted, that is, seafloor spreading occurred from 32 to 16 Ma (magnetic anomalies 11–5c). An N–S trending spreading event occurred first, forming the East Sub-basin (ESB) and Northwest Sub-basin, which continued until ~24 Ma, after then the spreading direction changed to NW–SE. The SWSB opened as seafloor spreading continued in the ESB. Seafloor spreading ceased at about 16 Ma because of the collision between the Dangerous Grounds and Borneo (Clift et al., 2008; Cullen et al., 2010; Hutchison, 2010; Hutchison, Bergman, Swauger, & Graves, 2000). Although scientists have proposed different seafloor spreading cessation ages on the basis of more recent ship-borne magnetic data (20.5 Ma, magnetic anomaly 6A1, Barckhausen & Roeser, 2004; Barckhausen, Engels, Franke, Ladage, & Pubellier, 2014), IODP Expedition 349 results and deep tow magnetic data (Expedition 349 Scientists, 2014; Li et al., 2014) have confirmed that the cessation time is ~16 Ma.

The SCS basin has been in a steady state since the Middle Mio-
cene. The continuous NNW motion of the Philippine Sea Plate resulted in eastward subduction of the SCS and the formation of the N–S trending Manila Trench (Sibuet & Hsu, 2004), which finally caused the SCS to become a semi-closed marginal sea.

The V-shaped, triangular SWSB opens to the northeast, including the abyssal basin, the Mekong continental shelf, and Mekong continental slope. The total length is nearly 600 km with an area of 115,000 km², with water depths between 3,000 and 4,300 m. It is bounded by several tectonic units: to the north are the Zhongsha and Xisha Islands; the Reed Bank and Dangerous Grounds lie in the south; the Indo-China Peninsula borders its west and is the closest continent to this basin; and the Zhongnan Fracture Zone separates the SWSB from the ESB in the east. The Mekong River mouth is located in the southwestern SWSB and forms the Mekong Delta on the Mekong shelf. As described above, the northern and southern margins of the SWSB have been in a tectonic steady state since the Middle Miocene. However, intra-plate tectonic activities were still occurring in the Indo-China Peninsula, including uplift of the Central Highland in Vietnam and extrusion of a basaltic layer (Carter, Roques, & Bristow, 2000; Cung et al., 1998). In the southern part of the SWSB, only weak current compressional movement occurred offshore and along the margins of northern Borneo (Hinz et al., 1989; Simons et al., 2007).

3 | DATA AND METHOD

Huang and Wang (2006) supposed that the thickness of each sedimentary unit between two seismic interfaces changed in proportion. In this study, we obtain large amount of seismic data and drilling data. Six multichannel seismic profiles were interpreted in this research, which run across the SWSB in a NW–SE orientation (Figure 1). Seismic Profiles N3, N7, and N10 were acquired during the National Ocean Project cruise by the Second Institute of Oceanography, State Oceanic Administration in 2004. Seismic Profile NH973-1 was obtained during “project 973 cruise” in 2009. Seismic Profiles SO49-22 and SO49-23 were collected by a China–Germany joint survey, SO49, in 1989.

IODP Expedition 349 drilled two sites in the SWSB that penetrated into the basaltic basement, U1433 and U1434. Seismic Profile N3 runs through these two drilling sites. Site U1433 is located in a sedimentary depression 50 km from the fossil spreading ridge and documents the integrated sedimentary records after seafloor spreading (Figure 2). Site
U1434 lies much closer, with thin sedimentary deposit. Based on the sedimentary lithology obtained from these two sites, as well as palaeomagnetism and palaeontology dating data, we divided the sedimentary units and set age controls of the sequence boundaries.

Interpreted multichannel seismic profiles were converted to depth by time-depth conversion. Logging was carried out at Site U1433 and provided accurate time-depth conversion information. The time-depth conversion function presents as follows (according to Li et al., 2014; Li et al., 2015):

\[ Z = 0.000152626t^2 + 0.714658t. \]

Where, \( t \) stands for the two-way travel time starting from the seafloor (in milliseconds), and \( z \) is the depth in meters below the seafloor (m-bsf).

After time-depth conversion, we decompacted each sedimentary unit in order to obtain their original thickness using the program FlexDecomp™ by Kusznir, Roberts, and Morley (1995). During the decompaction process, the porosity loss of the sediment and biogenic component should be estimated. Therefore, the average porosity of each sedimentary unit was utilized to estimate the porosity loss. Generally, lithology has a great effect on decompaction. For example, the porosity of shale is much lower than sandstone after burial (Sclater & Christie, 1980). We also constrained the decompaction with lithological information from Sites U1433 (Figure 3) and U1434. One the other hand, biogenic component can be assessed and removed from the budget by using the drilling data of U1433 (Figure 3) that determine the carbonate fraction (Clift, 2006).

After we obtained the uncompacted thickness of each sedimentary unit, we calculated the sediment volume at different geological times. The calculation process for each sedimentary unit is as follows: first, we used GeoFrame to obtain the top and bottom interface grid data for the sedimentary units by automatic interpolation; then we imported these grid data into Surfer software to calculate the volume between different interfaces. Finally, we obtained the sediment volume (km²) and average sedimentary rate for different sedimentary units. Total sedimentary budget of the whole basin is then calculated by adding all the sedimentary units together. Errors in the calculation results have several causes: (a) The time-depth conversion error is as assumed to be 5% (Li et al., 2014); (b) errors in estimating the sediment age, lithology, and compaction history rarely exceed 5% (Clift, 2006); (c) errors in calculating the sedimentary volume for different sedimentary units are assumed to be 10% at most, because of the limited 2D seismic lines. Even so, compared to previous study, these errors reduce because the confirmation of the sedimentary units are more accurate. Thus, we set the total error range as 20%.

Terrestrial matter will deposit on the continental shelf, slope, and abyssal basin sequentially after they enter the ocean. Therefore, we combined the sedimentary budget in the abyssal basin and the Mekong continental shelf and slope area together to study the total terrestrial sediment entering the SWSB, which can help us to understand the general change of terrestrial sediment volume and regional controlling factors. The sedimentary budget in the Mekong shelf and slope area is obtained from Clift (2006) and Li, Ding, Wu, Zhang, and Dong (2012).

## RESULTS

### 4.1 Seismic stratigraphy

At Site U1433, we find that the upper part of Pleistocene sediments is composed of dark–green mudstone interbedded with pelitic siltstone and the lower part is mudstone interbedded with thin carbonate (Figure 2). And the Pleistocene sediments in the seismic profile also show different seismic characteristics, that is, the upper part shows strong seismic reflectivity, and the lower part is much weaker (Figure 3). In addition, the upper Pleistocene sediments are more homogeneous than the lower part. The Pliocene sequence recovered at Site U1433 is dark–green mudstone interbedded with carbonate, which is the similar lithology as the lower Pleistocene. So, the two parts of sediments show similar weak reflectivity. And the existence of thin carbonate layers are interpreted as turbidite deposition (Expedition 349 Scientists, 2014). The boundary between the Pliocene and Late Miocene sediments is obvious in the seismic profile, that is, the seismic reflectivity is weak above the boundary but strong below this boundary. And the lithology of the Late Miocene sediments is dark–green or grey mudstone interbedded with thick to extremely thick (over 1 m in thickness) dark–green ultramicro fossil. The last sediments above the basement is bulk red–brown or yellow–brown mudstone and silty muddy shale with few coarse components, with occasional occurrence of thin silty turbidity and dark part caused by biological disturbance partially. Because Sites U1433 are very close to the fossil spreading ridge and does not reach the Early Miocene, we take the Early and Middle Miocene as one sedimentary unit. The basement is mainly composed of basalt and shows chaotic seismic reflectivity.

According to the division scheme of sedimentary units, we interpret six multichannel seismic profiles across the SWSB (Figure 4). The sediments are divided into four sedimentary units from top to bottom,

![FIGURE 3](The lithostratigraphy at Site U1433. See Figure 1 for location [Colour figure can be viewed at wileyonlinelibrary.com])

| Age       | Geological Time | Lithology                  | Lithology Description                          |
|-----------|----------------|----------------------------|-----------------------------------------------|
| 5 Ma      | Pleistocene-present | The upper part is dark green mudstone interbedded with pelitic siltstone. The lower part is mudstone interbedded with thin carbonate. |
| 10 Ma     | Pliocene       | Dark green mudstone interbedded with thin carbonate. |
| 15 Ma     | Miocene        | Bulk dark reddish or yellowish brown mudstones and silty muddy shales with few coarse components, with occasional occurrence of thin silty turbidity and dark part caused by biological disturbance. |
|           | early          | Bulk reddish brown or yellowish brown mudstones and silty muddy shales with few coarse components, with occasional occurrence of thin silty turbidity and dark part caused by biological disturbance. |
|           | middle         | Bulky reddish brown or yellowish brown mudstones and silty muddy shales with few coarse components, with occasional occurrence of thin silty turbidity and dark part caused by biological disturbance. |
|           | late           | Bulky reddish brown or yellowish brown mudstones and silty muddy shales with few coarse components, with occasional occurrence of thin silty turbidity and dark part caused by biological disturbance. |

### 4.2 Palaeomagnetism and palaeontology dating data

We divided the sedimentary lithology obtained from these two sites, as well as palaeomagnetism and palaeontology dating data, we divided the sedimentary units and set age controls of the sequence boundaries. Interpreted multichannel seismic profiles were converted to depth by time-depth conversion. Logging was carried out at Site U1433 and provided accurate time-depth conversion information. The time-depth conversion function presents as follows (according to Li et al., 2014; Li et al., 2015):

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According to the division scheme of sedimentary units, we interpret six multichannel seismic profiles across the SWSB (Figure 4). The sediments are divided into four sedimentary units from top to bottom,
with the sequence of the Pleistocene sediments, the Pliocene sediments, the Late Miocene sediments, and the Early–Middle Miocene sediments.

4.2 | Sediment budget calculation results

Based on the sediment budget calculation method described above, we estimated the sediment budget of the SWSB in different geological times. The results are shown in Figure 5a. At the same time, we also combined previous works on the Mekong shelf (including Mekong river delta, Jiulong Basin, and Wanan Basin, mainly according to Clift, 2006) and the Mekong slope (data from Li et al., 2012) to calculate the sediment budget in these areas (Figure 5b,c). All these results are added together to obtain sediment budget changes for the whole SWSB in different ages (Figure 5d).

The sediment budget of the four sedimentary units in the abyssal basin is in a U-shape (Figure 5a). The sedimentary rate during the Early–Middle Miocene was $5.0 \pm 1.0 \times 10^3 \text{ km}^3/\text{my}$ and reduced slightly to $4.0 \pm 0.8 \times 10^3 \text{ km}^3/\text{my}$ in the Late Miocene. During the Pliocene, this value increased and reached $7.5 \pm 1.5 \times 10^3 \text{ km}^3/\text{my}$. During the Pleistocene, the sedimentary rate increased again to $15.8 \pm 3.1 \times 10^3 \text{ km}^3/\text{my}$, almost twice of the previous rate.

In the Mekong continental shelf area (including the Wanan Basin and the Jiulong Basin), the sediment budget changed greatly over time (Figure 5b). The sedimentary rate was $10.0 \pm 2.0 \times 10^3 \text{ km}^3/\text{my}$ in the Palaeogene, and increased to $22.0 \pm 4.4 \times 10^3 \text{ km}^3/\text{my}$ in the Early Miocene. It increased sharply during the Middle Miocene and reached a peak of $31.0 \pm 6.2 \times 10^3 \text{ km}^3/\text{my}$. From approximately 8 Ma, the sedimentary rate decreased dramatically to about $23.0 \pm 4.6 \times 10^3 \text{ km}^3/\text{my}$, then increased slightly since the Pliocene and remained at $26 \pm 5.2 \text{ km}^3/\text{my}$ since then.

The change of the sedimentary rate in the Mekong continental slope area was similar with that of the shelf area in the Palaeogene and Early Miocene (Figure 5c). The sedimentary rate was
15.0 ± 3.0 × 10³ km³/my in the Palaeogene and increased to 25.0 ± 5.0 × 10³ km³/my in the Early Miocene. In the following stages, the sedimentary rate on the Mekong continental slope was high with some minor variations, and the peak appeared between 8 and 5 Ma. The sedimentary rate decreased during the Pliocene and increased again in the Pleistocene, reaching a maximum of approximately 36.0 ± 7.2 × 10³ km³/my.

The sediment budgets of the Mekong continental shelf, the Mekong continental slope, and the abyssal basin have distinct characteristics. The peak in sediment budget occurred in the Middle Miocene for the continental shelf, while in the Late Miocene for the continental slope, and much later for the abyssal basin. The extension of the southwestern continental margin continued until the Middle–Late Miocene and was continuously able to accommodate sediments. Terrestrial sediments filled the continental shelf first, then the continental slope areas before finally entered into the abyssal basin, explaining why peaks of the sediment budget occurred at different times for different regions.

We combined the sediment budgets of the abyssal basin, Mekong continental shelf and Mekong continental slope together to obtain the sediment budget changes for the whole SWSB (Figure 5d). The sedimentary budget generally increased since the Eocene and reached its first peak in the Middle Miocene. Then, it decreased during the Late Miocene, with a slight increase in the Pliocene. The sediment budget increased rapidly during the Pleistocene and has remained high to the present.

5 | DISCUSSION

5.1 | Controlling factors in sediment budget changes

The ESB of the SCS began seafloor spreading since the Early Oligocene, while the southwestern SCS was still part of a passive continental margin and developed thinned continental crust and rift basins. Sediments mainly deposited on the bottoms of continental margin basins during this stage with low volumes.

During the Early Miocene, the sediment budget of the SWSB increased sharply (the increment was about 20.0 × 10³ km³/my), especially in the Mekong continental shelf (10.0 × 10³ km³/my) and slope areas (10.0 × 10³ km³/my). Because there was no strong change in the global icehouse climate in the Early–Middle Miocene period (Zachos, Pagani, Sloan, Thomas, & Billups, 2001) (Figure 6), the trigger for the enhancement of land erosion during this stage was not sharp climate change. Clift et al. (2004) considered that the sedimentary rate change in East Asia since 33 Ma may reflect strong uplift of the Tibetan Plateau since the Late Oligocene, coupled with intensification of the summer monsoon, thereby increasing weathering and erosion. This point has been supported by works in other study areas of Himalayas (Finlayson, Montgomery, & Hallet, 2002; Lave & Avouac, 2001). Consequently, the increase of sediment budget in the SCS was mainly related to tectonic factors, that is, the uplift of the Tibetan Plateau and the southeastward extrusion of related blocks (including Indo-China and other blocks) (Molnar & Tapponnier, 1975; Tapponnier & Molnar, 1976, 1977; Tapponnier, Peltzer, Ledain, Armijo, & Cobbold, 1982). Quick basement thermal subsidence in the SWSB also contributed the increasing sedimentary rate. Cao, Li, and Yao (2017) calculated to the thermal subsidence by fitting the isostatically balanced basement depths from the seismic profiles with the half space cooling model. The estimated thermal diffusivity of the lithosphere in the SWSB is much higher than that in the ESB. As a result, more terrestrial sediments were transported to the space-increased SWSB via river systems.

The continued increase of the sediment budget for the whole basin during the Middle Miocene also might have related to the similar tectonic factors, that is, the uplift of the Tibetan Plateau and accelerated southeastward extrusion of Indo-China Peninsula.
The opening of the SWSB provided more space for terrestrial sediments, but the sediment budget of the abyssal basin in this period (5.0 ± 1.0 km³/ky) was lower than that of the continental shelf (31.0 ± 6.2 × 10³ km³/ky) and slope areas (25.7 ± 4.9 × 10³ km³/ky) (Figure 4). Previous researches on the Cenozoic SCS rifted margin imply a general pattern that the time of cessation of rifting differs, that is, it gets younger from east to west. The unconformity that marks rifting cessation in the Reed Bank and eastern Nansha area was in the Early Miocene, which was the Middle Miocene in the western Nansha area (Zhongjian, Wanan, and Jiulong basins in the southwest most (Ding et al., 2016; Franke et al., 2014; Li et al., 2012; Savva et al., 2014). The terrestrial sediment transported via river will deposited in the continental shelf and slope area first before entering the abyssal basin. Because the Mekong continental shelf basin was still rifting during the Middle Miocene and had space for terrestrial sediments, the continental shelf sediment budget in this stage reached its peak (Figure 4b). Although the continental slope sediment budget increased, the change was not as obvious as that in the continental shelf area (Figure 4c).

During the Late Miocene, especially since 8 Ma, the entire southwestern SCS sediment budget decreased about 6.4 × 10³ km³/ky. This was mainly due to the significantly reduced sediment budget in the Mekong continental shelf (the reduction was about 7.9 × 10³ km³/ky). Sediment budget reduced slightly in the basin area (1.0 km³/ky approximately) but increased about 3.6 km³/ky in the Mekong continental slope area. Clift (2006) believed that the reduction of the denudation rate in the Late Miocene may be bound up with the increased aridity and a stronger winter monsoon across Asia at that time. The reconstructed chemical weathering history, according to the "Chemical Index of alteration" (CIA), from samples of ODP Site 1148 in the northern margin of the SCS, also demonstrated that the humidity in South China has decreased since the Middle Miocene (Wan, Li, Berend, Stuut, & Xu, 2007; Wang et al., 2003). The cold and dry climate weakened land erosion, as well as the sediment transported via onshore river systems, resulting in low sediment budget both at the continental shelf area and in the abyssal basin. The increased sedimentary budget in the continental slope area might be linked to the cessation of rifting and infilling of related rifted sags in the Mekong continental shelf. The terrestrial sediments would have flowed over the shelf area and mainly deposited in the continental slope area. Geological studies of the Mekong slope area on the basis of interpreted seismic profiles implied that rifting continued until the Early Pliocene (5.3 Ma) (Li et al., 2012), and thus the continental slope still had space for sediments, leading to the increase of sediment budget.

During the Pliocene, the East Asian summer monsoon strengthened again, and the climate switched to warm and humid (Clift et al., 2014; Wang et al., 2003; Wang et al., 2011). As Figure 6 shows that the mass of global sediment and the δ¹⁸O value increased rapidly since the Pliocene, we can infer that more terrestrial sediments were transported into the SCS and the temperature increased obviously. Therefore, the sediment budget increased for the entire area. In terms of transport process, the rifted sags in the Mekong continental slope had been filled in by this stage. Sediment was transported over the continental slope and enter directly into the abyssal basin. This is indicated by the decreased sediment budget in the continental slope area and the increased one in the abyssal basin.

The sediment budget for the entire area significantly increased and reached a peak during the Pleistocene. This increase in sedimentation can be observed in many other regions as well, including the European Alps region (Kuhlemann, Frisch, & Szekely, 2002), the Angola continental margin of West Africa (Lavier, Steckler, & Brigaud, 2001), and the offshore part of the Amazon basin in South America (Figueiredo, Hoorn, van der Ven, & Soares, 2009). This indicates that land erosion was dominated by global climate change, which is consistent with the increasing δ¹⁸O curve in Figure 6. Zhang, Molnar, & Downs, 2001 suggested that this global sediment budget growth was driven by the glacial-interglacial climate variations that rapidly changed on time scales of ~100 Ky. On the other hand, the abrupt increment of the global sediment mass on the ocean floor since the Pleistocene also indicates that the sediment budget change is widely distributed around the world.

### 5.2 Sediment provenance

The Late Miocene marks the change of sediment budget in the abyssal basin. Site U1433 only penetrated thin Middle Miocene sediments,
that is, bulk red–brown or yellow–brown clay and silty clay, and the sedimentary rate was extremely low (Expedition 349 Scientists, 2014). Because this site was very close to the fossil spreading ridge, this sedimentary unit thickens towards the continental slope area, as well as southwest part of the abyssal basin. Sediment provenance in this stage had many possibilities, such as the Philippine Islands in the east, Borneo in the south, the Sunda in the southwest, and the Indo-China Peninsula in the west. The Nansha Block collided with Borneo at about 16 Ma, and uplift event occurred in southern Borneo first. No remarkable uplift occurred in northern Borneo until 12 Ma (Honza, John, & Banda, 2000). Moreover, Borneo and the abyssal basin area were separated by the wide Nansha area with well-developed rifted sags and basement highs, which trapped most of the sediments from the Borneo (Ding, Franke, Li, & Steuer, 2013). Thus, Borneo may not be the main sediment source area. The Red River and the Pearl River in the South China Block were also far away from the SWSB. Sediments transported by the Red River mainly accumulated in the Yinggehai Basin, especially after 5.5 Ma due to fast basement subsidence which generated huge accommodation for terrigenous sediments (Lei et al., 2015). While those transported by the Pearl River were trapped in the Pearl River Mouth Basin because of the fast thermal subsidence after the middle Miocene (Chen, 2014; Clift, Brune, & Quinteros, 2015). The Philippine Islands to the east not only have long distance from our study area but also are separated by the deep Manila Trench.

The Sunda Islands were probably the dominant sediment source for the abyssal basin area. During low stand of sea level, sediment transported from the Sunda Islands and the Malay Peninsula could enter the abyssal basin through rivers across the exposed Sunda continental shelf, such as the Molengraaff River. However, the global sea level eustatic curve reconstructed by Haq, Hardenbol, and Vail (1987) shows that during the Early–Middle Miocene, the sea level was in high stand. There is little possibility that the Sunda Islands were the sediment provenance of the SWSB during the Early–Middle Miocene period, although we cannot exclude it.

Sr isotope analysis of Site U1433 sediments demonstrated high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and relatively negative $e_{\text{Nd}}$ values (Liu et al., 2017), similar to small coastal rivers draining Indo-China Peninsula (Jonell et al., 2016). In addition, the Indo-China Peninsula continental shelf is narrow, thus the Indo-China Peninsula becomes the most probable sediment provenance. Meanwhile, on the west of the SWSB, the sedimentary units show well-developed steeply dipping clinoforms prograding toward the centre of the basin in six multichannel seismic profiles (Figure 4). These clinoform structures also provide paths for sediment influx from the Indo-China Peninsula. This observation is consistent with the opinion described above that the accelerated sediment budget in this stage was ascribed to uplift of the Tibetan Plateau and increased erosion resulting from accelerated extrusion of blocks on the southeastern margin of the plateau (including Indo-China). It is also likely that some of the sediments in the SWSB were derived from the reef areas of the Nansha area and the Reed Bank to the south, as well Palawan which is close to the abyssal basin. In seismic Profiles N3, N7, NH973-1 and N10 (Figure 4), downlapping structures well developed on the southeastern side of the abyssal basin. Downlapping relationship with the abyssal sedimentary units indicates a probable sediment flux from the Nansha area and the Reed Bank, even Palawan.

Since the Late Miocene, sediments in Site U1433 consist of dark-green or grey–green clay with thick grey–green chalk with rich nanofossils (Li et al., 2015). Based on sedimentary rate analyses in different regions of the SWSB, Ding et al. (2016) proved that sedimentary rate in the southwestern part is much higher than that in the northeast. Abundant buried channels are identified in the central valley, indicating active mass transportation from the southwest direction. Drilling data from the northern continental margin of SCS demonstrated that chemical weathering is weakening since 16 Ma (Clift et al., 2014). Thereby, the increasing sedimentation rate in the SWSB since the Late Miocene implies that the sediment probably is derived from the modern Mekong River under steady weather conditions and from small river systems of the Indo-China Peninsula. Of course, we could not exclude the contribution of the Sunda Islands and the Malay Peninsula during low stand of sea level.

Carbonate deposits, including carbonate platform and coral reef on the top of the basement highs, were well developed in both the southern and northern continental margins in the SCS since the Late Oligocene (Ding et al., 2013; Ding, Li, Dong, & Fang, 2015; Ma et al., 2011; Wu, Zhao, & Dong, 2011; Xie, Zhang, & Ren, 2011). Although most carbonate platforms were drowned since the Middle Miocene, the reefs on the basement highs could continue their growth even to the Late Miocene (Steuer et al., 2013), which was transported into the abyssal basin and formed thick carbonate interlayers in the clay or silty clay in the SWSB, with a thickness of 1m. Drilling data showed that since the Pliocene, carbonates thinned abruptly and disappeared in the Pleistocene (Li et al., 2015). We suggested that this phenomenon was associated with intensified tectonic subsidence in the SCS continental margin and rising sea level, resulting in the drowning of most of the coral reefs, which in turn reduced carbonate input into the abyssal basin. Coral reefs can grow to the present in limited areas, such as the Reed Bank, Zhongsha Islands, and the Nansha Islands, but their contributions to basin area carbonate deposit are minor.

6 CONCLUSIONS

We calculated the sediment budget of the SWSB at different times on the basis of the interpretation of six multichannel seismic profiles across the SWSB and the drilling data from IODP Expedition 349. The sediment budget data of the Mekong continental shelf and slope areas was also integrated to reconstruct the depositional evolution of the whole SWSB. Our researches showed that the increasing sediment budget were mainly related to the tectonic event in the Early–Middle Miocene, that is, strengthened erosion resulting from uplift of the Tibetan Plateau and southeastward extrusion of related blocks (including Indo-China and other blocks). During the Middle Miocene, the sediment budget was primarily controlled by Asian monsoon. The strengthened winter monsoon modified the climate to cold and dry, which reduced the sediment transportation to the SWSB via river systems. The summer monsoon in the Pliocene made the climate warm and wet again, favouring chemical weathering and erosion, increasing the sediment budget. The sediment budget of the whole area peaked during the Pleistocene, driven by global glacial–interglacial cycle changes.
On the basis of our research on the lithology information of the drilling data and analysis of the structure characteristics of seismic profiles, combined with Sr isotope analysis collected in the study area, we also examined the terrigenous sediment provenance and transport process of the SWSB. The sediment provenance of the SWSB is quite different before and after the Late Miocene, which corresponds with the results of the sediment budget changes of the SWSB. Before that time, detrital sediments in the SWSB mainly originated from the Indo-China Peninsula, the Nansha area, and Palawan. While after the Late Miocene, depositions were mainly derived from the Mekong River, probably together with minor contribution from the Indo-China Peninsula small river systems. The Sunda Islands and the Malay Peninsula during low stand of sea level might also have some additional contribution during this period. In addition, the carbonate interlayers developed in the abyssal basin area were derived from carbonate depositions that were widely distributed in the southern and northern continental margins of the SCS.

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