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1 **Spatial-temporal evolution of the source-to-sink system in the northwestern**
2 **South China Sea from the Eocene to the Miocene**

3 Chao Fu ^{a, b, c}, Shengli Li ^{a, *}, Shunli Li ^a, Jianyong Xu ^c

4 ^a School of Energy, China University of Geosciences, Beijing 100083, China.

5 ^b [Rennes Geosciences, Université de Rennes 1, Rennes 35000, France](#)

6 ^c [CNOOC Research Institute, Beijing 100028, China](#)

7 corresponding author: slli@cugb.edu.cn

8 **Abstract:** The northwestern South China Sea (NW-SCS) presents a spatial-temporal
9 evolution of its source-to-sink (S2S) system, that recorded the movement of the
10 Indochina block and the collision between the Indian and Eurasian plates. However,
11 complex tectonic movements and topographic evolution have led to controversial
12 studies about the spatial-temporal distribution of allogenic materials and autogenic
13 sediments. In this study, we integrated a number of multiscale data to review the S2S
14 system evolution of the northwestern area of the South China Sea from the Eocene to
15 the Miocene. The series include the initial synrift, postrift and thermal subsidence
16 stages. First, we identified the major sediment pathways using seismic profile
17 interpretation. We reconstructed the sediment distribution and lithofacies association
18 within the dispersal sink area based on seismic data, core samples and grain-size
19 analysis. We quantitatively studied the sediment flux and catchment area based on
20 mass balance calculation modeling. Following this, we acquired rare-earth element
21 (REE) data and zircon U–Pb age data from the bedrocks of the continental blocks and

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the South China Sea Cenozoic basement and rivers in the NW-SCS area to restore the provenance area and evaluate the migration distance by inspecting the heavy mineral assemblages. According to the above studies, three phases of S2S dynamics were identified. 1) The initial rifting stage occurred during the Eocene, and active rifting in the South China Sea induced a major topographic change. A large amount of autogenic slump sediments and a smaller amount of paleo-Red River sediments were injected into the Beibu Gulf Basin (BBGB) and the Yinggehai-Song Hong Basin (YGHB). 2) The postrift stage occurred during the Oligocene. Regional uplift and tectonic inversion probably linked to the clockwise rotation of the Indochina Block, broke the connection between the Beibu Gulf Basin and the Red River catchments. The paleo-Qin River and the paleo-Lian (Nanliu) River brought a large amount of clastic material into the Beibu Gulf Basin from the Cathaysia Block. 3) The thermal subsidence stage occurred during the Miocene: the eastward topographic tilt was enhanced, and the drainage basin entered postrift stage. The development of the Paleo-Red River and its branches, the Lam River and the Ma River, brought distal sediment into the YGHB, while the rivers in the west Cathaysia Block transported sediment into the BBGB. Statistical analysis of the S2S system parameters suggests that the average terrain altitude played a dominant role in determining the S2S system volume during the Eocene, while the dominant role transferred to the sediment supply during the Oligocene and Miocene.

Keywords: Northwestern South China Sea; Beibu Gulf Basin; Yinggehai-Song Hong

Basin; Source-to-sink system; Provenance area; Catchment evolution.

1. Introduction

The northwestern South China Sea (NW-SCS) is a ceaseless source of controversies regarding its tectonic evolution (Tapponnier et al., 1982; Biais et al., 1993; Müller et al., 2016; Ye et al., 2018). Several studies have used restored paleofluvial systems to tackle tectonic movements, considering that river morphological changes reflect tectonic events (Liu et al., 2016; Zhang et al., 2019). Meanwhile, flowing toward the half-closed embayment formed by the Beibu and Tonkin gulfs (Fig. 1), the rivers around the NW-SCS have carried more than 1.7 trillion metric tons (Mt) per year of clastic material into the marine basin since the Eocene (Holeman, 1968; Le et al., 2007). Restoring the dynamics of the source-to-sink system (S2S) in that area may thus provide a comprehensive insight on the regional tectonic framework, deciphering how tectonics control topographic changes and the erosion pattern in the NW-SCS.

Currently, many methods have been developed to assess sediment migration processes and rates in fluvial systems. Indeed, detrital geochronology, heavy mineral assemblages, or rare earth element (REE) composition represent excellent tools to trace the evolution of a fluvial catchment (see Gaillardet et al., 1999; von Blanckenburg, 2005; Borges et al., 2008; Hinderer, 2012; Jolivet et al., 2014; Garzanti, 2016). With these methods, many researchers have focused on the provenance area distribution of the allogenic materials around the NW-SCS (see Clift and Sun, 2006; Cao et al.,

2015; Fyhn et al., 2019; Wang et al., 2019; Zhao et al., 2020). As the primary pathway into the NW-SCS, previous literature has pointed out that during the Eocene, the paleo-Red River brought materials both from the Songpan Garze terrane (Brookfield, 1998; Clark et al., 2004; Clift et al., 2008) and the Indochina Block (van Hoang et al., 2009; Cheng et al., 2021; Gong et al., 2021), depositing them in the offshore sink area. However, accompanying the Eocene to late Miocene rifting process in the NW-SCS, drainage basins, including the Yinggehai-Song Hong Basin (YGHB) and the Beibu Gulf Basin (BBGB), experienced complicated source area evolution, and various S2S systems coexisted (Clark et al., 2004; Clift et al., 2008; Cao et al., 2015; Fyhn et al., 2019; Fyhn et al., 2020; Gong et al., 2021; Lei et al., 2021; Li et al., 2019; Liu et al., 2020; Lyu et al., 2021; Wang et al., 2021; Yao et al., 2021). Regarding the YGHB, situated in the western section of the NW-SCS, previous studies generally suggest that from the Oligocene to the early Miocene, the paleo-Red River brought small quantities of materials derived from igneous, ageing from 88 Ma to 159 Ma, and Precambrian metamorphic rocks exposed along the Red River Fault Zone and in the coastal mountain range (Clift et al., 2008; Zhu et al., 2009; Lin et al., 2012; Cao et al., 2015; Shao et al., 2018; Fyhn et al., 2019; Fyhn et al., 2020). The BBGB situated in the northern section of the NW-SCS, however, has been affected by drastic topographic reorganization of its fluvial feeding networks. as a result, estimating the extend of the provenance areas, especially with regard to the paleo-Red River evolution remains challenging (Liu et al., 2021; Gong et al., 2021; Liu et al., 2020).

85 In contrast, other studies explored several small rivers around the NW-SCS that
 86 could also bring a mass of sediments into the offshore sink area and serve as the
 87 prominent pathway in the S2S system. The Ma River and Lam River may bring
 88 basement-derived material from the Indochina Block to the Yinggehai-Song Hong
 89 Basin (see [Wang et al., 2015](#); [Liu et al., 2016](#); [Zhong et al., 2017](#); [Fyhn et al., 2019](#)),
 90 and the Qin River, Lian (Nanliu) River, Moyang River and Changhua River could serve
 91 as sediment routes to the Beibu Gulf Basin (see [Gong et al., 2021](#); [Liu et al., 2021](#)).
 92 Furthermore, zircon U–Pb dating and Lu–Hf isotope analysis ([Liu et al., 2016](#); [Ye et al.,](#)
 93 [2018](#); [He et al., 2020](#)) revealed that the western portion of the South China Block,
 94 including the Cathaysia Block and Yangtze Block ([Fig. 1](#)), may provide material from
 95 both Mesozoic-Cenozoic granitic rocks and Paleozoic sedimentary rocks. Thus,
 96 significant uncertainties remain about the evolution of the fluvial system. Especially
 97 controversial is the course of the rivers bringing the main proportion of sediment into
 98 the offshore drainage basin within the NW-SCS. In addition, previous studies argued
 99 that allogenic material was more abundant than autogenic sediment in the slope break
 100 area or the deep-sea basin where some sediment records include poorly sorted slump
 101 deposits ([Yuan et al., 2017](#); [Liu et al., 2014](#); [Liu et al., 2020](#); [Zhao et al., 2020](#)). Partly
 102 due to the limited amount of detrital geochronology data in the sink area, gaps are thus
 103 remaining in our understanding of the spatial and temporal evolution of the source-to-
 104 sink system of the NW-SCS ([Wang et al., 2019](#); [Fyhn et al., 2020](#); [Wang et al., 2020](#)).
 105 We use the sediment rare earth elements (REEs) patterns within the drainage

basin to evaluate the ratio of the material derived from the surrounding continental blocks and the Cenozoic basement of the NW-SCS. Using newly obtained seismic data we reconstruct the paleomorphology of the drainage basin. Sediment migration distances are estimated based on heavy mineral assemblages (HMA). Finally, new detrital zircon U–Pb data within three drainage basins and a compilation of U–Pb data from the fluvial sediments and the basement around the catchments [are used to decipher the source-to-sink pattern through time \(Fig.1 A\)](#). The zircon U–Pb ages of the basement and sediments are crucial in constraining the sources age patterns in the various drainage areas. Knowing this allows us to undertake an analysis of the data, identify the fluvial network [\(Moecher and Samson, 2006; Dickinson and Gehrels, 2009\)](#) and calculate the quantitative relationship between the dominate factors, including the terrain height, sedimentary supply and provenance area, to the S2S system formed [\(Syvitski and Milliman, 2007; Hinderer, 2012; Holbrook and Wanas, 2014; Nyberg et al., 2018\)](#). Our main object is to reconstruct the evolution of the sediment pathways around the NW-SCS, identify the large river catchments and describing the evolution of the drainage network in response to regional tectonic movements during the Eocene and Miocene.

2. Geological Setting

2.1 Tectonic setting

The South China Sea (SCS) [\(Fig. 1 A\)](#) is structurally situated at the junction of the Eurasian, Pacific, Philippines Sea, and Indo-Australian plates [\(Morley, 2012; Liu et al.,](#)

127 2016). The northwestern SCS (NW-SCS) is surrounded by the Hainan and Xisha
128 islands (also called the Paracel islands) to the East and the Indochina and Cathaysia
129 Blocks in the west and north, respectively (Clift and Sun, 2006; Zhu et al., 2009; Fyhn
130 et al., 2018). Since the Cretaceous period, three rift basins, the Beibu Gulf Basin
131 (BBGB), the Yinggehai-Song Hong Basin (YGHB) in the Tonkin Gulf and the
132 Qiongdongnan Basin (QDNB), have developed within the NW-SCS (Fig. 1) (Fyhn et
133 al., 2019; Wang et al., 2019). Seismic profiles show that basins within the NW-SCS
134 have a double-layer architecture with a syn-rift wedge-shaped sedimentary sequence
135 at the bottom, capped by a post-rift sequence corresponding to thermal subsidence
136 (Pigott and Ru, 1994; Rangin et al., 1995).

137 From the Paleocene to the Miocene, the Red River Fault that separates the
138 Indochina Block from the Cathaysia Block, developed as a northwest-trending, left-
139 lateral shear fault and induced the formation of depocenters and boundary faults
140 trending N–E in the BBGB and E–W in the YGHB (Schärer et al., 1994; Rangin et al.,
141 1995; Fyhn et al., 2019; Rizzi et al., 2020; Hoang et al., 2020). During the Oligocene,
142 as Indochina experienced extrusion and clockwise rotation in response to the India-
143 Eurasia collision, several NNW-directed faults developed within the BBGB and YGHB
144 basins (Ru and Pigott, 1986; Rangin et al., 1995; Zhu et al., 2009; Liu et al., 2014).

145 Finally, during the late Miocene - Pliocene, as the Red River shear zone activity
146 decreased, the basins in the NW-SCS changed from a rifting to a post-rifting stage as
147 the Red River Shear Zone switched to right-lateral shearing (Rangin et al., 1995;

148 [Schoenbohm et al., 2006](#)).

149 **2.2 Stratigraphic framework**

150 The stratigraphic framework of the NW-SCS has been superposed since the
151 Paleocene. The NW-SCS basement can be divided into two parts: The Beibu Gulf
152 Basin basement belongs to the extension of the Yunkai Massif and support a late
153 Paleocene to Quaternary cover sequence; The Yinggehai Basin basement is
154 composed of the fold belt that separates the Indochina Block from the Cathaysia Block,
155 and is covered by Oligocene deposits ([Sun et al., 2014](#); [Cui et al., 2021](#); [Liu et al.,](#)
156 [2021](#); [Wang et al., 2021](#)).

157 The Paleocene series are represented by the Changliu Fm. in the BBGB and the
158 Dongjun Fm. in the Shiwandashan Belt (SWDSB) (T_{100} to T_{95} in the seismic profile).
159 The Changliu Fm. is conformably followed by the Eocene Liushagang Fm., composed
160 of sand and mudstone interlayers. [Liu et al. \(2020\)](#) interpreted it as being deposited in
161 a fluvial-lacustrine setting. In the YGHB, the Lingtou Fm (**Fig. 2**) is dominated by a light
162 brown conglomerate.

163 During the Oligocene, the Weizhou Fm. developed in the BBGB,
164 contemporaneously to the Yacheng and Lingshui Fm. in the YGHB (**Fig. 2**). [Wang et](#)
165 [al. \(2019\)](#) concluded that rivers around the NW-SCS began to form since the Oligocene
166 and brought sediments from sources in the Cathaysia (Lo River) and Indochina blocks
167 (Ma River, Lam River, etc.).

168 The late Miocene series of the BBGB include the Xiayang Fm. (Aquitanian-

Burdigalian), the Jiaowei Fm. (Langhian-Serravallian), and the Denglouliao Fm. (Tortonian-Messinian), while the YGHB series are composed of the Sanya Fm. (Aquitania-Burdigalian), the Meishan Fm. (Langhian-Serravallian), and the Huangliu Fm. (Tortonian-Messinian) (Fig. 2). The lithology of these intervals mainly consists of gray mudstones, thin layers of light gray calcic siltstone, fine sandstone and limestone in a shallow marine setting (Clift et al., 2014; Liu et al., 2016; Yang et al., 2021).

3. Data and Methods

3.1 Seismic reflection data and core samples analysis

The NW-SCS has been imaged by 2D seismic data (approximately 3000 km of profiles) and 3D high-resolution seismic data (2000 km²) collected by the China National Offshore Oil Corporation (CNOOC) Zhanjiang branch and Shenzhen branch. The data cover the area of the Beibu Bay and Yinggehai-Song Hong basins. The 3D seismic cubes have a bin size of 12.5 × 12.5 km with sample rates of 2 ms. The peak frequency is ~30 Hz, which allows for a vertical resolution of ca. 20 m.

A total of 14 wells drilled in the NW-SCS were selected for stratigraphic analysis and seismic profile description. The positions of the cross-well seismic sections used in this work are shown in Fig. 1 B. The electric well log curves, including gamma rays, were acquired and processed via Schlumberger Petrel software. The grain size was measured using Mastersizer® 2000 with a laser particle size analyzer (SYE209) in Well Y4 and Y9 from YGHB and W1, W2 and W3 from BBGB. Analysis of the sediment rare earth element (REE) concentrations (standardized to chondrite, PAAS and NASC)

and the heavy mineral content was conducted on 26 samples from 12 wells by the Geological Laboratory of Research Institute of Shenzhen Corporation of the China National Offshore Oil Corporation.

3.2 Detrital zircon geochronology

LA-ICP-MS U-Pb analysis of detrital zircons from six core samples (W1 2362.8 m deep, W2 2910 m, W3 2264.85 m, W4 1450 m Y1 3804.5 m and Y2 4674 m) was completed by the Chinese Academy of Geological Sciences ([Appendix TABLES](#)). Laser ablation was conducted using an NWR193UC 193 nm deep-ultraviolet laser ablation sampling system (Elemental Scientific Lasers, USA). Mass spectrometry was performed using an Agilent 7900 inductively coupled plasma mass spectrometer (Agilent, USA). One hundred twenty detrital zircons from each sample were analyzed with a spot size of 30 μm . Every five analyses were followed by one analysis of standard zircon 91500, and GJ. -Common lead correction was conducted using ComPbCorr#3_15G. The U-Pb age calculations and concordia diagrams were obtained using IsoplotR software provided by University College London, UK (<http://pieter-vermeesch.es.ucl.ac.uk/shiny/IsoplotR/>). Only zircon ages concordant within 90%-110% are considered in the discussion section.

3.3 Research methods

3.3.1 Lithofacies identification and sediment dispersal pattern restoration

To characterize the sediment dispersal pattern, we integrated core samples and their grain size analysis from wells W1, W2, W3, and W4 in the BBGB and wells Y1 to

Y9 in the YGHB. Based on the identified lithofacies and their description ([Table 1](#)), we identified the facies association developed in the sink area. Then, by integrating 2D and 3D seismic data interpretations, we reconstructed the geometry of the sink area and the sedimentary facies association. Based on their seismic boundaries, three seismic facies (concave, linear, and sigmoidal) were identified. These facies can be interpreted as channels or sediment pathways, channel distributaries or semi-deep to deep lake fine-grained deposits, fan deltas or subaqueous deltas, respectively. Moreover, we evaluated statistics of the S2S according to the seismic profile interpretations, including the prograding distance, average slope angle, and terrain height, and listed the results in [Table 2](#).

3.3.2 Provenance area identification

Combining the results of previous provenance studies for the NW-SCS during the Eocene to the Miocene ([Liu et al., 2014](#); [Wang et al., 2016](#); [Yuan et al., 2017](#); [Fyhn et al., 2019](#); [Wang et al., 2019](#); [Wang et al., 2019](#); [Wang et al., 2019](#)), we established a detrital zircon U–Pb age distribution for sediments deposited in the basin and compared them with the potential provenance area.

We evaluated the evolution of the main provenance area during the interval from the Eocene to the Miocene using age data from basement rocks as well as heavy mineral assemblages (HMAs), REE patterns of sediments, and information on the tectonic background.

The heavy mineral assemblages of neighboring samples generally closely

resembled each other, providing a qualitative evaluation of the sedimentary distance with the heavy mineral assemblage index. We calculated the zircon-tourmaline-rutile (ZTR) index, the garnet-zircon (GZi) index, and the apatite-tourmaline (ATi) index (Table 3). ZTR represents mineralogical maturity and correlates positively with mineral stability; GZi is mostly used to differentiate among parent rock types, particularly metamorphic rocks and magmatic rocks; Finally, ATi allows to determine the degree of weathering during transportation (Morton et al., 2005; Morton and Hallsworth, 1994; Morton and Hallsworth, 1999). However, grain dissolution or chemical weathering could influence the heavy mineral content (Morton et al., 2005). In this study, the heavy mineral we collected are mostly from the layers less than the depth of 3000m, which may not sever a serious metamorphism, and the grains are observed as an original surface with SEM.

3.3.3 Source-to-sink system reconstruction and mass balance estimations

To study the S2S system, Syvitski and Milliman (2007) produced a fitting equation (BQART model) to calculate the amount of sediment in a fluvial-deltaic system.

$$Qs = \alpha A^{0.41} + b \quad (\text{Equation 1})$$

where Qs is the sediment load ($M.T./yr$), α is a constant of proportionality, and A represents the catchment area (in km^2). Then, Paola and Martin (2012) proposed an improved mass balance theory to describe the infilling process in an active extensional basin and calculated the volume of the S2S system following:

$$Qs = \frac{a}{x(x)} \int_0^x u(x) \cdot \sigma(x, t) dx + b \quad (\text{Equation 2})$$

where a is the rifting rate, x indicates the migration distance from the source area to the final deposition area. $\chi(x)$ is the mass balance coordinate, and it can serve as an index of the grain size distribution, and b is the thickness of the fine-grained sediment provided into the basin via suspension and flocculation. (Martin et al., 2009; Paola and Martin, 2012). The delta prograding distance ($u(x)$) and the sink area ($\sigma(x, t)$) that can vary over time may be obtained through the interpretation of seismic data. Using 2D seismic data, we determined ($u(x)$) according to successive prograding events.

As to the paleomorphology reconstruction, firstly, we built a stratigraphic framework based on the seismic package's terminal relationship after well-seismic calibration. Then, as shale deposits have a much higher compaction coefficient than sandstone layers, we divided the strata using the sand content evaluated within the reference wells shown in Fig. 1 B. The layer's pre-compaction thicknesses were calculated using coefficients of 0.00037 m^{-1} for mudstone and 0.00025 m^{-1} for sandstone (He et al., 2002; Luo et al., 2003; Zhou et al., 2019). This approach allowed generating a series of paleogeomorphology maps covering the Eocene to the Miocene period.

Based on those maps, we were able to identify the sink areas of these offshore drainage basins ($\sigma(x, t)$) and to calculate the sediment supply rates (V_{sed}) with the following equation:

$$V_{sed} = [\sigma(x, t) \cdot u(x)]/T. \quad (\text{Equation 3})$$

T is the time interval, which can be obtained from results of well-seismic calibration and the geochronology U–Pb data from wells W1, W2, W3, W4, Y1, Y2 and Y7.

274 4. Seismic interpretation and sedimentology study

275 We selected two typical seismic profiles across the BBGB and three across the
276 YGHB to interpret the prograding/retrogradation process in addition to 6 wells to
277 explore their depositional environment.

278 4.1 Core sample description and lithofacies association

279 The grain sizes of sediments in the NW-SCS during the Eocene to the Miocene
280 ranged from mudstone to fine-grained gravel. We classified the deposits into the
281 following 16 types: massive mudstone (M), bioclastic fine-grained sandstone (Fb),
282 cross-bedded fine-grained sandstone (Fc); bioturbated fine-grained sandstone (Fcb),
283 laminated fine-grained sandstone (Fcl), slump structured fine-grained sandstone (Fd),
284 bioturbated sandstone (Sb), cross-bedded sandstone (Sc), compound banded
285 sandstone (Scb), herringbone cross-bedded sandstone (Scc), muddy strip composite
286 sandstone (Scm), slump structured sandstone (Sd), massive sandstone (Sm), planar
287 cross-bedded sandstone (Sp), massive gravel (Gm), and planar cross-bedded gravel
288 (Gp).

289 The above lithofacies associations were identified and classified based on the
290 cores from Wells W1, W2, W3, Y7, and Y8 (Figs. 3 and 4). Detailed descriptions of
291 these lithofacies can be found in Table 1.

292 4.2 Grain size vertical distribution and sedimentology interpretation

293 4.2.1 Eocene to Oligocene

294 As seen in the stratigraphic column in wells W1, W2, and W3 (Fig. 5), the

lithofacies associations included LF.8, LF.9, and LF.11, and the grain size distribution curve in this interval shows two peaks ($\phi=1$ and 2.5).

Based on the lithofacies association interpretation in Fig. 4 and Table.1, the deposits in the BBGB during the Eocene are characterized by an interlayer of coarse-grained mass flow deposits and coarse-grained sandstone. This may be caused by high-energy traction flow or gravity flow, possibly associated to a regional slump or deposition in a coarse-grained delta (including a fan delta or fluvial fan). In the early Oligocene period, the lithofacies association in the BBGB evolved upward to LF.2, with a one-peak grain size curve ($\phi=1.5$). We can infer from this that fluvial deltaic environments dominated during this interval.

In the YGHB, we focused on the sedimentary facies during the Eocene to the Oligocene. As to the Eocene interval, Y9 and Y4 display an association of lithofacies LF.9 and LF.10, with grain sizes ranging from $\phi=0$ to $\phi=3$, indicating that a fine-grained traction flow had developed upward. Up to the Oligocene interval, the deformation structure identified in well Y9 suggests that coarse-grained sediments dominated in the YGHB.

4.2.2 Miocene

In the early Miocene, the lithofacies associations include LF.3, LF.4, LF.5, LF.6, and LF.7. We identified some mud concretions and mud clasts in well Y8 in the YGHB (Fig. 3), which indicate that increasing traction flow had developed among the core samples. The fine-grain bias grain size curve also indicates that more fine-grained

delta had been injected into the sink area.

The late Miocene deposits are characterized by lithofacies LF.1, LF.2, and LF.5. The herringbone cross-bedding (Scc) developed in LF.2 can be interpreted as a tidal-dominated shallow water environment. We believe that fine-grained sediments dominated in the NW-SCS during the late Miocene. Furthermore, the significant presence of trace fossils, including pholadid burrows, *Diplocraterion*, and *Rhizocorallium* (Fig. 3), indicates an offshore setting in this interval.

4.3 Seismic interpretation

4.3.1 The Beibu Gulf Basin

The seismic profiles acquired in the BBGB may be divided into four layers based on the well-seismic calibrated: Eocene (Liushagang Fm., T90-T80), Oligocene (Weizhou Fm., T80-T70), early Miocene (Xiayang Fm. and Jiaowei Fm., T60-T40), and late Miocene (Dengloujiao Fm., T40-T30). We distinguished several boundary faults in the northern BBGB, with vertical displacement ranging from 300 to 1000 m.

The thickness of the Eocene strata is 2000 m in the northern area and less than 1500 m in the southern area. In this interval, we identified a series of seismic facies with clear concave and lenticular boundaries, which were interpreted as prograding deltas. These were then numbered as B.N.T.1-B.N.T.7 and B.S.T.1-B.S.T.4 (Figure 6).

In the Upper Oligocene and the Miocene, the prograding seismic package is observed to have decreased in thickness while increasing in continuity. We determined the delta geometric parameters to be an average thickness and prograde distance of

50-80 m and 500 km, respectively. We subsequently named these prograding deltas B.N.T.8- B.N.T.17 in the northern BBGB and B.S.T. 5- B.S.T.16 in the southern BBGB (Fig. 6).

4.3.2 The Yinggehai-Song Hong Basin

Referring to the well calibration, we divided the YGHB into three time slices, namely, the Oligocene (including the Yacheng Fm. and Lingshui Fm., T80-T60), the early Miocene (Sanya Fm. and Meishan Fm., T60- T40), and the late Miocene (Huangliu Fm., T40-T30). The average thickness of the Oligocene interval was 600~800 m. The thicknesses of the early Miocene and the late Miocene had similar thickness values of 750~1000 m.

In the Oligocene interval, the seismic facies featured high-continuity packages and a concave seismic boundary, suggesting a prograding delta. We were able to distinguish 12 prograding deltas, including Y.W.T.1-Y.W.T.3 in the western part (Fig. 7 A), Y.C.T.1-Y.C.T.4 in the central part (Fig. 7 B), and Y.E.T.1-Y.E.T.6 in the eastern part (Fig. 7 C). These prograding deltas appeared to have average thicknesses ranging from 50~100 m, and their sink area was 200 km².

Toward the Miocene, the seismic events showed an increasing continuity and high reflection amplitudes. Based on the core samples mentioned above, we interpreted them as belonging to an alluvial delta and numbered them Y.W.T.4-Y.W.T.9, Y.C.T.4-Y.C.T.9, Y.E.T.6- Y.E.T.14 (Fig. 7). The average thickness of these prograding delta ranges from 40 to 70 m, and they covered over 100 km².

5. Results

5.1. Geochronological data

5.1.1 Geochronological data from the river samples

1) The Red River and its tributaries

The Red River is formed by the confluence of the Da and Lo rivers (Fig. 1 A). Samples were collected on the bank and bars of the Red River and its major branches (Van Hoang et al, 2009; Fyhn et al, 2019). Major detrital zircon U-Pb age peaks at ~262 Ma and ~448 Ma characterize the upper stream samples of the Red River (Fig. 8). The Red River tributaries (Da river) displayed a peak at 245 Ma, and the Lo River shows a peak at ~396 Ma.

2) The Ma River and Lam River from the Indochina Block

The zircon samples were acquired from the rivers' downstream areas. The samples from these rivers display peaks at 240~260 Ma and 420~460 Ma. Additionally, some older age zircons observed at the Ma River included clusters of ~1028 Ma, ~1732 Ma, etc.

3) The Qin River and Lian River (Nanliu River) from the Cathaysia Block

The Qin River is flowing southward from the west of the Cathaysia Block. The sample within this river were acquired from its upper stream. Its age spectra showed a major age peak at 230~240 Ma. The Lian River runs parallel to the Qin River. The sample acquired from its mouth area include age clusters at ~97 Ma, ~162 Ma, ~239 Ma and ~433~530Ma.

4) The Changhua River from Northern Hainan Island

The Changhua River flows from the northern part of Hainan Island and carries sediments into the NW-SCS. The downstream area samples display three age peaks at ~65 Ma, ~205 Ma, and ~450 Ma.

5) Rivers from the Cathaysia Block (Upper stream tributaries of the Pearl River and Moyang River)

As previous studies have explored the connection between the Red River catchment and the Pearl River ([van Hoang et al., 2009](#); [Wissink et al., 2016](#); [Cao et al., 2018](#)), we decided to explore the age distribution of the upper stream tributaries of the Pearl River. Zircon samples from the Moyang River, which flows southward, show a strongly multimodal curve, including peak ages of ~205 Ma, ~420 Ma, and ~910 Ma ([Zhong et al., 2017](#)).

5.1.2 Geochronological data from the basement rocks of the surrounding continental block and South China Sea Cenozoic basement.

To build the relationship between the base rock (or the basement) and the offshore dispersal area, we collected U–Pb data from previous studies, covering the continental block that surrounds the NW-SCS and the basement.

1) Cathaysia Block and East Tibetan Plateau

We acquired samples from the surrounding continental block, especially for the Yunkai Massif in the eastern Cathaysia Block and Shiwandashan Belt (SWB) in the western block. The Yunkai Massif, serving as the Lian River provenance area, showed

a peak age of ~435 Ma. In the northern part of the NW-SCS, the Qin River brings sediments from the Shiwandashan Belt. Thus, we acquired zircon from the SWB, and the ages of these grains encompassed three groups, ~250 Ma, ~420~500 Ma and ~805~980 Ma.

Furthermore, according to the study of [Brookfield \(1998\)](#), [Clark et al. \(2004\)](#) and [Clift et al. \(2008\)](#), the paleo-Red River may have brought some sediments from the East Tibetan Plateau. We obtained zircon data from the Danba Domal Terrane or the Southwest Sichuan Basin, all of which showed the East Tibetan Plateau's age distribution. The Danba Domal Terrane and the Southwest Sichuan Basin showed unimodal age peaks at ~810 Ma and ~820 Ma.

2) Indochina Block and the Red River Faults Zone

Regarding the western and southern portions of the NW-SCS, previous studies noted that the rivers along the Indochina Block, such as the paleo-Red River, Ma River, and Lam River, have carried sediments into the offshore area during the interval from the Eocene to the present ([Wang et al., 2016](#); [Fyhn et al., 2019](#); [Wissink et al., 2016](#)). As the Red River Fault Zone developed metamorphic rocks, its age presented multiple peaks ([Cao et al., 2011](#); [Wang et al., 2017](#)). However, we focused on the potential source area during the Cenozoic period and concluded that its base rock age was ~60~80 Ma. The blocks on the west side of the NW-SCS presented a younger age distribution, such as ~37 Ma in Dai Nui Con Voi (DNCV), ~273 Ma in the Khorat Basin ~53.9 Ma, and ~110 Ma in the Tengchong Terranes.

3) Hainan Island

Many previous studies have elucidated the relationship between the provenance area distribution on Hainan Island (Clift and Sun, 2006; Yan et al., 2017; Miluch et al., 2021) and the ways in which their age distribution varies sharply in terms of space. This study collected U–Pb data from the basement along the Changhua River. They were observed to have a unimodal peak at ~63 Ma.

4) South China Sea Cenozoic basement

As mentioned above, the pre-Cenozoic basement of the South China Sea extends the Cathaysia block and Indochina block (Sun et al., 2014; Lei et al., 2015; Cui et al., 2021). Regarding the basement of the BBGB, the zircons from metavolcaniclastic samples showed a multimodal curve, with peak ages of ~100 Ma, ~251 Ma, ~421 Ma, and ~820 Ma. The youngest detrital zircon age collected was ~98 Ma (Fig. 9). In the basement of the eastern margin of the YHGB, the zircons from granite showed a peak age of ~98.4 Ma, and their youngest zircon was ~87.0 Ma (Fig. 9).

5.1.3 Geochronological data from offshore drainage basins

Detrital zircon U–Pb age data were used to constrain the potential source area of sediments deposited in the NW-SCS during the Eocene and Miocene. Four original samples were selected in the BBGB, including wells W1 (2362 m Eocene and 2631 m Oligocene), W2 (2910 m Eocene), W3 (2776 m Eocene), and W4 (775.2 Miocene), and three samples were acquired in the YGHB, Y2 (4674 m Oligocene), Y1 (3804.5 m Oligocene) and Y7 (2581 m Miocene). Concordia plots are shown in Fig. 10 and

individual age spectra in [Fig. 11](#).

1) U–Pb age data during the Eocene

In the Eocene, a total of 304 crystals were analyzed from three samples in the BBGB. Of that total, 280 had a >90% concordance, which was considered to be adequate (age data in [Appendix Table](#)) ([Fig. 10](#)). The individual ages were grouped into ~260 Ma, 410 Ma, ~980 Ma, and ~1875 Ma ([Fig. 10](#)). The Th/U in W1 and W3 (the eastern BBGB) showed a value of 0.1~2.0, while that of the western BBGB (W2) was 0.01~0.5 ([Fig. 11](#)). There has yet to be sufficient drilling data collected from the YGHB, so we have chosen not to present that information.

2) U–Pb age data during the Oligocene

For the Upper Oligocene, we collected zircon from well W1 in the BBGB and two samples from the YGHB. Among 74 grains of the BBGB, a total of 66 in this interval were deemed adequate for dating ([Fig. 10](#)). The age data in W1 (BBGB) were found to have three clusters, ~235 Ma, ~420 Ma, and ~980 Ma. The ~235 Ma and ~420 Ma groups contained 80% of all the grains.

Two samples in the YGHB showed a varied age distribution. The individual ages in Y1 and Y2 were grouped into ~75 Ma, ~210 Ma, and ~420 Ma. Groups ~220 Ma and ~420 Ma, representing 90% of all the zircon grains in Y1 (Yingdong Slope Zone of YGHB). Y2 had high percentages of groups ~75Ma and ~220Ma. The Th/U ratio of the YGHB ranged from 0.05 to 0.8.

3) U–Pb age data during the Miocene

463 From the Upper Miocene, we collected 147 grains in W4 (BBGB) and 90 grains in
 464 Y7 (YGHB). The U–Pb concordia plots in [Fig. 10](#) show that all the grains had a
 465 concordance of over 90%. The U–Pb age spectrum of W4 revealed three groups, ~65
 466 Ma, ~220 Ma, and ~410 Ma ([Fig. 11](#)), and grains with ages of ~220 Ma and ~410 Ma
 467 were prominent. The Th/U ratios of these samples had values between 0.1 and 5.0.
 468 Samples from Y7 showed three age clusters, ~30 Ma, ~230 Ma and ~390 Ma, and
 469 their Th/U values ranged from 0.08 to 3.0.

470 5.2 Heavy Mineral Assemblage (HMA)

471 1) HMA during Eocene

472 As shown in [Fig. 12 A](#), we calculated the GZi, ATi, and ZTR indices in the Eocene,
 473 which showed various spatial discrepancies in W1, W2 and W3. Well W2 showed a
 474 high GZi index (0.55), similar to what has been observed in North Vietnam and the Qin
 475 River ([Xia et al., 2017](#); [Fyhn et al., 2019](#)). Wells W1 and W3 had high contents of
 476 tourmaline and zircon, and their ZTR indices were 42.12% and 75.09%, respectively.

477 2) HMA during the Oligocene

478 From the Upper Oligocene, we selected 6 wells around the NW-SCS to explore
 479 the HMA distribution ([Fig. 12 B](#)). HMA in the BBGB showed a similar distribution
 480 pattern. Titanium, garnet and zircon were prominent, and the ZTR index of the wells in
 481 the BBGB was over 40%.

482 In the YGHB, the HMA distribution varies sharply. There was a high content of
 483 titanium (43%) in the western YGHB, although its value decreased to 15% in the East

484 Slope Zone of the YGHB. In the deep area of the YGHB, hematite dominated and was
485 also found in Y8.

486 3) HMA during the Miocene

487 During the Miocene, the BBGB and YGHB had varied HMA patterns ([Fig. 12 C](#)
488 and D). HMA in the BBGB featured high contents of titanium, garnet, zircon, and
489 tourmaline. These wells showed similar ZTR and ATi indices, while the GZi index
490 increased from the northern BBGB to the southern part (Well W1 had a GZi index of
491 0.46, the GZi index of W2 was 1.02, and that of W3 was 1.86). In the Upper Eocene,
492 the HMA maintained a similar pattern, and the GZi index showed signs of a gentle rise.

493 For the early Miocene interval in the YGHB, the hematite contents in Y4, Y6, and
494 Y8 were found to be higher than those of the BBGB, and their ZTR values were 20.62%,
495 15.87%, and 18.58%, respectively. In the Upper Miocene, the garnet content increased
496 in Y4 and Y6, and the GZi index rose to 0.89 and 2.70, respectively.

497 5.3 Rare earth elements

498 The chondrite-normalized analyses show ubiquitous light REE enrichment from
499 the Eocene to Pliocene. RRE had a gentle negative Eu anomaly in the BBGB, whereas
500 in the YHGB, there was strong Eu enrichment. By referring to a wealth of previous
501 studies ([Dou et al., 2012](#); [Cao et al., 2015](#); [Cui et al., 2016](#); [Shao et al., 2016](#); [Shao et al., 2018](#)), we collected data from the fluvial sediments around the NW-SCS ([Fig. 13](#)
502 A~F), which also showed a slight-negative Eu anomaly.

504 The Eocene interval samples taken from the BBGB showed a slight negative Eu

anomaly; their $\delta(\text{Eu})$ values ranged from 0.8 to 0.95, and $\delta(\text{Ce})$ was 0.9~1.0. The ΣREE values of the samples in wells W1 and W3 were 36.1~232.7 $\mu\text{g/g}$, and the average value was 152.1 $\mu\text{g/g}$. The $\Sigma\text{LREE}/\Sigma\text{HREE}$ ranged from 5.93 to 10.9, with an average value of 9.12. The YGHB had a similar REE distribution pattern in the BBGB during the Eocene.

In the Upper Oligocene, sediment samples from the BBGB and YGHB maintained REE patterns similar to those of Eocene samples (Fig. 13 H), including W1 (2640 m), W2 (2530 m and 2700 m), Y1 (3802 m) and Y2 (3906 m). They also showed a slight negative Eu anomaly. However, the samples from Y5 in the northern part of the YGHB showed ΣREE values of 87.17~260.2 $\mu\text{g/g}$ with $\delta(\text{Eu})$ carrying a strong positive signal.

In the Miocene, the ΣREE in the BBGB decreased to 27.83~198.50 $\mu\text{g/g}$. The distribution pattern evolved sharply (Fig. 13 I and J). The $\delta(\text{Ce})$ and $\delta(\text{Eu})$ in well W1 were over 1.0, exhibiting unobvious Eu depletion. The $\Sigma\text{LREE}/\Sigma\text{HREE}$ values ranged from 8.63 to 16.9, with an average value of 12.5. In contrast, samples collected from Y1 and Y5 showed a strong positive Eu anomaly, while Y2, Y3, Y4 and Y8 featured negative anomalies. The $\Sigma\text{LREE}/\Sigma\text{HREE}$ values of the YGHB ranged from 9.62 to 25.3, with an average value of 16.5, which was higher than that of the BBGB.

Ratios such as Co/Th-La/Sc (Fig. 14. A), Cr/V-Y/Ni (Fig. 14. B) and La/Yb - ΣREE ($\times 10^{-6}$) (Fig. 14. C) can therefore provide information about the source rock characteristics of sedimentary rocks (Fig. 14). According to the diagrams in Fig. 14 A, B and C, most of the Eocene samples were close to the felsic volcanic and granite

fields. The Co/Th-La/Sc diagram (Fig. 14) depicts how the Eocene and Oligocene samples from the BBGB and YGHB fell mainly in the field between felsic volcanic rock and granites, although those collected from the YGHB were closer to the andesite and basalt areas. During the Miocene, samples from the BBGB plotted in a wide field between granites, felsic volcanic rock, basalt and andesites. In addition, we plotted the points in a triangle diagram at Th-Hf-Co (Fig. 14 D), La-Th-Sc (Fig. 14 E), and Th-Sc-Zr/10 (Fig. 14 F), which showed that samples from the BBGB were mainly from an active continental margin (ACM) setting during the Eocene. They then transferred to a passive margin (PM) in the late Oligocene. For the YGHB, samples ranged from the Oligocene to the Miocene, with points located in the area of active continental margin (ACM) and passive margin (PM) setting.

6. Discussion

6.1 Provenance implication

U-Pb ages of the detrital zircon in the offshore basin were comparable with the geochronological fingerprints of the potential source area, including the fluvial sediments around the NW-SCS. The base rocks in the Cathaysia and Indochina Blocks and the pre-Cenozoic basement of the NW-SCS provide useful provenance information and reflect the supply of zircon grains. We can ascertain the provenance evolution by integrating the above data with the data gained from river samples, basements, and dispersal areas.

6.1.1 Paleocene-Eocene

1) The Beibu Gulf Basin

As shown by the HMA and REE data, the high ZTR index indicates that some distal sediment migrated into the BBGB. Meanwhile, the GZi and ATi indices were observed to have a spatial difference distribution. A similar HMA pattern in W1 and W3 showed a sharp variety to W2, indicating that they may be different provenance areas. The right declining Σ REE pattern and slight negative Eu anomalies typically confirm the characteristics of intermediate rocks (McLennan, 1989; Basu et al., 1991; Cullers, 1995; Hoskin and Ireland, 2000). The Th/U ratio in Fig. 11 implies that both sedimentary rock and metamorphic rock mixed together in the BBGB. Well W2 in the BBGB presents a peak age of ~80 Ma, suggesting that the provenance area of these zircon grains is derived mainly from the Red River Shear Zone (peak age ~80 Ma) (Fig. 9). Wells W1, W2, and W3 show prominent ~270 Ma peaks. The aforementioned results (Fig. 9) show that North Vietnam has peak ages of ~60 Ma and ~250 Ma, and the Red River may have served as a pathway in the S2S system (Zhao et al., 2020; Fyhn et al., 2018; Clift et al., 2008). Moreover, Li et al. (2017) and Gong et al. (2021) argued that some small rivers from the Shiwandashan Belt or Yunkai Massif might bring sediments, including the Lian (Nanliu) River or the Qin River. They are observed to have peak ages of ~270 Ma. According to the MDS plot analysis, wells W1 and W3 have a strong link to the provenance area of SWB, while samples from W2 indicate a contribution from the Red River Shear Zone. All of the above results reveal that spatial differences in provenance are developed in the BBGB, and multiple isolated

depocenters are separated by intrabasial highs (Fig. 12). Zircons with ages of ~270, ~410 Ma, and ~820 Ma were found in W1, W2, and W3, presenting an age distribution similar to that of the basement (Cui et al., 2021). These findings suggest that the sediments from the exposed area of the basement in the BBGB provided proximal sediments and developed slump deposits in both the eastern and western BBGBs.

6.1.2 Oligocene

1) The Beibu Gulf Basin

Based on findings from the HMA, we found that titanium and zircon are prominent in the BBGB (Fig.12 B). The REEs in the BBGB during the Oligocene present a similar Eocene pattern (Fig. 13 H), indicating that the intermediate rock was deposited in the dispersal area. The $\Sigma\text{LREE}/\Sigma\text{HREE}$ ratio declined as shown in the samples from well W1, indicating a decrease in the relative depth of sea level (Jian et al., 2012; Liu et al., 2014). Additionally, more allogenic sediments were injected into the BBGB during this period.

With regard to the zircon age in well W1 (2631.9 m), its age spectrum may be ordered into three groups: 235 Ma, 420 Ma, and 980 Ma (Fig. 11). Compared with the samples from well W1 in the Eocene interval, zircon grains at ~78 Ma decreased sharply. The decrease discovered indicates a reduced number of sediments being brought by rivers from the west tectonic block, including North Vietnam and the Red River Shear Zone. Peak ages of ~235 Ma and ~420 Ma can be found in both the pre-Cenozoic basement and the SWB or the Yunkai Massif (Gong et al., 2021). This

indicates that both the allogenic distal sediments and the proximal slump deposited developed in the drainage basin.

2) Yinggehai-Song Hong Basin

Due to the Indochina Block's rotation, the YGHB had isolated grabens or half-grabens during this period. During the late Oligocene, faults joined, and the rift depression merged (Gilley et al., 2003; Clift et al., 2008; Fyhn et al., 2020). Thus, the HMA and REE pattern shows heterogeneity.

Regarding the northwestern area of the YGHB, the REE sample in Y5 (Fig.13 H) shows a strong positive Eu anomaly that indicates that the mafic-ultramafic rock area had eroded and migrated into the dispersal area (McLennan, 1989). Thanh et al. (2014), Faure et al. (2014) and Halpin et al. (2016) determined that mafic-ultramafic rocks developed in the block located in northeastern Vietnam may have provided sediments into this area during the Oligocene (geological map can be seen in Fig. 8).

For the eastern YGHB, zircon U–Pb data in Y1 and Y2 reveal that the provenance was during the Yacheng Fm. Interval and the Lingshui Fm. Interval, respectively. The age cluster included three groups, 75 Ma (Y1 samples), 210–220 Ma (Y1 and Y2 samples), and 420 Ma (Y1 samples) (Fig. 11), which may have been derived from the base rock of the Khorat Basin or North Vietnam (Fig. 9). Th/U in the YGHB is lower than that in the BBGB, which indicates the increased presence of mafic rock and metamorphic rock in the YGHB (Fig. 11). Analysis via the MDS plot in Fig. 15 makes us speculate that Y1 and Y2 are close to the above block in the Indochina Block and

610 Hainan Island, reflecting some sediments provided from the above blocks.

611 6.1.3 Miocene

612 1) Beibu Gulf Basin

613 During the Miocene, HMA in the BBGB had high contents of titanium, tourmaline
614 and zircon. Compared with the HMA found in the land area around the offshore basin,
615 the Leizhou Peninsula shows a high value for the GZi index and a low value for the
616 ZTR index. The Qin River Block and Hainan Island may be characterized by their high
617 ZTR index and low GZi index (Xu et al., 2010; Xia et al., 2017; Fyhn et al., 2019). Thus,
618 we infer that the sediments around the basin may have provided distal sediment and
619 mixed in the sink area.

620 The zircon age of W4 can be divided into three groups: 65 Ma, 220 Ma and 410
621 Ma. The peak ages of 220 Ma and 410 Ma indicate that the SWB and Yunkai Massif
622 provided sediments to the BBGB. Moreover, 20% of zircon grains show an age of 85
623 Ma, which indicates that some sediments were provided by Hainan Island through the
624 Changhua or Nandu Rivers, as seen in the MDS plots (Fig. 15). Concurring with Liu et
625 al. (2020), we speculate that distal sediments dominated in the sink area and that they
626 migrated from the Shiwandashan Belt, the Yunkai Massif and Hainan Island.

627 2) The Yinggehai-Song Hong Basin

628 The provenance during the Miocene in the YGHB has been the topic of numerous
629 studies (Clift and Sun, 2006; Cao et al., 2015; Wang et al., 2019; Wang et al., 2019).
630 HMA presents a pattern similar to that of the Red River, revealing a high titanium

content ([Fig. 12](#)). For REE distribution, the Paleo-Red River, Ma River or Lam River supplies sediments with positive Eu anomalies from basic-ultrabasic metamorphic and volcanic parent rocks in Indochina to the drainage basin. In contrast, Hainan Island has delivered sediments with negative Eu anomalies from granitic and sedimentary parent rocks to the basin's eastern slope area ([Zhao et al., 2015](#)). Thus, we speculate that both the Red River Shear Zone and Hainan Island provided sediments into the catchments.

This conclusion can be proven by the U–Pb data in Y7, which has an age cluster of three peaks: 30 Ma, 230 Ma and 390–430 Ma. Source rock with peak ages of 30 Ma and 230 Ma is mainly found in the Red River Shear Zone, Dai Nui Con Voi, and Khorat Basin. The Red, Ma, or Lam Rivers likely served as a pathway. According to past studies ([Clift et al., 2008](#); [Fyhn et al., 2019](#); [Wang et al., 2019](#)), we infer that the above river headwater area carried sediments from the Red River Shear Zone and transported them through distal routing.

6.2 Spatial-temporal evolution of the source-to-sink system

Influenced by the convergence of the Pacific Plate, the Indochina Block and the Cathaysia Block, the NE-SCS presents a complex evolution process from Andean-type subduction transitioning to continental rifting, which occurred from the Eocene to the Miocene ([Maruyama et al., 1997](#); [Burrett et al., 2014](#); [Fyhn et al., 2020](#); [He et al., 2020](#)). Moreover, [Cawood et al. \(2012\)](#) developed a method for identifying the S2S system tectonic setting insight from zircon U–Pb data with a crystallization age-deposition age

(CAD) diagram (Fig. 16 A). Accordingly, we believe that the dispersal area of the BBGB shows a collisional or an extension set during the Eocene. In addition, up to the Miocene (Fig. 16 B), the BBGB and YGHB had different tectonic settings in terms of their bottom strata, indicating that the BBGB transferred to a collisional or convergent setting and that the YGHB was in an extension set. Thus, based on the S2S segments recovered, we discuss the corresponding system evolution process in the NW-SCS and their impact factors from the Eocene to the Miocene.

6.2.1 Source-to-sink system during the Eocene

According to the above provenance implications, we infer that the sediments in the BBGB are derived from the Red River Shear Zone (Eocene), the SWB and the Yunkai Massif (Eocene to Miocene), Hainan Island (Oligocene to Miocene) and the pre-Cenozoic basement, which collectively cover a large area in the west Cathaysia Block. According to the paleomorphology map, which can be seen in Fig. 12 A, and the paleocurrent direction recovered by Wissink et al. (2016) and Xue et al. (2020), we identified the responding provenance boundary and its provenance area and were able to estimate that its provenance area of the BBGB covered over 3500 sq. km. Then, with the identified prograding distance from the seismic profiles, we obtained migration distances ($u(x)$) ranging from 450-900 km in the BBGB (Fig. 6) and 200-500 km in the YGHB (Fig. 7). Furthermore, as seen in Equation 1, we calculated that the amount of sediments supplied (Q_s) during the Eocene was as high as 800 cubic km/Ma for the BBGB and 300 cubic km/Ma for the YGHB. Applying all of these parameters into

Equation 2, we calculated the mass balance coordinate ($\chi(x)$) in the BBGB (0.2~1.0) and YGHB (>1.5). Integrating the sedimentology study above and geochronological data (Fig.17 A), it was found that the BBGB received sediments from both the distal areas around the offshore basins by meandering or braided rivers and the proximal area slump during the Eocene interval. For the YGHB, the sediment infilling process was mainly dominated by round uplift, which included the Lingao Uplift or the Yingdong Slope Zone.

To determine the dominant factors involved in the S2S system developed during the Eocene, we plotted the critical factors in a bubble chart (Fig. 17 A) and used the parameters in Table 2. As the fitting formula shows, the evaluated height positively correlates with the S2S system volume.

6.2.2 Source-to-sink system during the Oligocene

A series of faults developed along the Indochina Block, including the Red River Faults (Zhang et al., 2013) (Fig. 17 B). From the paleomorphology map and topography process (Hoang et al., 2020; Rizzi et al., 2020), we infer that the rising Lingao Uplift and the Qixi Uplift found between the BBGB and YGHB broke off the process (Hoang et al., 2020), causing sediment from the Red River to be injected into the BBGB. As implied by the above provenance area and the topography, the sediments in the BBGB that were mainly captured from the SWB and the Yunkai Massif along with the sediments in the YGHB were mainly from the mafic-ultramafic rocks area in the Indochina Block and Hainan Island. Then, referring to the paleocurrent

direction found by [Wissink et al. \(2016\)](#) and [Xue et al. \(2020\)](#), we measured the cover area of the provenance areas for the BBGB (2500 sq. km) and the YGHB (2000 sq. km). Then, applying the parameters in [Table 2](#) to [Equation 1](#), we determined that the sediment supply (Q_s) was 600 cubic km/Ma in the BBGB and 1000 cubic km/Ma in the YGHB. Additionally, [Equation 2](#) shows the mass balance coordinates ($\chi(x)$) in the BBGB (0.2~0.5) and the YGHB (0.6~1.0), which indicate fine grain material once brought in by the meandering river. Furthermore, the diapiric record, as seen in the sink area of the YGHB, suggests that both distal and proximal sediments mixed together ([Fyhn et al., 2020](#); [Lei et al., 2011](#)).

In addition, this study plotted the S2S parameters of [Table 2](#) in the bubble chart seen in [Fig. 17 B](#). Both evaluations for height and sediment supply positively fit the S2S volume. The correlation between the S2S system volume and its sediment supply is also much higher in the sags within the BBGB than in the YGHB ([Fig. 17 B](#)). This finding implies that the S2S in the BBGB during the Oligocene was dominated by the evaluation height. Our finding is consistent with the conclusions drawn by [Fyhn et al. \(2020\)](#), who noted that sediments may influence regional uplift or diapiric development during this interval.

6.2.3 Source-to-sink system during the Miocene

During the Miocene, the NW-SCS transferred to the thermal subsidence stage ([Sun et al., 2003](#)). Due to the relative sea-level rise of the NW-SCS ([Fig. 2](#)), the sedimentary facies in the YGHB and the BBGB changed to a tidal influence delta or a

meandering river delta. As implied by the provenance area, the SWB, Yunkai Massif and Hainan Island provided sediments to the BBGB, whereas the Red River Shear Zone, Dai Nui Con Voi and Khorat Basin provided sediments to the YGHB. We identified the provenance area by referring to the paleocurrent recovered by Huang et al. (2016). This resulted in the discovery of decreasing provenance areas of 2000 sq. km for the BBGB and 1200 sq. km for the YGHB. By applying these parameters to Equation 1, we obtained sediment supplies (Q_s) of 300 cubic km/Ma in the BBGB and 500 cubic km/Ma in the YGHB. Then, the mass balance coordinate ($\chi(x)$) was calculated according to Equation 2, which resulted in 0.2~0.5 for the BBGB and 0.4~0.6 for the YGHB. These findings indicate that the fine-grained sediments infilled the NW-SCS during this period.

Additionally, we plotted the S2S system segments in Table 2 into a bubble chart (Fig. 17 C and D). As the correlation calculated between these three parameters, we identified that both sediment supplies (Q_s) served as the dominant factor in the S2S system volume.

6.3 Drainage evolution of NW-SCS

6.3.1 Paleocene-Eocene

According to the interpretation results in the profiles (Fig. 6) along with the geomorphology map generated from the 2D seismic map (Fig. 12) and the above controlling factor discussion, we determined that several boundary faults and regional uplifts, including the Qixi, Xuwen, and Liusha Uplifts, controlled the sediment

736 distribution. It has also been found that the sags in the BBGB were isolated during the
737 initial rifting stage ([Jian et al., 2012](#); [Zhao et al., 2020](#)). We demonstrate that the
738 tributaries from the Red River fault zone, the SWB and the Yunkai Massif were likely
739 sources of the BBGB in the Eocene. [Nyberg and Howell \(2016\)](#) and [Nyberg et al. \(2018\)](#)
740 classified the S2S system into three types, steep, short and deep patterns, wide and
741 deep patterns, and wide and shallow patterns, according to their geomorphic features
742 from the source area to the sink area. The S2S system during the Eocene could be
743 categorized by its wide and deep pattern, which means that the S2S system has large
744 catchments and wide shelves of high gradient bathymetry, which acquired sediments
745 from the surrounding continental block and the pre-Cenozoic basement.

746 Based on the assessments of [Wang et al. \(2001\)](#) and [Sun et al. \(2003\)](#), the YBHB
747 was in the initial rifting stage. As [Gong \(2004\)](#) argued, the YGHB was in a convergent
748 setting. Meanwhile, the triangle diagram in [Fig. 14](#) shows that the S2S system was in
749 the CIA or PM setting. The paleomorphology reveals that the YGHB had a steep, short
750 and deep pattern ([Helland-Hansen et al., 2012](#); [Nyberg et al., 2018](#)), suggesting a short
751 catchment infilled by proximal sediments.

752 From the coupling between the initial rifting stage that occurred during the Eocene
753 and S2S system development, the BBGB and the YGHB acquired sediments from the
754 proximal basement and their surrounding continental blocks, including the Red River
755 Shear Zone, the Shiwandashan Belt and the Yunkai massif ([Gong et al., 2021](#); [Fu et](#)
756 [al., 2021c](#)), resulting in separate structural units dividing and isolating distinct

757 depressions. These structural highs blocked sediment transport so that sediment was
758 transported from separate sources and locally deposited within individual grains.

759 6.3.2 Oligocene

760 The NW-SCS shows a complex topographical evolution because it was impacted
761 by the South China Sea Movement and Indochina Block rotation during the Oligocene
762 (Fyhn et al., 2020). As shown through the paleomorphology and seismic profile
763 interpreted by (Hoang et al. 2020), the Liusha Uplift and the Xuwen Uplift were eroded,
764 thus connecting the northern BBGB sink area. Therefore, we can infer that the BBGB
765 should have been characterized as having a wide and shallow system during the
766 Oligocene.

767 In the YGHB, many strike-slip faults initially developed, including the Red River
768 Faults, Zhai River Faults, Heishui River Faults, Majiang River Faults and Changshan
769 Faults (Hoang et al., 2020; Fyhn et al., 2020). Furthermore, paleomorphology indicates
770 that the dip angle of the Oligocene maintained similarities to what has been seen in
771 the Eocene (Fig. 12). Through the statistical analysis of the prograding distance for the
772 seismic event, we can see that the YGHB had a steep, short and deep system during
773 the Oligocene.

774 The sediment mass is injected into the drainage basin during the postrifting stage,
775 and the inverted structure between the YGHB and BBGB breaks the linkage between
776 the Red River Shear Zone and the BBGB. Moreover, the surrounding topographic
777 highs have been denuded so that the more distally derived detritus will reach the

778 depocenters (Fu et al., 2021a, b; Cawood and Nemchin, 2000).

779 6.3.3 Miocene

780 During the Miocene, the NW-SCC entered a rifting-thermal subsidence stage, and
781 sea level transgression occurred in the southeastern area (Sun et al., 2003; Morley,
782 2016; Ye et al., 2018). Additionally, as is indicated from the CAD plots in Fig. 16 B, the
783 BBGB and YGHB had different tectonic settings in terms of their bottom strata,
784 indicating that the BBGB transferred to a collisional or convergent setting and that the
785 YGHB was in an extension set. Furthermore, insights derived from the seismic profiles
786 in Figs. 6 and 7 as well as the paleomorphology seen in Figs. 12 C and D suggest
787 that the strata during the Miocene interval had a gentle dip angle and that fewer faults
788 had developed. Based on the definitions provided by Nyberg et al. (2018), the BBGB
789 and YGHB are both assumed to be wide and shallow S2S systems.

790 7. Conclusions

791 In this study, we reviewed a significant amount of original data and data from the
792 literature, including detrital zircon U–Pb data from offshore basins, fluvial sand samples
793 around the NW-SCS and the basement of the potential source area. Beyond this, by
794 combining the sedimentology interpretation of the core sample and seismic data, we
795 reconstructed the spatial-temporal evolution of the source-to-sink system in the NW-
796 SCS.

797 1) During the Eocene, the NW-SCS developed several isolated depressions,
798 including the BBGB in the north and the YGHB in the west. The BBGB was infilled by

799 local proximal sediments, including slump deposits and some distal sediments from
800 the Red River Shear Zone, Dai Nui Con Voi or North Vietnam as well as from the
801 Shiwandashan Belt and Yunkai Massif. We rebuilt the topography in this interval, which
802 revealed a high dip slope angle. A quantitative analysis suggested that the sediment
803 supply was critical to the S2S developed in the NW-SCS during the initial rifting stage.

804 2) In the Upper Oligocene, the increasing rifting process in the NW-SCS resulted
805 in boundary faults developing in the BBGB, and a series of strike-slip faults developed
806 along the Indochina Block. According to multiprovenance data, the Qixi Uplift rise led
807 sediments from the Red River Shear Zone, Dai Nui Con Voi or North Vietnam toward
808 the YGHB. The sediments in the BBGB were contributed by the Shiwandashan Belt,
809 the Yunkai Massif and Hainan Island. Topography reveals that the faults developed,
810 and the evaluation height controlled the distribution of sediments.

811 3) For the Miocene before the Red River Faults transferred to a dextral strike-slip
812 fault (5.5 Ma), the drainage basin received sediments as the present provenance area.
813 The Shiwandashan Belt, the Yunkai Massif and Hainan Island provided the sediment
814 found in the BBGB. The Red River Shear Zone, Dai Nui Con Voi, and Khorat Basin
815 contributed sediments to the YGHB. As the S2S system was distributed in the NW-
816 SCS offshore basin, its wide and narrow pattern was controlled by sediment supply
817 and evaluation height.

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Figure Captions

Fig. 1

A present the location of the rivers and the tectonic blocks around the NW-SCS. In a clockwise direction, the river named the Pearl River (in Chinese called Zhujiang) and its tributaries are shown: The Moyang River, Lian River (also called Nanliu River), Qin River, Red River and its tributaries, the Ma River, Lam River and Changhua River on Hainan Island. B shows the tectonic division map of the NW-SCS. The yellow bend indicates the uplift area, and the blue bend shows the subsidence area during the Paleogene. The NW-SCS can be divided into two large drainage basins, namely, the Beibu Gulf Basin and the Yinggehai-Song Hong Basin. Modified from the study by Rangin et al. (1995), C and D are two profiles that cross the NW-SCS and show how the strata developed since the Cretaceous period.

Fig. 2

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Stratum column in the NW-SCS area and from around its block. From left to right, we present the strata developed in the Shiwandashan belt (SWB), the Beibu Gulf Basin (BBGB), the Yinggehai-Song Hong (offshore part of YGHB) and the Hanoi Depression (land part of YGHB). The tectonic moment column shows the evolution phases since the Paleocene. From bottom to top are the prerifting stage, the early synrifting stage, the late synrifting stage, and the thermal subsidence stage. Meanwhile, the dominant stress direction also shows a clockwise rotation (Peltzer and Tapponnier, 1988; Tapponnier et al., 1982). The sea-level curve was noted by Miller et al. (2020), and the sedimentary rate and speculated environments are from Wang et al. (2020).

Fig. 3

Core samples and lithofacies identified in the YGHB during the Miocene interval. From left to right, we infer that the identified transfer from shallow water to exposed water results in a decrease in trace fossils and an increase in red sandstone.

Fig. 4

Core samples and lithofacies identified in the BBGB during the Oligocene and the Eocene. From left to right, more coarse-grained gravel accumulated. We infer that the lithofacies from left to right responded to an increase in the hydrodynamics and a decrease in the water level.

Fig. 5

Well connections show the strata that developed in the NW-SCS. From left to right, they are Y9, Y4, W4, W1 and W3. We present the Gamma curve, lithology, and

corresponding grain size-frequency distribution curves in each well. Most wells in the YGHB did not reveal Eocene strata. They present a fining upward coarse-grained sandstone in the sandstone's bottom layers and interlayers and mudstone upward. Wells in the BBGB have sediments from the Eocene to the early Miocene, which shows coarser-grained sediments than the YGHB.

Fig. 6

Seismic profiles in the BBGB and its location are displayed in **Fig. 1 B**. **A** presents an EW infilling process in the northern BBGB, and **B** shows the sedimentary process in the southern BBGB.

Fig. 7

Seismic profiles in the YGHB and its location are shown in **Fig. 1 B**. **A** presents an NE infilling process in the eastern YGHB, **B** is in the central parts, and **C** is in the western parts.

Fig. 8

1. RR: Red River (van Hoang et al., 2009; Fyhn et al., 2019); 2. DaR: Da River (van Hoang et al., 2009); 3. LoR: Lo River (van Hoang et al., 2009); 4. MR: Ma River (Fyhn et al., 2019); 5. LR: Lam River (Fyhn et al., 2019); 6. QR: Qin River (He et al., 2020); 7. NR: Nanliu River (Zheng et al., 2020); 8. CR: Changhua/Nandu River (Wang et al., 2015); 9. MJNR: Moyang River Jian River (Zhong et al., 2017).

Fig. 9

II. YM: Yunkin Massif (Wang et al., 2007); II. SWB: Shiwandashan Belt (Hu et al.,

883 2015); III. NV: North Vietnam (Roger et al., 2012); IV. HI: Hainan Island (Yan et al.,
884 2017); V. RRF: Red River Shear Zone (Tang et al., 2013); VI. DNCV: Dai Nui Con Voi
885 (Cao et al., 2011); VII. KB: Khorat Basin (Yan et al., 2017); VIII. DDT: Danba Domal
886 Terrane, East Tibet (Jolivet et al., 2015); IX and X present the basement of the NW-
887 SCS (Cui et al., 2021).

888 **Fig. 10**

889 Concordia plots of 8 detrital zircons in NW-SCS. Data influenced by Pb loss and
890 inclusion are deleted. Only analyses with concordances of 90% are included in the
891 combination of the probability density plot and histogram and discussed in the
892 subsequent sections.

893 **Fig. 11**

894 Zircon U–Pb age spectra of the samples from the intervals of the Eocene,
895 Oligocene, and Miocene. The left plots show the ratio of Th/U, and we can infer that
896 the sediments are mainly provided by igneous (Th/U value over 0.5) or metamorphic
897 sources (Th/U less than 0.1) or that Th/U values between 0.2–0.5 indicate a mixed
898 source (Teipel et al., 2004; Hoskin and Black, 2000).

899 **Fig. 12**

900 The paleomorphology based on 2D seismic data and the main provenance are
901 indices (heavy mineral assemblage), including the GZi, ATi and ZTR indices.

902 **Fig. 13**

903 Chondrite-normalized rare earth element (REE) patterns of the Eocene – Upper

904 Miocene from the NW-SCS. Eu anomaly values are highlighted on each plot, which
905 are gray in positive and gray in negative. A-F indicate the REE distribution pattern
906 around the tectonic block, including the Pearl River mouth, the Qin River mouth, the
907 Red River mouth, Central and northern Vietnam, Hainan Island, and the Yunkai Massif
908 (Leizhou Peninsula).

909 **Fig. 14**

910 Points in the source rock discrimination chart show the tectonic setting of NW-
911 SCS sediment. The first line shows Co/Th-La/Sc; Cr/V-Y/Ni, La/Yb-ΣREE. The second
912 line from left to right shows Th-Hf-Co; La-Th-Sc; Th-Sc-Zr/10.

913 **Fig. 15**

914 Multidimensional scaling (MDS) map for U-Pb ages of detrital zircons in the NW-
915 SCS. We rebuilt their relative geographical positions, including the drainage basin,
916 basements and pathway. Solid and dashed lines link the closest and second closest
917 neighbors, respectively. The stress values of the configuration indicate a fair goodness
918 of fit ([Vermeesch, 2013](#)).

919 **Fig. 16**

920 Cumulative probability-age (CAD) plot (A: red field), collisional (B: blue field) and
921 extensional basins (C: green field). From the variations observed between the different
922 fields, the model highlighted by [Cawood et al., \(2012\)](#) that enables the prediction of the
923 tectonic setting of sedimentary packages of unknown origin is proposed based on
924 differences between the crystallization and depositional ages (CA – DA) of the zircons.

Extensional (including intracratonic) settings have CA – DA greater than 150 Ma in the youngest 5% of the zircons (step 1), and all convergent settings have CA – DA less than 100 Ma in the youngest 30% of zircons (step 2).

Fig. 17

Envisaged paleogeographic evolution of the NW-SCS drainage basin from the rifting stage (Eocene and Oligocene) to the postrifting stage (Miocene) (Panels **A** to **D**; based on [Maruyama et al., 1997](#); [Fyhn et al., 2020](#); [He et al., 2020](#)). We plotted the S2S parameters in a bubble chart. During the Eocene (**A**), the fitting equation is $V = 0.04A + 0.05Qs + 0.6e^H + 0.5$, $R^2=0.46$, where **V** is the volume of the sink, **Qs** is the sediment supply, **A** is the provenance area, **H** is the relative height of the pathway, and **a**, **b**, and **c** are the fitting coefficients. In the Oligocene (**B**), we obtain the fitting equation that $V = 0.03H + 0.5A \cdot e^{Qs} + 0.8$, $R^2=0.55$. In the early Miocene and the late Miocene, the bubble chart shows a similar pattern, and we combine them together and obtain the fitting equation: $V = 0.2A \cdot H + 0.08\ln(Qs) + 1.8$, $R^2=0.76$.

Table Caption

TABLE 1

Lithofacies description and inference of the depositional environment

TABLE 2

S2S segment statistics based on the seismic interpretation in [Figs. 6](#) and [7](#). T.

distance=Transported distance

TABLE 3

Heavy mineral content and its HMA index

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