A model for oblique accretion on the South China Sea margin; Red River (Song Hong) sediment transport into Qiongdongnan Basin since Upper Miocene

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\textbf{ARTICLE INFO}

Editor: Edward Anthony

\textbf{Keywords:}
Continental margin
Shell processes
South China Sea
Red River
Fluid mud
Oblique accretion

\textbf{Abstract}

Located on the northwestern margin of the South China Sea, the origin of asymmetrical shelf-slope clinoforms accumulated on the continental margin of the Qiongdongnan Basin since the late Miocene is ambiguous and it likely is the first case of oblique sediment transport and dispersal among the most studied mud-rich shelves of the world during Neogene to Recent sea-level changes. We calculate the paleo-sediment flux required to build the shelf-slope clinoforms based on 2-D seismic data, and the results are 3 to 17 time larger than the estimated paleo-sediment discharge from the proximal catchment area of Hainan Island. This large mismatch suggests that sediments on the shelf-edge of Qiongdongnan Basin were not only from Hainan Island but more likely from a larger drainage system. The strong (tens km) southward migration of the western portion of the Qiongdongnan shelf-edge break compared to the weak (1–2 km) shelf-edge progradation in the eastern portion, suggests that the Qiongdongnan shelf prism is highly asymmetric and is caused by a large sediment supply centered to the west, with most likely the Red River (Song Hong) as the sediment supply driver. The fine-grained lithology of the studied shelf margin sediments off Hainan Island, especially since the end Miocene, suggests that they were derived mainly from the Red River and were transported southeastward from the Gulf of Tonkin by shelf currents. We propose a model for asymmetric shelf-slope accretion of mud-rich shelves in which a significant part of the sediment-prism volume was obliquely dispersed across the subsiding shelf as fluid mud during highstand sealevels. The model presented here describes oblique construction of shelf-slope clinoforms in a mud-rich system in response to variations in sediment dispersal and depocenter during multiple sea-level cycles. This model of long-term (~10\textsuperscript{7} years), lateral asymmetric accretion contrasts with oblique sediment transport in other source-to-sink sedimentary systems around the world.

1. Introduction

The shelf-slope system of the northwestern South China Sea (SCS) developed since the middle-late Miocene (Jiang et al., 2005; Yuan et al., 2009). Located on the southeast margin of Hainan Island, the Qiongdongnan Basin (QDNB) developed a set of depositional environments from neritic to bathyal (Xie et al., 2006) with present shelf break near the ~200 m isobath (Fig. 1).

QDNB is a prolific hydrocarbon basin with significant reserves in the Cenozoic section (Su et al., 2014; Zhao et al., 2019a). Due to the rapid thermal subsidence since ~20 Ma and dextral movement of regional faults since ~5 Ma in northwest SCS (Clift and Sun, 2006; Xie et al., 2006; Shi et al., 2011), huge sediments sequences were formed in QDNB and Yinggehai Basin (YGHB), and the thickness of Quaternary strata in deep water of QDNB reaches > 2000 m (Xia, 1988; Wang et al., 1991). There have been a large number of studies on provenance for sediments in the deep water of QDNB involving mineralogy, geochronology and regional seismic-geology analyses. The Red River (Song Hong) with large (> 100 Mt/yr.) sediment flux in the northwest is suggested as the dominant source since the late Miocene. The eustatic
Sea-level changes during the late Miocene triggered large-scale regressions and exposed the shelf during periods of sea-level lowstand (Gong et al., 1997; He, 2012; Cao et al., 2015), and the associated long-distance shoreline migration facilitated the transport of sediments derived from Red River through the YGHB farther to the southeast and deposited in QDNB (Van Hoang et al., 2010; Yuan et al., 2010; Shi et al., 2011; He, 2012), especially the sediment supplied by the Red River outstripped the subsidence in YGHB, allowing overspill to QDNB in the Pliocene (Clift and Sun, 2006). A delta-channel/submarine canyon-submarine fan depositional system in the YGHB and QDNB is suggested to accomplish this process of sediment transportation in deep water (Wang et al., 2011). Based on heavy minerals data, several studies (Cao et al., 2013, 2015; Jiang et al., 2015; Liu et al., 2015a; Chen et al., 2016a; Liu et al., 2019) suggested that Hainan Island proximally located to the north was another main source for sediments accumulated in deep water of QDNB since the late Miocene. However, most of these studies concentrated on the coarse-grained sediments in the west-east oriented Central Canyon (Fig. 1). The provenance for over 1000 m-thick sediments preserved on the continental shelf and upper slope of QDNB has not been fully documented, although some scholars focused on the shelf-edge trajectories (Gong et al., 2015a; Ren, 2016). The contribution of proximal catchment area Hainan Island to shelf-slope clinoforms in QDNB is ambiguous.

In this paper, based on the calculation of the sediment volume preserved in the shelf-slope profiles, we argue that Hainan Island with a small drainage area and a low sediment discharge potential was not the dominant source area for the sediments on the shelf and upper slope of QDNB since the late Miocene. Although gravity flow deposits sampled in the lower slope and basin-floor deep water areas in the QDNB contain granitic features derived from the Hainan Island (Cao et al., 2013, 2015), it is possible that there was a different transport model (mass transport) and those sediments were not sourced directly from the adjacent shelf. The tectono-stratigraphic evolution of the QDNB and adjacent area suggests that the large-scale shelf-slope clinoforms that are spectacularly visible on seismic data were formed rather by southeastward transported sediment derived from the Red River.

On the shelf, waves/longshore currents and tidal currents are reworking sediments away from river mouths building subaqueous clinoforms (Allison et al., 2000; Walsh and Nittrouer, 2009; Pellegrini et al., 2015; Amorosi et al., 2016; Peng et al., 2018; Peng et al., in preparation). "Oblique" sediment transport across the shelf due to longshore currents is a well-known process and was documented previously (e.g. Komar, 1998) as well as "across-shelf" sediment transport during present "highstand" sea-level conditions (Nittrouer and Wright, 1994; Warrick, 2014; Zhang et al., 2017a). In Amazon-Orinoco coast (Peng et al., 2018), southeast Australia (Boyd et al., 2008), Po Plain-Adriatic Sea (Ridente et al., 2007), and Karoo Basin, South Africa (Jones et al., 2015), sediments transport across the shelf margin with the help of fluvial input, tidal flows, incised valleys or failures. In QDNB, however, during multiple fourth-order shelf regressions and transgressions, the entire shelf-slope clinoforms are built "obliquely" prograding into the deeper basin off the main river mouth, possessing characteristic features distinguished from other cases around the world.

River deltas are known to form asymmetric sandbodies during one regression cycle (Psuty, 1966; Coleman and Wright, 1975; Bhattacharya and Giosan, 2003; Sabatier and Suárez, 2003) with the deltas typical thickness of tens of meters (Korus and Fielding, 2015) formed during one single sea level cycle. The shelf-slope clinoforms, build during multiple regression cycles, have wider topsets/shelves in the areas where more sediments are delivered by rivers, in front of the deltas...
The equation which can calculate sediment flux to about 500 modern river systems to estimate the paleo-sediments introduced by Syvitski and Milliman (2007), which is based on applying the model proposed in this study of oblique shelf-slope margin accretion during multiple sea-level cycles was not previously described despite multiple studies that describe river delta asymmetry (e.g., Korus and Fielding, 2015). A model for "lateral" asymmetric accretion of the shelf-slope clinoforms over multiple fourth-order cycles of the Plio-Pleistocene Icehouse period is proposed in this study.

2. Database and methodology

The names and main channels of 11 modern rivers that discharge sediments into western SCS are plotted in Fig. 1, and the sediment flux of these rivers represented by the total suspended-sediment (million tons per year, Mt/yr.) of present rivers discharging into the South China Sea (SCS) and surrounding areas. Rivers on Hainan Island are shown in bold.

<table>
<thead>
<tr>
<th>River name</th>
<th>Total suspended-sediment (Mt/yr.)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanjiang</td>
<td>7.2</td>
<td>Cheng and Zhao, 1985; Li et al., 1988; Zhang et al., 2002; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Pearl River</td>
<td>82.7</td>
<td>Cheng and Zhao, 1985; Wang, 1986; Li et al., 1988; Zhang et al., 2002; Dai et al., 2008; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Moyangjiang</td>
<td>0.8</td>
<td>Wang, 1986; Li et al., 1988; Zhang et al., 2002; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Jianjiang</td>
<td>1.9</td>
<td>Wang, 1986; Li et al., 1988; Zhang et al., 2002; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Nanliujiang</td>
<td>1.1</td>
<td>Wang, 1986; Li et al., 1988; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Nandu</td>
<td>0.5</td>
<td>Xiang, 1981; Wang, 1986; Li et al., 1988; Bai and Gao, 1990; Zhang et al., 2002; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Wanquan</td>
<td>0.5</td>
<td>Xiang, 1981; Wang, 1986; Bai and Gao, 1990; Zhang et al., 2002; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Changhua</td>
<td>0.8</td>
<td>Zhang et al., 2002; Milliman and Farnsworth, 2013; Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Red River (Song Hong)</td>
<td>120.0</td>
<td>Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Ma River</td>
<td>3.0</td>
<td>Milliman and Farnsworth, 2013</td>
</tr>
<tr>
<td>Ca River</td>
<td>4.0</td>
<td>Milliman and Farnsworth, 2013</td>
</tr>
</tbody>
</table>

(Olariu and Steel, 2009). The mechanism to build the shelf-edge protrusions in front of large rivers is by migrating the delta deposceters to the shelf edge (Olariu et al., 2012; Sanchez et al., 2012). The long-term Cenozoic shelf-edge protrusion in the northern Gulf of Mexico changes its location along strike as the delta deponents migrate differently in successive sequences (Winker, 1982; Galloway, 2001). However, the model proposed in this study of oblique shelf-slope margin accretion during multiple sea-level cycles was not previously described despite multiple studies that describe river delta asymmetry (e.g., Korus and Fielding, 2015). A model for "lateral" asymmetric accretion of the shelf-slope clinoforms over multiple fourth-order cycles of the Plio-Pleistocene Icehouse period is proposed in this study.

3. Results

3.1. The sediment discharge from Hainan Island rivers

The modern sediment discharge from Hainan Island (Fig. 1) is low (1.8 Mt./yr.) and consists of three main rivers Changhua (0.8 Mt./yr.), Wanquan (0.5 Mt./yr.), and Nandu (0.5 Mt./yr.) (shown in bold in Table 1).

We set the present sediment flux off Hainan Island as $Q_{0}$ (1.8 Mt./yr.) which is composed of the area ($A_0$), relief ($R_0$) and temperature ($T_0$) of modern Hainan Island of about 35,354 km² (Si et al., 2014), 1876 m (Shi et al., 2011), and 23.57 °C (Zhang et al., 2012), and the averaged paleo-sediment flux of T30-T40, T20-T30, and T0-T20 are assumed as $Q_{21}$, $Q_{23}$, and $Q_{25}$, respectively. The relative changes of global sea-level and that in QDNB are approximately coincident since the late Miocene in Fig. 2. Thus, the global sea-level data with high precision reported by Miller et al. (2011) is adopted to calculate the averaged values of paleo-sea-levels and the results are 2.71 m, 20.16 m, and 54.55 m lower than that of the present (assumed as 0 m), respectively. With the help of ImageJ software introduced by Schneider et al. (2012), we approximate paleo-drainage areas of Hainan Island with available 0 m, −25 m, and −50 m bathymetric data from Weatherall et al. (2015), and the results of $A_1$, $A_2$, and $A_3$ during T30-T40, T20-T30, and T0-T20 are equal to $A_0$, 1.15 times of $A_0$, and 1.46 times of $A_0$, respectively. As for the relief, Shi et al. (2011) suggest that the elevation of southern Hainan Island continuously decreased since the late Eocene and was 200 m higher than the present of around 22 Ma based on low-temperature thermochronology, and the fluctuations of sea-level can be ignored relative to relief in the calculation. Moreover, the mean annual temperature of Hainan Island in the middle-late Eocene was about 17 °C from the paleo-vegetation reconstruction by Yao et al. (2009), and Wei et al. (2006) indicate a fluctuating but decreasing trend of temperature in SCS since the early Miocene from the geochemical record. Therefore, substituting parameters of each period into the equation, we get the upper limits for $Q_{21}$, $Q_{23}$, and $Q_{25}$ of 1.4Mt/yr., 1.6Mt/yr., and 1.9Mt/yr., respectively, as shown in Table 2.

3.2. The sediments preserved on the shelf margin of QDNB

To quantify the contribution of the sediments sourced from Hainan Island, the sediment volume preserved offshore is calculated. The results are shown by isopach maps of strata thickness distribution in period intervals of T0 (present)-T20, T20-T27, T27-T30, and T30-T40 in Fig. 4B. The sequence thickness maps in Fig. 4B indicate the area with stronger deposition at the shelf margin (slope) to be to the south-west.
The thickness trends of narrowing thick depocenter from west to east suggest oblique accretion and asymmetrical clinoforms on the shelf margin. On the T27-T30 map, there existed a submarine canyon having thick strata called Great Central Canyon, however, the trend of shelf margin accretion is similar despite smaller values of the absolute thickness. Sediment volumes preserved on the shelf and upper slope of the study area (areas bordered by red polygons in Fig. 4B) in QDNB during T0-T20, T20-T30 (sum of T20-T27 and T27-T30), and T30-T40 periods are presented in Table 3, respectively. We multiply the volume by the density of the sediments (2.66 Mt/km³ of rock on the shelf of QDNB which is calculated based on drilling samples, Henry et al., 1968; Li, 1987; Zhao et al., 2015; and 2.00 Mt./km³ which is typical for loose sediment) and divide by the time duration, then the paleo-sediment flux supplied from Hainan Island to study area during each period can be estimated (marked by single asterisk in Table 3). The results suggest that estimated paleo-sediment fluxes are about 1Mt/yr., 6Mt/yr., and 11Mt/yr. in the T40-T30 (10.5–5.5 Ma), T30-T20 (5.5–1.9 Ma), and T20-T0 (1.9 Ma–present), respectively, showing a significant increasing trend. Note that the sediments in the red polygons on the shelf margin of QDNB we calculated is only a part of the southern Hainan Island area covered by the seismic data set, and even taking account of the volume between our dataset and shoreline of Hainan Island, the enlarged volume was just a quarter of that from the Hainan Island to four directions, north, east, south, and west. Besides, in consideration that the Hainan Island would connect to the mainland in the north and become a peninsula during sea-level lowstands, we enlarge the sediment volume of red polygon three times as the total paleo-sediment flux from Hainan Island. Therefore, the lower limits of T30-T40, T20-T30, and
Table 2

<table>
<thead>
<tr>
<th>Boundaries (Time duration)</th>
<th>Average sea level (m)</th>
<th>Area of Hainan Island (drainage area A, km²)</th>
<th>Maximum relief of Hainan Island (R, km)</th>
<th>Averaged temperature of Hainan Island (T, °C)</th>
<th>Discharge from Hainan Island (Qs, Mt/yr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0-T20 (1.9 Ma)</td>
<td>0</td>
<td>35,354</td>
<td>1.9 (R0)</td>
<td>23.6 (T0)</td>
<td>1.9 (&lt; Qs0 = 1.46αBA0 A0 T0 (present))</td>
</tr>
<tr>
<td>T20-T30 (5.5 Ma-1.9 Ma)</td>
<td>-5.55</td>
<td>51,456</td>
<td>1.56 (R2)</td>
<td>22.6 (T2)</td>
<td>1.9 (&lt; Qs2 = 1.99αBA2 A2 T2)</td>
</tr>
<tr>
<td>T30-T40 (10.5 Ma-5.5 Ma)</td>
<td>-20.16</td>
<td>40,786</td>
<td>1.56 (R3)</td>
<td>1.9 (&lt; Qs3 = 1.99αBA3 A3 T3)</td>
<td></td>
</tr>
<tr>
<td>T40-T10 (15.5 Ma)</td>
<td>-27.71</td>
<td>35,354</td>
<td>1.9 (&lt; Qs4 = 1.99αBA4 A4 T4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We delineate the shelf-edge trajectories along the shelf margin of QDNB and calculate the growth (progradation and aggradation) rate in each profile during T40-T30 (10.5 Ma-5.5 Ma), T30-T20 (5.5 Ma-1.9 Ma), and T20-T0 (1.9 Ma-present) periods. From west to east the seismic lines L1 to L21, show the shelf-edge trajectories change from strongly progradational to aggradational (steeply rising) (Fig. 5). The progradation and aggradation rates (Fig. 6A and B) indicate that the accumulation of sediments on the western shelf margin is higher than that of the eastern part, especially the shelf build-out/progradation is significant with up to 10 km/My rates. In each profile, the growth rate becomes higher through time, and the profiles in the western margin have larger growth than that of the eastern shelf (Figs. 5 and 6). Comparing the progradation and aggradation rates of QDNB to the global shelf margins from literature (Fig. 7), the shelf-edge of QDNB is characterized significantly asymmetrical growth rates between western (hollow circles and dotted lines) and eastern (solid circles and lines) parts.

4. Discussion

4.1. The comparison between the preserved sediment volume in the clinoforms and the sediment flux discharge, the discovery of the mismatch

Our estimated paleo-sediment fluxes that built the clinoforms on shelf-edge of QDNB are significantly higher (3 to 17 times) than the total paleo-sediment fluxes coming off the Hainan Island in corresponding periods (Tables 2, and 3). Thus, the sediments supplied by Hainan Island to the south are not enough to form such large shelf-slope clinoforms that preserve large sediment volume on the shelf-slope sediment wedge of the QDNB. Therefore, we suggest that the Hainan Island was not the dominant source area supplying sediments to the shelf of QDNB since the late Miocene, although it is the most proximal area and contributed to part of sediments in the deep water of QDNB. The next questions are: Where did the sediment accrete to the south of Hainan Island come from? What is the mechanism to build such large-scale clinoforms if there was no large river landward?

4.2. The sourcing of the sediments building QDNB clinoforms; the search for the large sediment supply

The characteristics of growth rate on shelf margin in QDNB from west to east suggest that there is a large and growing source in the west. Adjacent to the study area are two large river systems, Red River (120 Mt/yr. –modern sediment flux) to the west and Pearl River (82.7 Mt/yr. –modern sediment flux) to the east (Fig. 1). The Red River was the main provenance for sediments in the deep water of QDNB, and it is possible that the Red River was the dominant source for the shelf-slope clinoforms of QDNB as well.

The nearest denudation area to QDNB, Hainan Island experienced the most rapid uplift event during the late Eocene and Oligocene (Shi et al., 2011), whereas since then the sediment supply from Hainan Island was low, similar to modern fluxes (1.8 Mt/yr.). As the largest sedimentary system in the northwestern SCS, the paleo-Red River was captured by Yangtze River in middle China several times in geological history and this peaked in the middle-late Miocene (Clark et al., 2004), and as a result, the sediment flux of Red River and the sedimentary rates in YGHB and QDNB decreased significantly through time to late Miocene after which they increased (Fig. 8, Clift and Sun, 2006). Although sediment discharge from Red River and Hainan Island to QDNB were relatively low in the late Miocene, a typical continental shelf-slope...
system had gradually developed along the southern margin of Hainan Island during that time (Jiang, 2005; Cao et al., 2015). The shelf break of the late Miocene (10.5 Ma, T40) was roughly parallel to the present coastline of Hainan Island (Figs. 3 and 4B), and the distance between Hainan Island and the shelf-edge was short (about 60 km) and approximately equidistant.

Starting in the earliest Pliocene (5.5 Ma, T30), the western shelf-edge break migrated southward with higher progradation and aggradation rates to the east (Figs. 5, 6, and 7). Xie et al. (2008) mapped the migration of shelf-edge since the 5.5 Ma (Figs. 3 and 4B), and the distance between Hainan Island and the shelf-edge was short (about 60 km) and approximately equidistant.

Fig. 4. Mio-Pliocene sequence thickness distribution. A. Sketch with explanation of the thickness trends observed on the map based on a cross-section trending SSE between sequence boundaries, reflecting shelf-slope-basin floor parts of the system with thin-thick-thin thickness pattern. B. Isopach maps of T40-T30, T30-T27, T27-T20, and T20-T0 periods with projection of shelf-edges identified from 2-D seismic profiles in this study. Oblique accretion on the shelf margin is suggested by the stronger progradation of the western area. Calculated sediment volumes building shelf-slope clinoforms (red polygons) during T40-T30, T30-T20 (sum of T30-T27 and T27-T20), and T20-T0 supplied from Hainan Island are presented in Table 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 3

| Boundaries | Time duration | Sediments in the shelf-slope clinoforms (red polygons in Fig. 4) required to build shelf-edge break more prominent (higher progradation rates) in front of the shelf to the west and its gradual decrease (progradation, aggradation rates) to the east. Combined with volume analysis we argue that the main sediment source building the shelf-slope clinoforms in QDNB was likely the Red River since the late Miocene. However, no comprehensive sediment fairways to deep water or sediment volume estimations studies have been done.

4.3. The model of "oblique" building the shelf-slope clinoforms

River-derived, oblique mud transport along the shelf and the littoral zone for significant distances have been noted (e.g., Nittouer and Wright, 1994) with the longest migration along the 1600-km-long Amazon-Orinoco coastline (Bisma et al., 1991; Allison et al., 2000; Peng et al., 2018). Fluid mud figures prominently in this oblique mud transport, and is a type of nearby, highly concentrated mud suspension generated in estuaries (Gallenne, 1974; Kineke et al., 1996) that can be transported long distances onto the shelf. It primarily consists of clay, silt and organic material (Ichaso and Dalrymple, 2009). Fluid mud has been described on muddy coasts, nearshore/littoral mud belts, mid- and outer-shelf mud belts (McCave, 1972; Nittouer and Wright, 1994; Chen et al., 2014, 2016b, 2018a, 2018b; Hanebuth et al., 2015). The seismic reflectors of sediments on the shelf of QDNB appear as flat and continuous, lacking significant changes in the geometry or amplitude, especially in the strata of the western shelf and in the younger periods, suggesting a relatively low energy/low grain size variability. This notion of dominantly fine-grained sediment is also supported by the published well-log data on the shelf of QDNB (Wang et al., 2016; Wang et al., 2015; Liu et al., 2015b) that report fine-grain deposits with mudstones and intercalated fine-grained sandstones in Miocene, and mudstones-siltstone alternations in Pliocene. In the northwestern SCS, close to the present location of the Red River mouth, the river-derived sediment dispersal is mainly controlled by oceanic current transport (Liu et al., 2016). Although the directions of modern surface currents during summer and winter in the Gulf of Tonkin remain controversial (orange and blue arrows in Fig. 9A, He et al., 2013; Liu et al., 2016; and references therein), the distribution of clay minerals (Liu et al., 2016) carried by the year-round cyclonic gyre suggests the dominant direction of modern surface current in the Gulf of Tonkin toward southeast. Together with the consistent northeastward current along the shelf break, named the South China Sea Warm Current (grey arrow in Fig. 9A, Kwan, 1978), modern surface currents prevailing in northwestern SCS are beneficial for the southeastward dispersal of fine-grained sediments derived from the tide-dominated Red River Delta (Goodbred and Saito, 2012), and which were later reworked along the coastline and aligned with bathymetric contours. The exact reconstruction of paleo-surface current is difficult due to the considerable variation of monsoon intensity (He, 2012), nevertheless, the dispersal of Red River-derived sediments since the late Miocene was restricted by the geological setting in the Gulf of Tonkin as an embayment, and the general trend was considered toward the southeast as well. The sediment transport distance is significant (tens to hundreds of kilometers) from the source (river mouth) in the entire Gulf of Tonkin (Fig. 9). Considering the large sediment supply, long-distance transport capacity, and the shallow water sedimentary environments west of Hainan Island, we infer the fine-grained sediments on the shelf of QDNB are transported toward southeast by the shelf currents from Red River as the possible pattern of fluid mud.

Because the shelf is flooded during sea-level highstand times, this is the likely period for sediment transport eastward to the south of Hainan Island (Fig. 9). During low sea-level stands, the Red River sediments...
were directed southward to deep water. In the late Miocene (Fig. 10A and B), the shelf-edge was north (~200 km) of its present location (Fig. 3) and the shelf sediment transport had a longer pathway to QDNB and contributed little to the progradation of the QDNB margin which was mainly controlled by Hainan source area. Although the late Miocene sedimentary rate of the Red River was relatively low (Fig. 8), the sediments delivered by the Red River were coarser grained than Pliocene and Pleistocene sediments (Zhu et al., 2007; Shi et al., 2011). Therefore, it is likely that during the lowstand periods of the late Miocene (Stage 1, Fig. 10A), the large paleo-Red River Delta had braided river channels on the coastal plain which connected, via the narrow shelf, the sandy deltas with canyon head and fed sediments to a large submarine fan. During the high sea-level phases of the late Miocene (Stage 2, Fig. 10B), sediment was discharged by Red River Delta into an embayment/epicontinental sea where the coarse-grained sediment formed sandy lobes close to the river mouth while the fine-grained (clay, silt) sediment was transported away from the river mouth by the current along the shelf Gulf of Tonkin (Fig. 9). The mudbelt around Hainan Island was likely thin and narrow due to the low sediment-transport rate and low content of fine-grained sediments in the Red River during the late Miocene. Since the Pliocene, the sediment supply rate of the Red River increased significantly (Fig. 8), and at the same time, the content of fine-grained sediments increased. The shelf-edges of Pliocene and Pleistocene migrated further to the south close to the recent location. During the lowstand periods (Stage 3, Fig. 10C) in the proximal reaches of the system, where accommodation was likely low, the southeast-oriented fluvial channels possibly incised the exposed shelf and delivered sediment directly to the deep water without forming deltas because of the low volume of sand. However, during the highstands (Stage 4, Fig. 10D), the drowning and widening of the shelf allowed the initiation of eastward shelf currents and shallow marine mud dispersal processes dominated by the shore-parallel mud advection. The Red River sourced mudbelt extended to the east on the shelf around the Hainan Island but gradually thinned toward the eastern shelf of QDNB.

As a consequence, during the Icehouse highstands and transgressive periods of the Pliocene and Pleistocene, when muddy sediments were transported eastward on the shelf of QDNB and eventually reached the shelf break, they accreted the margin in an oblique fashion (Figs. 9 and 10). Repeated accretions overwhelmed repeated periods of Icehouse eustatic sea-level fall, causing the entire succession to aggrade with the appearance of a prolonged accumulation. Supplied by the large sediment flux from Red River, coastal and shelf currents of QDNB transported sediments beyond shelf-edge prograding and changing the margin orientation. In QDNB the subsidence accelerated since 10.5 Ma with averaged total subsidence rate reaching about 160 m/My compared with 116 m/My of the early and middle Miocene (Zhang et al., 2008), and this acceleration increased within the last 5 Ma as a result of the dextral strike-slip movement of buried basin marginal fault (No.1 Fault, ④ in Fig. 9) to the west, which is associated with the movement of the Red River Fault (① in Fig. 9, Xie et al., 2006; Shi et al., 2011), accommodating the dispersal of Red River-derived sediments. Red
River-derived sediments are thought to be transported to the shelf margin of QDNB obliquely with a large acute angle (Fig. 9) which contribute to southward component diverging from the main eastward longshore current. In this way, the continental margin of QDNB prograded/bulged more in the west over multiple fourth-order cycles. In addition, shelf-slope clinoforms are well developed and preserved in western QDNB where shelf-edge incisions are absent due to the dominance of the fine-grained sediments. The model proposed is a combination of similar geometries to muddy-subaqueous shelf clinoforms that are coming to the shelf edge, and shelf-edge deltas protruding the shelf-edge that is oblique to the main sediment fairway.

5. Conclusions

The paleo-sediment flux required to build the shelf-slope clinoforms in Qiongdongnan Basin (QDNB) calculated using regional 2D seismic (4–32 Mt/yr.) is between 3 and 17 times larger than the estimated possible paleo-sediment flux discharged from Hainan Island (1.4–1.9 Mt/yr.) since the late Miocene. This difference indicates that most sediments on the shelf margin of QDNB were transported from a larger adjacent source, possibly Red River in the northwest. The present southeastward surface current along the shelf of Gulf of Tonkin was likely also active during the past sea-level highstands and was the main driver in transporting fine-grained (clay-silts) sediments from Red River into QDNB. Due to the obliquely intersecting shelf margin and surface currents, rapidly and locally (along strike-slip fault system) subsiding shelf and larger sediment flux, Red River deliver more sediments to the western margin of QDNB while the east was starving by low sediment supply from Hainan Island. The shelf-edge trajectory in QDNB shows stronger progradation to the west (closer to Red River) than to the east. The asymmetrical shelf-margin accretion with the Red River sediments progradating strongly in the western QDNB and building an aggradational-dominated margin to the east has implications for the sediments transport across the shelf-edge to deep water. This study is the first to report the oblique construction of shelf-slope clinoforms during multiple 4th order sea-level cycles in mud-rich shelves.
Fig. 9. Red River derived sediment dispersal. A. Sediment transport of recent ages suggested by grey arrows with estimated sediment flux (Mt/yr.) in circles, the 0.6Mt/yr. of sediment flux discharge from Hainan Island to the south are one third of total discharge of modern rivers in Hainan Island (1.8Mt/yr.); Surface current directions in the northwestern SCS are modified after He et al. (2013) and Liu et al. (2016); Grey dotted lines are time map of 5.5 Ma structure, northwestern SCS modified from (Zhu et al., 2009). Isochron contours are two-way traveltime (TWT) in seconds. Numbers in red circles near faults denote their names, e.g. ①=Red River Fault, ②=Yingxi Fault, ③=Yingdong Fault, ④=No.1 Fault, ⑤=No.5 Fault. Note that all these faults are buried normal faults underlying the Miocene strata. B. 3-D schematic diagrams and cross profiles illustrate oblique margin accretion on shelf margin of QDNB. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Acknowledgment

This project is supported by the State Scholarship Fund (No. 201806410030) offered by the China Scholarship Council (CSC), the scholarship from the China University of Geosciences (Wuhan; No. 007-G132541821), and the National Natural Science Foundation of China (No. 41702114). We thank Editor-in-Chief of Marine Geology, Dr. Edward Anthony for editorial handing and editing, and two reviewers, Dr. Jesse Korus, and Dr. Andrea Artoni for their constructive reviews that significantly improved the manuscript.

Software

DigitizeIt: version 1.5.8b, https://www.digitizeit.de/.

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Fig. 10. Schematic three-dimensional block diagrams illustrating sediments derived from the Red River transported southeastward to YGHB-QDNB. Oblique margin accretion was orderly formed from stage 1 to 4. A. Paleogeography during the late Miocene lowstands; B. Paleogeography during the late Miocene highstands; C. Paleogeography during the Pleistocene lowstands; D. Paleogeography during the Pleistocene highstands. Sediments was delivered to the slope during the low sea-level stands, whereas during the highstands, falling stage and transgression periods, sediments were mainly dispersed as fluid mud and accumulated on the shelf and transported over shelf-edge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)


