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

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

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1. Introduction

Variations in sedimentary budgets through time in onshore and offshore basins can be used to constrain erosion rates and be related to tectonic and climate changes to test for possible links (Clift and Sun 2006; Yan et al. 2011). As one of the largest marginal sea basins in the Western Pacific, the South China Sea (SCS) plays a significant role in mass transport and accumulation since the initial continental rifting in the Late Cretaceous (e.g. Clift 2006, 2015; Huang and Wang 2006; Liu and Stattegger 2014). The SCS is a significant sink and receives approximately 700 million tons of sediments annually, of which approximately 80% are supplied by the Mekong, Red, and Pearl Rivers, while the remainder is derived from smaller mountainous rivers (Huang 2004; Liu et al. 2008). Sedimentary flux changes in the SCS could reflect its response to interplays between climate, tectonics, and the evolution of large-scale drainage patterns during different geological times (Clark et al. 2004; Clift 2006; Clift and Sun 2006; Yan et al. 2011).

Systematic reconstruction of the sedimentary budget of the SCS must consider the sediments deposited both on the continental margin and the abyssal basin. Given the abundant multichannel seismic surveys and commercial drilling works for hydrocarbon exploration in the continental margins, sedimentary processes and tectonic activities in those settings have been extensively studied, including the Yinggehai-Song Hong Basin (Clift and Sun 2006; Yan et al. 2011; Lei et al. 2015), Qiongdongnan Basin (Gong et al. 2011; Hu et al. 2013), and Pearl River Mouth Basin (Ding et al. 2013a; Li et al. 2016; Sun et al. 2017) in the northern continental margin, the Indo-China Peninsula continental margin in the west (Lee et al. 2001; Murray and Dorobek 2004; Clift 2006; Liu et al. 2007; Li et al. 2013), and the southern continental margin (Steinke et al. 2003; Charles and Hutchison 2004). All these previous works significantly contributed to our understanding of Cenozoic sedimentary processes and controlling factors in the SCS. However, the sedimentary budget analysis of the abyssal basin remains limited because of the lack of drilling wells.
In 2014, International Ocean Discovery Program (IODP) Expedition 349 drilled five sites in the abyssal basin; at three sites, basalt near the fossil spreading ridge was penetrated and the overlying sedimentary cover was recovered (Li et al. 2015a). In the subsequent IODP Expeditions 367 and 368 in 2017, seven sites were drilled in the continent-ocean transition zone, with two of which penetrated the basaltic basement of the oceanic basin (Jian et al. 2018; Sun et al. 2018). With these drilling results and multichannel seismic (MCS) data, well dated abyssal stratigraphy and the lithologies of different sedimentary units are now possible. The sedimentary budget of the Southwest Sub-basin has been constrained using this approach (Ding et al. 2016; Wu et al. 2018). Results show that the uplift of Tibetan Plateau, the accelerated southeastward extrusion of the Indochina Peninsula, and the East Asia monsoon dominated control of the sedimentary budget. The sedimentary provenance was mainly the Indochina, with minor contributions from the Dangerous Grounds/Nansha areas and Palawan.

Huang and Wang (2006) calculated the sediment mass for the entire SCS for the first time, but their result remains contentious because their seismic stratigraphic and sedimentary framework was not precisely constrained. In this study, we integrated the drilling results and downhole geophysical logging from IODP Expeditions 367 and 368, with MCS data to conduct a detailed seismic stratigraphy study of the Northwest Sub-basin (NWSB), and then calculated the sedimentary budget through time, in doing so we reconstructed the sedimentary history of the NWSB. To better understand the significance of sediment volumes deposited in the NWSB, we compared our results with the sedimentary budget of continental margin basins, such as the Pearl River Mouth Basin, the Yinggehai-Song Hong Basin, and the Qiongdongnan Basin (Clift 2006; Clift and Sun 2006), as well as the Southwest Sub-basin (Wu et al. 2018). The objective of the sedimentary budget studies is to determine the flux and transport paths of terrestrial sediments, and to identify the major controlling factors over the sedimentary budget in order to increase understanding of the interaction between solid earth tectonic activity, climate change, and sedimentary evolution of the NWSB, SCS.

2. Geological setting

The SCS is comprised of three major sub-basins: the NWSB, the East Sub-basin (ESB), and the Southwest Sub-basin (SWSB) (Li et al. 2015a; Gao et al. 2018). Among the three sub-basins, the NWSB is the smallest one with a total width of nearly 200 km and a total length of about 140 km. Its water depth is between 3500 m and 4000 m (Gao 2012). The NWSB is bounded by several tectonic units: the Baiyun Sag of the Pearl River Mouth Basin to the north, the Xisha Islands to the west, the Qiongdongnan Basin to the northwest, and the Zhongsha Islands to the south. The NWSB is separated from the ESB by the Zhongnan Fault in the (Figure 1) (Ding et al. 2011; Gao 2012).

Recent results acquired from IODP Expedition 349 confirmed that seafloor spreading in the East Sub-basin initiated at ~32 Ma and terminated at ~15 Ma, and the Southwest Sub-basin started seafloor spreading at ~23.6 Ma and ceased at ~15 Ma (Expedition 349 Scientists 2014; Koppers 2014; Li et al. 2014, 2015b). However, the study on the spreading stage of the NWSB was limited. Early magnetic anomaly interpretations suggested that the spreading of the NWSB began at about 30–32 Ma (Briais et al. 1993). Seismic stratigraphic correlation also confirmed that the NWSB started spreading nearly at the same time as the ESB (Sun et al. 2006; Li et al. 2015a). The NWSB stopped spreading after a southward ridge jump at 25–23 Ma, and experienced thermal subsidence thereafter (Barckhausen et al. 2014; Cameselle et al. 2015), indicating the cessation of the spreading.

Since the opening of the SCS, terrigenous materials were transported from the continental shelf to the abyssal basin during the lowstand stage through canyon and channel systems, including the Pearl River Canyon system in the north and the Central Canyon in the west (Ding et al. 2013a, 2013b; Shang et al. 2015; Li et al. 2017). The Pearl River Canyon was initially formed as a result of the rapid thermal subsidence in the Baiyun Sag and several eustatic events of the Pearl River Mouth Basin since the Early Miocene, and it was the main sediment transport conduit in this region (Ding et al. 2013b). Meanwhile, the Central Canyon developed along the Xisha Trough, and its formation time was delayed until the Late Miocene (Su et al. 2013, 2014).

3. Data and method

In this study, we reinterpret four multichannel seismic profiles across the NWSB in two different orientations with new dating constraints from IODP Expeditions 367 and 368 (Figure 1). Seismic profiles SO49-17, SO49-18, and SO49-25 were collected during the ‘Joint Sino-German South China Sea Cruise’ in 1987, and seismic profile 97303 was obtained by the ‘Project 973 Cruise’ in 2009. More details about the acquire parameters of the seismic profiles are presented in Table 1.

Five sites in the continental slope and abyssal basin were drilled during IODP Expeditions 367 and 368 (Sites
Figure 1. (a) Major tectonic units and sedimentary basins in the South China Sea. Red dashed square shows the study area. And purple dashed square shows the location of the base map in the Figure 7. Red broken line shows the boundary between the Northwest Sub-basin, the Southwest Sub-basin and the East Sub-basin. Red solid line shows the Red River Fault Zone. (b) Bathymetric map showing geophysical context of the study area around the Northwest Sub-basin. The black lines indicate the locations of seismic profiles described in this paper. The red dots indicate the location of ODP Site 1148, IODP Sites U1499, U1500, U1501, U1502, and U1504.
U1499, U1500, U1501, U1502 and U1504 (Figure 1), coring through Cenozoic sediments overlying basement. Drilling sites from these expeditions were used to interpret sediment units and sequence boundaries, especially for seismic profile 97303, which lies very close to the drilling area so that the lithology and age of both sediments and the basement are now well constrained by along-line projection from Site U1499. Age control of the sequence boundaries is mostly provided by biostratigraphic analysis (Sun et al. 2018). In this study, we distinguished six distinct seismic units in Cenozoic sediments corresponding to distinct tectono-sedimentary environments, i.e. the Oligocene, the Lower Miocene, the Middle Miocene, the Upper Miocene, the Pliocene, and the Pleistocene, from bottom to top respectively (Figure 2).

The calculation of the sedimentary budget involves time-depth conversions of the interpreted seismic sections (Figures 3–6). A full suite of geophysical logging was carried out at Site U1499, which enabled an accurate time-depth conversion. With core-log-seismic integration, Sun et al. (2018) built a time-depth conversion function, expressed as follows:

\[ Z = 0.000188295t^2 + 0.695896t, \]

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 (mbsf).

After time-depth conversion, we decompacted each sedimentary unit in order to obtain their original thickness using the program Flex-Decomp™ by Kusznir et al. (1995). During the decompaction process, the loss of porosity of each sedimentary unit is estimated. In this study, an accurate porosity-depth relationship was built by employing porosity data obtained from Site U1502 during IODP Expeditions 367 and 368 (Jian et al. 2018; Sun et al. 2018). As the resulting equation expresses, an exponential fit for shallow depths (\( z < 150 \) m below seafloor, mbsf) coupled with a linear fit for greater depths (\( z > 150 \) mbsf) best describes the porosity trend. The porosity-depth equation is expressed as below:

\[ \phi(z) = \begin{cases} 0.356e^{-0.00759z} + 0.426 & (z \leq 150 \text{ mbsf}) \\ -2.053 \times 10^{-4}z + 0.586 & (z > 150 \text{ mbsf}) \end{cases} \]

Here, \( \phi(z) \) is the porosity function and in decimal, and depth \( z \) is in mbsf.

With this porosity-depth relationship, we decompacted deeply buried stratigraphic units to sedimentary units, assuming a constant volume of rock grains before and after the decompaction (Steckler and Watts 1978), using the following equation:

\[ \int_{y_1}^{y_2} [1 - \phi(z)] dz = \int_{y_1}^{y_2} [1 - \phi(z)] dz \]

Here, \( \phi(z) \) is the porosity-depth function, \( x \) is the decompacted thickness, and \( y_1 \) and \( y_2 \) are the top and bottom depths of the sedimentary unit, respectively. \( y_1 \) and \( y_2 \) will change with the depth of different sedimentary units. The left term is the volume of rock grains after decompaction, and the right term defines the volume before decompaction.

After obtaining the uncompacted thickness of each sedimentary unit (Figures 3(c), 4(c), 5(c) and 6(c)), we calculated the sediment volume of the NWSB at different times using Surfer software. By importing the unloaded and decompacted depth of each sedimentary boundary into the Surfer software by Golden Software, LLC, the interface grid data can be generated and followed by a planar graph. Longitude and latitude data from each seismic profile are also used to directly constrain the surface area of the NWSB. The sediment volume between two sequence boundaries can be finally determined by computing the grid volume in between these two boundaries. After the sediment volume and average sedimentary rate for five sedimentary units are confirmed, the sedimentary budget of the NWSB in different geological time periods is determined.

Errors in the calculation results can be caused by various processes: (a) The time–depth conversion error is assumed to be 3%. Three different sites in the central SCS basin

### Table 1. Acquisition paraments for seismic lines used in this study.

<table>
<thead>
<tr>
<th>Profile</th>
<th>R/V</th>
<th>Acquisition date</th>
<th>Streamer channel</th>
<th>Record length (s)</th>
<th>Sampling rate (ms)</th>
<th>Shot interval (m)</th>
<th>Airgun volume (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO49-17</td>
<td>SONNE</td>
<td>1987</td>
<td>48</td>
<td>12</td>
<td>4</td>
<td>50</td>
<td>25.6</td>
</tr>
<tr>
<td>SO49-18</td>
<td>TANBAO</td>
<td>2009</td>
<td>480</td>
<td>12</td>
<td>2</td>
<td>50</td>
<td>83.3</td>
</tr>
<tr>
<td>SO49-25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97303</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Calculation results of the sedimentary budget of the NWSB.

<table>
<thead>
<tr>
<th>Time</th>
<th>Duration (Ma)</th>
<th>Sediment Volume (km³)</th>
<th>Surface Area (km²)</th>
<th>Average Sediment Thickness (m)</th>
<th>Sedimentary Budget (1000 km³/my)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pliocene</td>
<td>1.8–0</td>
<td>1.8</td>
<td>4050</td>
<td>22,200</td>
<td>2.25 ± 0.22</td>
</tr>
<tr>
<td>L. Mio.</td>
<td>5.3–3.5</td>
<td>3.5</td>
<td>4482</td>
<td>22,152</td>
<td>1.28 ± 0.13</td>
</tr>
<tr>
<td>M. Mio.</td>
<td>10.6–5.3</td>
<td>5.3</td>
<td>14,198</td>
<td>22,155</td>
<td>2.68 ± 0.26</td>
</tr>
<tr>
<td>E. Mio.-Oli</td>
<td>16–10.6</td>
<td>5.4</td>
<td>8577</td>
<td>22,154</td>
<td>1.59 ± 0.16</td>
</tr>
<tr>
<td>32–16</td>
<td>11.5</td>
<td>7506</td>
<td>22,155</td>
<td>340</td>
<td>0.65 ± 0.07</td>
</tr>
</tbody>
</table>

(As the basement boundary is diachronous, the duration of the Lower Miocene-Oligocene sediment is taken the average as 11.5 Ma.)
(U1431, U1432 and U1433 from IODP Expedition 349) also give nearly identical time-depth relationships (Li et al. 2015a), indicating the high accuracy of the time-depth conversion. (b) Errors in estimating the sediment age, lithology, and compaction history rarely exceed 2% (Clift 2006). Especially during the decompaction process, the porosity-depth data cluster closely around the function, suggesting the homogenous sedimentation in the abyssal basin. (c) Errors in calculating the sedimentary volume for different sedimentary units are estimated to be 5% at most, because of limited 2D seismic profiles. In addition, the errors in calculating the sedimentary volume are generally set as 5% in previous study (Clift 2006; Lei et al. 2015). Compared to previous studies, these errors are reduced because the confirmation of the sedimentary units is more accurate. Thus, we set the total error range as ±10%.

4. Results

4.1. Sediment isopach mapping in five time-periods since Oligocene

The multichannel seismic profiles constrained by the biostratigraphy of Site U1499 allowed us to explore the sedimentary filling history. We consider the Oligocene and Lower Miocene as one unit because they represent the syn-rift sediment of the SCS. Isopach maps of five sediment units, i.e. the Oligocene and Lower Miocene, the Middle Miocene, the Upper Miocene, the Pliocene, and the Pleistocene, are shown in Figure 7.

During the Oligocene and Early Miocene, the sediment thickness was between 200–400 m in the slope area, but decreased to less than 100 m in most parts of the abyssal basin (Figure 7(a)). A sediment belt with higher thickness ran across the abyssal basin with an N-S trend. The belt started from the mouth of Pearl River Canyon and thickened towards the south. Extremely thick sediments, reaching 1000 m, existed in the southeastern part of the NWSB. The thick sediment belt generally developed along the Zhongnan Fault.

During the Middle Miocene, sedimentary rate increased, and the sedimentary thickness of this stage was generally over 100 m, reaching up to 500 m in the central part (Figure 7(b)). A thick N-S trending sedimentary belt can still be observed along the Zhongnan Fault, which connects with the Pearl River Canyon in the north. Only restricted areas, such as the basement

Figure 2. Calibration of seismic horizons from Site U1499. The interpreted boundaries are calibrated from recovered lithostratigraphy. Site U1499 is located on a basement ridge within the continent-ocean transition zone of the SCS. At Site U1499, the basaltic basement was not penetrated but most Cenozoic sediments could be recovered. See location in Figure 1.
Figure 3. MCS section SO49-17 oriented in a SE-NW direction. (a) Original seismic section; (b) geological interpretation with line drawing; (c) time-depth conversion of the geological interpretations. Oligocene and Lower Miocene sediments that experienced the syn-rift stage of the South China Sea. Decompacted thicknesses of each sedimentary unit provide the foundation for sedimentary budget calculation of the NWSB. Vertical exaggeration is 3:1.
Figure 4. MCS section SO49-18 oriented in a SE-NW direction. (a) Original seismic section; (b) geological interpretation with line drawing; (c) time-depth conversion of the geological interpretations. A buried seamount developed in the central part of the seismic profile. Vertical exaggeration is 3:1.
Figure 5. MCS section SO49-25 oriented in a NE-SW direction. (a) Original seismic section; (b) geological interpretation with line drawing; (c) time-depth conversion of the geological interpretations. Vertical exaggeration is 3:1.
highs in the abyssal basin, exhibited limited sedimentation with thicknesses lower than 100 m.

A sharp increase in sedimentation occurred during the Late Miocene, and the thickness of the Upper Miocene in the abyssal basin was generally over 500 m, reaching ~800 m in the central part (Figure 7(c)), with the exceptions above the buried seamounts (Figure 4). The isopach map also shows a similar sedimentary belt with thickness higher than 600 m, which again starts from the mouth of the Pearl River Canyon and develops further south along the Zhongnan Fault.

Since the Pliocene, the sediments were generally sheet-like and have no obvious depocenter. Both of the sediment thickness of the Pliocene and the Pleistocene were ~200 m, reaching 300 m locally (Figure 7(d,e)).

4.2. Sedimentary budget calculation results

Based on the methods described above, we calculated the sedimentary budget of the NWSB for different geological times. Previous works on the Qiongdongnan Basin (Clift and Sun 2006), the Pearl River Mouth Basin (Clift 2006), and the Baiyun Sag (Xie et al. 2013) are also presented in Figure 7 for comparison.

The sedimentary budget in the abyssal basin exhibits a wavy shape. As shown in Table 12 the sedimentary budget was $0.65 \pm 0.07 \times 10^3$ km$^3$/my from the Late Oligocene to the Early Miocene (32–16 Ma), and gradually increased to $1.59 \pm 0.16 \times 10^3$ km$^3$/my during the Middle Miocene (16–10.6 Ma). It reached its peak during the Late Miocene (10.6–5.3 Ma), which was approximately $2.68 \pm 0.27 \times 10^3$ km$^3$/my. Since the Pliocene (5.3–1.8 Ma), there was an obvious decline with the sedimentary budget value reduced to $1.28 \pm 0.13 \times 10^3$ km$^3$/my, almost half of the previous rate. Nevertheless, it increased again to $2.25 \pm 0.23 \times 10^3$ km$^3$/my in the Pleistocene (1.8 Ma–present).

5. Discussion

5.1. Controls on sedimentary budget

Sedimentary basins in the continental margin of the SCS, such as the Pearl River Basin, had sufficient accommodation space and acquired most terrestrial sediments from South China since Cenozoic. Furthermore, the Baiyun Sag experienced rapid thermal subsidence from 29 Ma to 23.3 Ma (Zhou et al. 2009; Xie et al. 2013), which not only trapped abundant terrigenous sediments, but also...
Figure 7. Isopach map showing the decompacted thicknesses of sediments for different geological times. (a) Late Oligocene to Early Miocene, (b) Middle Miocene, (c) Late Miocene, (d) Pliocene, (e) Pleistocene. The red dashed line indicates the Zhongnan Fault based on Li et al. (2014). The blue dashed line indicates the continent-ocean boundary (COB) (Li et al. 2014). Black lines indicate four multichannel seismic profiles. The red dot indicates the location of Site U1499. The question marks indicate the lack of constraints from seismic data.
caused the northward migration of the continental shelf break. This could explain the extremely low sedimentary rate in most of the NWSB despite the increased sedimentary flux in the Yinggehai-Song Hong Basin, Pearl River Mouth Basin, and Baiyun Sag. An exception is the abyssal basin near the Zhongnan Fault, which preserved relatively thick sediments. This may be attributed to the dramatically decreased relative sea level after 21 Ma (Pang et al. 2005, 2009). Terrigenous sediments carried by the Paleo-Pearl River incised the continental slope area, resulting in the development of the Pearl River Canyon (Ding et al. 2013a, 2013b; Cao et al. 2018). As a result, some terrigenous sediments could be transported into the abyssal basin and accumulated along the negative traps due to the activities of the Zhongnan Fault during the Early Miocene.

During the Middle Miocene (16–10.6 Ma), the sediment flux to the NWSB increased dramatically, with an average increment of about 0.94 × 10^3 km^3/my (Figure 8(f)). Although the sediment flux to the Qiongdongnan Basin did not significantly change (Figure 8(b)), the mass of sediments in the Yinggehai-Song Hong Basin and Pearl River Mouth Basin showed significant increase (Figure 9(a,c)). Both basins were connected to onland rivers, i.e. the Red River and the Pearl River. Meanwhile, the increased sediment flux from the Red River could be attributed to the uplifting event of the Tibetan Plateau and the intensification of the Asian summer monsoon (Clift 2006; Clift and Sun 2006; Wan et al. 2010; Tada et al. 2016), while that from the Pearl River was mainly controlled by a climate trigger (Sun et al. 2008; Clift et al. 2015) (Figure 9(c)). During this stage, the sedimentary rate of the Pearl River Mouth Basin (Figure 8(c)), as well as the Baiyun Sag (Figure 8(d)), was much higher than that of the Qiongdongnan Basin, indicating that the sediment influx into the NWSB was primarily from the north. Sediments were transported through the Pearl River Canyon, which developed and matured during the Middle Miocene with the apparent decline of relative sea level of the SCS (Figure 9(a)), although most sediments were deposited in the Baiyun Sag.

The sedimentary budget of the NWSB reached its peak during the Late Miocene (10.6–5.5 Ma). It is noteworthy that in most other places, either in the continental margins or in the SWSB, the sediment rate dramatically decreased, which may be associated with the increased aridity and stronger winter monsoon across Asia at that time (Clift 2006). This arid climate decreased erosion rates in terrestrial drainage basins and resulted in low sedimentation rates (Wan et al. 2006, 2007). The opposite trend in the NWSB may be attributed to an uplift event near the Dongsha Islands, known as the Dongsha Event, which commenced in the Late Miocene and had a peak of activity at ~5.5 Ma, interpreted to be caused by magma intrusion within the basement (Luedmann and Wong 1999; Sun et al. 2014). The region near the Dongsha Islands experienced intensive erosion, as evidenced by the missing Neogene sediments around the crest of the Dongsha Uplift (Luan et al. 2012). The eroded sediments would initially have been transported into the Baiyun Sag (Ma et al. 2015; He et al. 2017). Studies of the sedimentary process have demonstrated that the Baiyun Sag was infilled by sediment delivered from the Pearl River with extremely low sedimentary rates since 10.5 Ma (Wang et al. 2018) (Figure 8(d)). Thus little sediments were captured by the Baiyun Sag at that time, allowing overspill into the NWSB though the Pearl River Canyon. Consequently, the sedimentary rate of the Pearl River Mouth Basin decreased while the sedimentary rate of the NWSB increased at the same time (Figure 9(c,f)).

During the Pliocene (5.3–1.8 Ma), the East Asian summer monsoon strengthened again, and the climate switched to warm and humid (Wang et al. 2003; Clift et al. 2014). As shown in Figure 9(b), δ^18O increased rapidly during the Pliocene, indicating increased temperature. As a result, the sedimentary budget increased in marginal basins including the Pearl River Basin, Yinggehai-Song Hong Basin, and Qiongdongnan Basin, and in the SWSB. However, the sedimentary budget of the NWSB again showed a contrasting trend, decreasing to about 1.40 × 10^3 km^3/my during this stage. Compared with the narrow Indochina continental shelf in the west of the SWSB, the northern continental shelf exceeds 350 km in the N-S orientation, and most of the terrestrial sediments were deposited in the continental shelf area during high-stand stage (Pang et al. 2009; Xie et al. 2013) (Figure 9(a)). Therefore, the sedimentary rate increased in the Pearl River Mouth Basin but declined both in the Baiyun Sag and NWSB (Figure 9(c,d,f)). In contrast, the SWSB showed a swift response to the strengthened summer monsoon and chemical weathering, resulting in an increased sedimentation rate.

The sedimentary budget for the entire abyssal basin increased again during the Pleistocene (1.8–0 Ma). The intensification of the Asian monsoon during interglacial periods and the variation of glacial-interglacial climate (Figure 9(b)) is consistent with the observation that the Pleistocene was indeed a period of rapid sedimentation for many other basins, not only in the SCS, but also in other regions, such as the European Alps region (Kuhlemann et al. 2002), or the Angola continental margin of West Africa (Lavier et al. 2001). Furthermore, global sea level declined during this period (Haq et al. 1987). The rejuvenation of the Pearl River Canyon and the Central Canyon System led to the increased
Figure 8. Sedimentary budgets for the major marginal and abyssal basins in the South China Sea. (a) Yinggehai-Song Hong Basin (Clift and Sun 2006), (b) Qiongdongnan Basin (Clift and Sun 2006), (c) Pearl River Mouth Basin (Clift 2006), (d) Baiyun Sag (Xie et al. 2013), (e) Southwest Sub-basin (Wu et al. 2018), and (f) Northwest Sub-basin.
Figure 9. (a) Relative eustatic fluctuations of the Pearl River Mouth Basin from Pang et al. (2005). (b) δ18O curve (red line) with global deep-sea oxygen isotope records (purple squares) indicating climatic shifts (Zachos et al. 2001). MMCO: Middle Miocene climatic optimum. (c) Chemical weathering index CRAT (errors ± 0.1) as a function of time (Clift et al. 2008). (d) Sedimentary budget changes for the entire study area. Vertical dashed lines across all frames indicate boundaries between periods of dominantly weak or strong summer monsoon.
sediment shedding from the Pearl River, Red River, and Hainan Island (Su et al. 2013, 2014; Ding et al. 2013a) (Figure 9(d)).

5.2. Sediment provenance

Since its opening, the SCS has received hundreds of million metric tons (Mt) of fluvial sediments annually from numerous surrounding rivers, including the Pearl River, Red River, and Mekong River (Liu and Stattegger 2014). Considering the location of the NWSB, the Pearl River in the north and the Red River in the northwest might have dominated the source-to-sink transport process of the NWSB and adjacent areas, although sediments from Hainan Island in the northwest, Macclesfield Bank/Zhongsha and Xisha Islands in the south, as well as local basement uplifts in the continental shelf area should be taken into account.

As evidenced by both Nd bulk sediment and single grain zircon provenance methods, the drainage of the Pearl River progressively expanded since the opening of the NWSB, evolving from relatively small rivers confined to coastal South China in the Early Oligocene to a near-modern continental-scale drainage configuration in the Early Miocene (Liu et al. 2017; Cao et al. 2018). Bulk sediment geochemical analyses of Site U1435 and industrial wells indicated that the Pearl River and its tributaries have been the primary source of sediments to the northern continental margin of the SCS (Liu et al. 2017). Sediments of the NWSB mainly originated from South China and were transported by the Paleo-Pearl River through the Pearl River canyon during the sea-level lowstand. The Central Canyon was not formed in this stage, and sediments from northern and central Vietnam and Hainan Island were generally deposited in the Qiongdongnan Basin, contributing little to the NWSB (Yao et al. 2008; Zhao et al. 2015).

Since the Late Miocene, Southeast Asia has been affected by colder and drier climates due to the strengthened winter monsoon, which weakened erosion, either from South China or from the Indochina Peninsula. We suggest that during this stage the increased sediment flux in the NWSB is mainly attributable to structural highs within the basin, such as the Dongsha Uplift.

To the west, the Central Canyon within the Xisha Trough began to develop (Su et al. 2013, 2014, 2015). However, the low sedimentary rate in both the Yinggehai-Song Hong Basin and the Qiongdongnan Basin at this time indicate slow terrestrial erosion (Figure 8(a,b)). We speculate that contributions to the NWSB from the west remained limited.

During the Pliocene, the sedimentary flux to the NWSB was decreased due to the sea-level highstand. Most terrestrial sediments were deposited on the continental shelf to the north. Both the Pearl and Red Rivers contributed little to sedimentation in the NWSB. The isopach map for this stage shows that the sedimentary thickness is generally higher in the west than that in the east, indicating active mass transportation from the west at that time. Using constraints from low temperature thermochronology, Shi et al. (2011) described the Cenozoic denudation history of southern Hainan Island and indicated two periods of increased potential sediment supply, which were the Late Eocene–Oligocene and since 5 Ma. Zhu et al. (2007) further argued that a fan delta developed in the south of the Hainan Island during 4.2–3.7 Ma. Sediments originating mainly from Hainan would have been transported into the NWSB through the Central Canyon.

Sediments were mainly transported from the modern Pearl River Canyon and Central Canyon during episodic sea-level lowstand events, as shown by the presence of two thick sedimentary zones near the mouths of these canyons (Figure 7(e)). After 1.8 Ma, there were several potential sources of sediment, including the Red River and Hainan Island in the northwest, small rivers in eastern Vietnam, and the Pearl River to the north (Liu et al. 2016). Even suspended sediments delivered by small mountainous rivers in southwestern Taiwan could be deposited in the NWSB after transport by deep water currents (Liu et al. 2008).

Carbonate deposits, including carbonate platforms and coral reefs on top of the basement highs, were well developed in the Xisha and Macclesfield Bank/Zhongsha Islands since the Late Oligocene (Ma et al. 2011). While in the NWSB the cored sediments mainly comprised nanofossil-rich clay, clay with silt interbeds, claystone, silty sandstone, and sandstone (Sites U1499, U1500, and U1502, Jian et al. 2018; Sun et al. 2018). Biogenic carbonate was only recovered at Site U1500, corresponding to Middle Miocene, but the carbonate contents were very low, all <0.5 wt% (Sun et al. 2018). We suggest that the contribution from the Xisha and Macclesfield Bank/Zhongsha Islands was extremely limited because most of the carbonate deposits were drowned since the middle Miocene.

6. Conclusions

Based on geological interpretations of four seismic profiles across the NWSB and drilling results from IODP Expeditions 367 and 368, we calculate the sedimentary budget of the NWSB during different geological times. The sedimentary budget of the Pearl River Mouth Basin,
Yinggehai-Song Hong Basin, Qiongdongnan Basin, and SWSB were also integrated to constrain the sediment delivery history of the SCS. We reconstruct a relatively low sedimentation rate during the Oligocene and Early Miocene, which increased in the Middle Miocene and peaked during the Late Miocene. The sedimentary rate decreased sharply during the Pleistocene but increased again since the Pleistocene.

Cenozoic sediment delivery to the SCS is dominated by major tectonic events linked to the geological history of Southeast Asia, including uplift of the SE Tibetan Plateau, continental rifting, the evolution of Asian monsoon, development of the drainage systems of the Pearl River and Red River, as well as eustatic sea level changes. However, sedimentation is complicated due to geographic position and local tectonic events. The sedimentary budget of the NWSB shows two trends that being opposite to those of the SWB and the continental margins of the SCS. In the late Miocene, the sedimentary rate peaked, while most of the continental margins showed low rates because of the colder and drier climate and low intensive chemical weathering, attributable to the strengthened winter Asian Monsoon and weak summer rains. Uplifting event near the Dongsha Islands occurred in the late Miocene, and Neogene sediments with thicknesses of hundreds of meters were eroded and transported into the abyssal basin through the channel/canyon system, driving increasing sedimentary flux to the NWSB. The second opposite trend occurred in the Pliocene, during which the sedimentary budget sharply decreased, while most basins in the northern continental margin and the SWB experienced an enhanced sedimentary budget due to the wet and warm climate and enhanced chemical weathering and erosion with strengthened summer Asian monsoon. We suggest that most of the terrestrial sediments would have been deposited on the wide northern continental shelf because of the high eustatic sea level during this stage. Few sediments were transported into the abyssal basin. In contrast, such as offshore central Vietnam in the west of the SWB, may be significant sources of sediment delivered to the abyssal basin even during high sea level.

Structural analysis of the seismic profiles combined with bulk sediment geochemical analyses indicates that the primary sediment provenance was South China since the opening of the NWSB. In particular, during sea level lowstands, terrigenous sediments carried by the Pearl River were probably transported directly to the slope area and abyssal basin through well-developed channel/canyon systems, such as the Pearl River Canyon, since the Early Miocene. Although the Red River or SE Tibet cannot be excluded, their contribution to the NWSB was likely limited until the development of the Central Canyon since the Late Miocene. The rejuvenation of the Central Canyon, strengthened summer monsoon, and episodic low-stand sea level events since the Pleistocene would have enhanced sediment transportation into the NWSB. Local tectonic events, including the uplift event in the Dongsha Islands in the Late Miocene, and the uplift event in Hainan Island at ~5 Ma, also contributed to the NWSB since the Pliocene. We suggest that the contribution of the Xisha and Macclesfield Bank/ Zhongsha Islands, as submerged banks, is extremely minor because almost no carbonate depositions have been discovered in IODP drilling sites in this area.

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