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

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

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

44 **1. Introduction**

45 The northwestern South China Sea (NW-SCS) is a ceaseless source of
46 controversies regarding its tectonic evolution ([Tapponnier et al., 1982](#); [Briais et al.,](#)
47 [1993](#); [Müller et al., 2016](#); [Ye et al., 2018](#)). Several studies have used restored
48 paleofluvial systems to tackle tectonic movements, considering that river
49 morphological changes reflect tectonic events ([Liu et al., 2016](#); [Zhang et al., 2019](#)).
50 Meanwhile, flowing toward the half-closed embayment formed by the Beibu and Tonkin
51 gulfs ([Fig. 1](#)), the rivers around the NW-SCS have carried more than 1.7 trillion metric
52 tons (Mt) per year of clastic material into the marine basin since the Eocene ([Holeman,](#)
53 [1968](#); [Le et al., 2007](#)). Restoring the dynamics of the source-to-sink system (S2S) in
54 that area may thus provide a comprehensive insight on the regional tectonic framework,
55 deciphering how tectonics control topographic changes and the erosion pattern in the
56 NW-SCS.

57 Currently, many methods have been developed to assess sediment migration
58 processes and rates in fluvial systems. Indeed, detrital geochronology, heavy mineral
59 assemblages, or rare earth element (REE) composition represent excellent tools to
60 trace the evolution of a fluvial catchment (see [Gaillardet et al., 1999](#); [von Blanckenburg,](#)
61 [2005](#); [Borges et al., 2008](#); [Hinderer, 2012](#); [Jolivet et al., 2014](#); [Garzanti, 2016](#)). With
62 these methods, many researchers have focused on the provenance area distribution
63 of the allogenic materials around the NW-SCS (see [Clift and Sun, 2006](#); [Cao et al.,](#)

64 2015; Fyhn et al., 2019; Wang et al., 2019; Zhao et al., 2020). As the primary pathway
65 into the NW-SCS, previous literature has pointed out that during the Eocene, the paleo-
66 Red River brought materials both from the Songpan Garze terrane (Brookfield, 1998;
67 Clark et al., 2004; Clift et al., 2008) and the Indochina Block (van Hoang et al., 2009;
68 Cheng et al., 2021; Gong et al., 2021), depositing them in the offshore sink area.
69 However, accompanying the Eocene to late Miocene rifting process in the NW-SCS,
70 drainage basins, including the Yinggehai-Song Hong Basin (YGHB) and the Beibu Gulf
71 Basin (BBGB), experienced complicated source area evolution, and various S2S
72 systems coexisted (Clark et al., 2004; Clift et al., 2008; Cao et al., 2015; Fyhn et al.,
73 2019; Fyhn et al., 2020; Gong et al., 2021; Lei et al., 2021; Li et al., 2019; Liu et al.,
74 2020; Lyu et al., 2021; Wang et al., 2021; Yao et al., 2021). Regarding the YGHB,
75 situated in the western section of the NW-SCS, previous studies generally suggest that
76 from the Oligocene to the early Miocene, the paleo-Red River brought small quantities
77 of materials derived from igneous, ageing from 88 Ma to 159 Ma, and Precambrian
78 metamorphic rocks exposed along the Red River Fault Zone and in the coastal
79 mountain range (Clift et al., 2008; Zhu et al., 2009; Lin et al., 2012; Cao et al., 2015;
80 Shao et al., 2018; Fyhn et al., 2019; Fyhn et al., 2020). The BBGB situated in the
81 northern section of the NW-SCS, however, has been affected by drastic topographic
82 reorganization of its fluvial feeding networks. as a result, estimating the extend of the
83 provenance areas, especially with regard to the paleo-Red River evolution remains
84 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 were some sediment record 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

106 basin to evaluate the ratio of the material derived from the surrounding continental
107 blocks and the Cenozoic basement of the NW-SCS. Using newly obtained seismic data
108 we reconstruct the paleomorphology of the drainage basin. Sediment migration
109 distances are estimated based on heavy mineral assemblages (HMA). Finally, new
110 detrital zircon U–Pb data within three drainage basins and a compilation of U–Pb data
111 from the fluvial sediments and the basement around the catchments [are used to](#)
112 [decipher the source-to-sink pattern through time \(Fig.1 A\)](#). The zircon U–Pb ages of
113 the basement and sediments are crucial in constraining the sources age patterns in
114 the various drainage areas. Knowing this allows us to undertake an analysis of the
115 data, identify the fluvial network ([Moecher and Samson, 2006; Dickinson and Gehrels,](#)
116 [2009](#)) and calculate the quantitative relationship between the dominate factors,
117 including the terrain height, sedimentary supply and provenance area, to the S2S
118 system formed ([Syvitski and Milliman, 2007; Hinderer, 2012; Holbrook and Wanas,](#)
119 [2014; Nyberg et al., 2018](#)). Our main object is to reconstruct the evolution of the
120 sediment pathways around the NW-SCS, identify the large river catchments and
121 describing the evolution of the drainage network in response to regional tectonic
122 movements during the Eocene and Miocene.

123 **2. Geological Setting**

124 **2.1 Tectonic setting**

125 The South China Sea (SCS) ([Fig. 1 A](#)) is structurally situated at the junction of the
126 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) (T₁₀₀ to T₉₅ 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-

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

175 3. Data and Methods

176 3.1 Seismic reflection data and core samples analysis

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

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

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

193 **3.2 Detrital zircon geochronology**

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

207 **3.3 Research methods**

208 3.3.1 Lithofacies identification and sediment dispersal pattern restoration

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

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

221 3.3.2 Provenance area identification

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

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

231 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.

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

where Q_s 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:

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

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

260 As to the paleomorphology reconstruction, firstly, we built a stratigraphic framework
261 based on the seismic package's terminal relationship after well-seismic calibration.
262 Then, as shale deposits have a much higher compaction coefficient than sandstone
263 layers, we divided the strata using the sand content evaluated within the reference
264 wells shown in Fig. 1 B. The layer's pre-compaction thicknesses were calculated using
265 coefficients of 0.00037 m^{-1} for mudstone and 0.00025 m^{-1} for sandstone (He et al.,
266 2002; Luo et al., 2003; Zhou et al., 2019). This approach allowed generating a series
267 of paleogeomorphology maps covering the Eocene to the Miocene period.

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

$$271 \quad V_{sed} = [\sigma(x, t) \cdot u(x)]/T. \quad (\text{Equation 3})$$

272 T is the time interval, which can be obtained from results of well-seismic calibration
273 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

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

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

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

311 4.2.2 Miocene

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

316 delta had been injected into the sink area.

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

323 4.3 Seismic interpretation

324 4.3.1 The Beibu Gulf Basin

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

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

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

337 50-80 m and 500 km, respectively. We subsequently named these prograding deltas
338 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
339 (Fig. 6).

340 4.3.2 The Yinggehai-Song Hong Basin

341 Referring to the well calibration, we divided the YGHB into three time slices,
342 namely, the Oligocene (including the Yacheng Fm. and Lingshui Fm., T80-T60), the
343 early Miocene (Sanya Fm. and Meishan Fm., T60- T40), and the late Miocene
344 (Huangliu Fm., T40-T30). The average thickness of the Oligocene interval was
345 600~800 m. The thicknesses of the early Miocene and the late Miocene had similar
346 thickness values of 750~1000 m.

347 In the Oligocene interval, the seismic facies featured high-continuity packages and
348 a concave seismic boundary, suggesting a prograding delta. We were able to
349 distinguish 12 prograding deltas, including Y.W.T.1-Y.W.T.3 in the western part (Fig.
350 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
351 part (Fig. 7 C). These prograding deltas appeared to have average thicknesses
352 ranging from 50~100 m, and their sink area was 200 km².

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

358 5. Results

359 5.1. Geochronological data

360 5.1.1 Geochronological data from the river samples

361 1) The Red River and its tributaries

362 The Red River is formed by the confluence of the Da and Lo rivers ([Fig. 1 A](#)).
363 Samples were collected on the bank and bars of the Red River and its major branches
364 ([Van Hoang et al, 2009](#); [Fyhn et al, 2019](#)). Major detrital zircon U-Pb age peaks at
365 ~262 Ma and ~448 Ma characterize the upper stream samples of the Red River ([Fig.](#)
366 [8](#)). The Red River tributaries (Da river) displayed a peak at 245 Ma, and the Lo River
367 shows a peak at ~396 Ma.

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

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

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

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

379 4) The Changhua River from Northern Hainan Island

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

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

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

391 5.1.2 Geochronological data from the basement rocks of the surrounding
392 continental block and South China Sea Cenozoic basement.

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

396 1) Cathaysia Block and East Tibetan Plateau

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

400 a peak age of ~435 Ma. In the northern part of the NW-SCS, the Qin River brings
401 sediments from the Shiwandashan Belt. Thus, we acquired zircon from the SWB, and
402 the ages of these grains encompassed three groups, ~250 Ma, ~420~500 Ma and
403 ~805~980 Ma.

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

410 2) Indochina Block and the Red River Faults Zone

411 Regarding the western and southern portions of the NW-SCS, previous studies
412 noted that the rivers along the Indochina Block, such as the paleo-Red River, Ma River,
413 and Lam River, have carried sediments into the offshore area during the interval from
414 the Eocene to the present ([Wang et al., 2016](#); [Fyhn et al., 2019](#); [Wissink et al., 2016](#)).
415 As the Red River Fault Zone developed metamorphic rocks, its age presented multiple
416 peaks ([Cao et al., 2011](#); [Wang et al., 2017](#)). However, we focused on the potential
417 source area during the Cenozoic period and concluded that its base rock age was
418 ~60~80 Ma. The blocks on the west side of the NW-SCS presented a younger age
419 distribution, such as ~37 Ma in Dai Nui Con Voi (DNCV), ~273 Ma in the Khorat Basin
420 ~53.9 Ma, and ~110 Ma in the Tengchong Terranes.

421 3) Hainan Island

422 Many previous studies have elucidated the relationship between the provenance
423 area distribution on Hainan Island (Clift and Sun, 2006; Yan et al., 2017; Miluch et al.,
424 2021) and the ways in which their age distribution varies sharply in terms of space.
425 This study collected U–Pb data from the basement along the Changhua River. They
426 were observed to have a unimodal peak at ~63 Ma.

427 4) South China Sea Cenozoic basement

428 As mentioned above, the pre-Cenozoic basement of the South China Sea extends
429 the Cathaysia block and Indochina block (Sun et al., 2014; Lei et al., 2015; Cui et al.,
430 2021). Regarding the basement of the BBGB, the zircons from metavolcaniclastic
431 samples showed a multimodal curve, with peak ages of ~100 Ma, ~251 Ma, ~421 Ma,
432 and ~820 Ma. The youngest detrital zircon age collected was ~98 Ma (Fig. 9). In the
433 basement of the eastern margin of the YHGB, the zircons from granite showed a peak
434 age of ~98.4 Ma, and their youngest zircon was ~87.0 Ma (Fig. 9).

435 5.1.3 Geochronological data from offshore drainage basins

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

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

443 1) U–Pb age data during the Eocene

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

451 2) U–Pb age data during the Oligocene

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

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

462 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](#)
502 [al., 2018](#)), we collected data from the fluvial sediments around the NW-SCS ([Fig. 13](#)
503 A~F), which also showed a slight-negative Eu anomaly.

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

505 anomaly; their $\delta(\text{Eu})$ values ranged from 0.8 to 0.95, and $\delta(\text{Ce})$ was 0.9~1.0. The
506 ΣREE values of the samples in wells W1 and W3 were 36.1~232.7 $\mu\text{g/g}$, and the
507 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
508 average value of 9.12. The YGHB had a similar REE distribution pattern in the BBGB
509 during the Eocene.

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

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

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

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

537 6. Discussion

538 6.1 Provenance implication

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

546 6.1.1 Paleocene-Eocene

547 1) The Beibu Gulf Basin

548 As shown by the HMA and REE data, the high ZTR index indicates that some
549 distal sediment migrated into the BBGB. Meanwhile, the GZi and ATi indices were
550 observed to have a spatial difference distribution. A similar HMA pattern in W1 and W3
551 showed a sharp variety to W2, indicating that they may be different provenance areas.
552 The right declining Σ REE pattern and slight negative Eu anomalies typically confirm
553 the characteristics of intermediate rocks (McLennan, 1989; Basu et al., 1991; Cullers,
554 1995; Hoskin and Ireland, 2000). The Th/U ratio in Fig. 11 implies that both
555 sedimentary rock and metamorphic rock mixed together in the BBGB. Well W2 in the
556 BBGB presents a peak age of ~80 Ma, suggesting that the provenance area of these
557 zircon grains is derived mainly from the Red River Shear Zone (peak age ~80 Ma) (Fig.
558 9). Wells W1, W2, and W3 show prominent ~270 Ma peaks. The aforementioned
559 results (Fig. 9) show that North Vietnam has peak ages of ~60 Ma and ~250 Ma, and
560 the Red River may have served as a pathway in the S2S system (Zhao et al., 2020;
561 Fyhn et al., 2018; Clift et al., 2008). Moreover, Li et al. (2017) and Gong et al. (2021)
562 argued that some small rivers from the Shiwandashan Belt or Yunkai Massif might
563 bring sediments, including the Lian (Nanliu) River or the Qin River. They are observed
564 to have peak ages of ~270 Ma. According to the MDS plot analysis, wells W1 and W3
565 have a strong link to the provenance area of SWB, while samples from W2 indicate a
566 contribution from the Red River Shear Zone. All of the above results reveal that spatial
567 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

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

591 2) Yinggehai-Song Hong Basin

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

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

602 For the eastern YGHB, zircon U–Pb data in Y1 and Y2 reveal that the provenance
603 was during the Yacheng Fm. Interval and the Lingshui Fm. Interval, respectively. The
604 age cluster included three groups, 75 Ma (Y1 samples), 210–220 Ma (Y1 and Y2
605 samples), and 420 Ma (Y1 samples) (Fig. 11), which may have been derived from the
606 base rock of the Khorat Basin or North Vietnam (Fig. 9). Th/U in the YGHB is lower
607 than that in the BBGB, which indicates the increased presence of mafic rock and
608 metamorphic rock in the YGHB (Fig. 11). Analysis via the MDS plot in Fig. 15 makes
609 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

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

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

645 **6.2 Spatial-temporal evolution of the source-to-sink system**

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

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

659 6.2.1 Source-to-sink system during the Eocene

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

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

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

684 6.2.2 Source-to-sink system during the Oligocene

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

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

703 In addition, this study plotted the S2S parameters of [Table 2](#) in the bubble chart
704 seen in [Fig. 17 B](#). Both evaluations for height and sediment supply positively fit the
705 S2S volume. The correlation between the S2S system volume and its sediment supply
706 is also much higher in the sags within the BBGB than in the YGHB ([Fig. 17 B](#)). This
707 finding implies that the S2S in the BBGB during the Oligocene was dominated by the
708 evaluation height. Our finding is consistent with the conclusions drawn by [Fyhn et al.](#)
709 ([2020](#)), who noted that sediments may influence regional uplift or diapiric development
710 during this interval.

711 6.2.3 Source-to-sink system during the Miocene

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

715 meandering river delta. As implied by the provenance area, the SWB, Yunkai Massif
716 and Hainan Island provided sediments to the BBGB, whereas the Red River Shear
717 Zone, Dai Nui Con Voi and Khorat Basin provided sediments to the YGHB. We
718 identified the provenance area by referring to the paleocurrent recovered by [Huang et](#)
719 [al. \(2016\)](#). This resulted in the discovery of decreasing provenance areas of 2000 sq.
720 km for the BBGB and 1200 sq. km for the YGHB. By applying these parameters to
721 [Equation 1](#), we obtained sediment supplies (Q_s) of 300 cubic km/Ma in the BBGB and
722 500 cubic km/Ma in the YGHB. Then, the mass balance coordinate ($\chi(x)$) was
723 calculated according to [Equation 2](#), which resulted in 0.2~0.5 for the BBGB and
724 0.4~0.6 for the YGHB. These findings indicate that the fine-grained sediments infilled
725 the NW-SCS during this period.

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

730 **6.3 Drainage evolution of NW-SCS**

731 6.3.1 Paleocene-Eocene

732 According to the interpretation results in the profiles ([Fig. 6](#)) along with the
733 geomorphology map generated from the 2D seismic map ([Fig. 12](#)) and the above
734 controlling factor discussion, we determined that several boundary faults and regional
735 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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827

828 **Figure Captions**

829 **Fig. 1**

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

840 **Fig. 2**

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

850 **Fig. 3**

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

854 **Fig. 4**

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

859 **Fig. 5**

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

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

867 **Fig. 6**

868 Seismic profiles in the BBGB and its location are displayed in [Fig. 1 B](#). **A** presents
869 an EW infilling process in the northern BBGB, and **B** shows the sedimentary process
870 in the southern BBGB.

871 **Fig. 7**

872 Seismic profiles in the YGHB and its location are shown in [Fig. 1 B](#). **A** presents
873 an NE infilling process in the eastern YGHB, **B** is in the central parts, and **C** is in the
874 western parts.

875 **Fig. 8**

876 1. RR: Red River ([van Hoang et al., 2009](#); [Fyhn et al., 2019](#)); 2. DaR: Da River
877 ([van Hoang et al., 2009](#)); 3. LoR: Lo River ([van Hoang et al., 2009](#)); 4. MR: Ma River
878 ([Fyhn et al., 2019](#)); 5. LR: Lam River ([Fyhn et al., 2019](#)); 6. QR: Qin River ([He et al.,](#)
879 [2020](#)); 7. NR: Nanliu River ([Zheng et al., 2020](#)); 8. CR: Changhua/Nandu River ([Wang](#)
880 [et al., 2015](#)); 9. MJNR: Moyang River Jian River ([Zhong et al., 2017](#)).

881 **Fig. 9**

882 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.

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

928 **Fig. 17**

929 Envisaged paleogeographic evolution of the NW-SCS drainage basin from the
930 rifting stage (Eocene and Oligocene) to the postrifting stage (Miocene) (Panels **A** to **D**;
931 based on [Maruyama et al., 1997](#); [Fyhn et al., 2020](#); [He et al., 2020](#)). We plotted the
932 S2S parameters in a bubble chart. During the Eocene (**A**), the fitting equation is $V =$
933 $0.04A + 0.05Qs + 0.6e^H + 0.5$, $R^2=0.46$, where **V** is the volume of the sink, **Qs** is the
934 sediment supply, **A** is the provenance area, **H** is the relative height of the pathway, and
935 **a**, **b**, and **c** are the fitting coefficients. In the Oligocene (**B**), we obtain the fitting equation
936 that $V = 0.03H + 0.5A \cdot e^{Qs} + 0.8$, $R^2=0.55$. In the early Miocene and the late Miocene,
937 the bubble chart shows a similar pattern, and we combine them together and obtain
938 the fitting equation: $V = 0.2A \cdot H + 0.08\ln(Qs) + 1.8$, $R^2=0.76$.

939 **Table Caption**

940 **TABLE 1**

941 Lithofacies description and inference of the depositional environment

942 **TABLE 2**

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

945 **TABLE 3**

946 Heavy mineral content and its HMA index

947 **References**

948 Basu, A.R., Junwen, W., Wankang, H., Guanghong, X. and Tatsumoto, M., 1991.
949 Major element, REE, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic
950 rocks of eastern China: implications for their origin from suboceanic-type mantle
951 reservoirs. ***Earth and Planetary Science Letters***, 105(1-3): 149-169.

952 Borges, J.B., Huh, Y., Moon, S. and Noh, H., 2008. Provenance and weathering
953 control on riverbed sediments of the eastern Tibetan Plateau and the Russian Far East.
954 ***Chemical Geology***, 254(1-2): 52-72.

955 Briais, A., Patriat, P. and Tapponnier, P., 1993. Updated interpretation of magnetic
956 anomalies and seafloor spreading stages in the South China Sea: Implications for the
957 Tertiary tectonics of Southeast Asia. ***Journal of Geophysical Research: Solid Earth***,
958 98(B4): 6299-6328.

959 Brookfield, M.E., 1998. The evolution of the great river systems of southern Asia
960 during the Cenozoic India-Asia collision: rivers draining southwards. ***Geomorphology***,
961 22(3-4): 285-312.

962 Burrett, C. F., K. Zaw, S. Meffre, C. Lai, S. Khositantont, P. Chaodumrong, M.
963 Udchachon, S. Ekins, and J. A. Halpin, 2014, The configuration of Greater Gondwana-
964 Evidence from LA ICPMS, u Pb geochronology of detrital zircons from the Palaeozoic
965 and Mesozoic of Southeast Asia and China: ***Gondwana Research***, 26: 31-51.

966 Cao, L., Jiang, T., Wang, Z., Zhang, Y. and Sun, H., 2015. Provenance of Upper

967 Miocene sediments in the Yinggehai and Qiongdongnan basins, northwestern South
968 China Sea: Evidence from REE, heavy minerals and zircon U-Pb ages. **Marine**
969 **Geology**, 361: 136-146.

970 Cao, L., Shao, L., Qiao, P., Zhao, Z. and van Hinsbergen, D.J.J., 2018. Early
971 Miocene birth of modern Pearl River recorded low-relief, high-elevation surface
972 formation of SE Tibetan Plateau. **Earth and Planetary Science Letters**, 496: 120-131.

973 Cao, S., Liu, J., Leiss, B., Neubauer, F., Genser, J. and Zhao, C. et al., 2011.
974 Oligo-Miocene shearing along the Ailao Shan-Red River shear zone: Constraints from
975 structural analysis and zircon U/Pb geochronology of magmatic rocks in the Diancang
976 Shan massif, SE Tibet, China. **Gondwana Research**, 19(4): 975-993.

977 Cawood, P.A., Hawkesworth, C.J. and Dhuime, B., 2012. Detrital zircon record
978 and tectonic setting. **Geology**, 40(10): 875-878.

979 Cawood, P.A. and Nemchin, A.A., 2000. Provenance record of a rift basin: U/Pb
980 ages of detrital zircons from the Perth Basin, Western Australia. **Sedimentary**
981 **Geology**, 134(3-4): 209-234.

982 Cheng, Y., Z. Wu, J. Zhang, Y. Liu, Z. Wang, and Y. Dai, 2021, Cenozoic rifting
983 and inversion of Beibuwan Basin and its linkage with the strike-slip movement along
984 the Ailao Shan-Red River Shear Zone: International Geology Review. 1-18.

985 Clark, M. K., L. M. Schoenbohm, L. H. Royden, K. X. Whipple, B. C. Burchfiel, X.
986 Zhang, W. Tang, E. Wang, and L. Chen., 2004. Surface uplift, tectonics, and erosion
987 of eastern Tibet from large-scale drainage patterns. **Tectonics**, 23(1): n/a-n/a.

988 Clift, P. D., H. V. Long, R. Hinton, R. M. Ellam, R. Hannigan, M. T. Tan, J. Blusztajn,
989 and N. A. Duc., 2008. Evolving east Asian river systems reconstructed by trace
990 element and Pb and Nd isotope variations in modern and ancient Red River-Song
991 Hong sediments. **Geochemistry, Geophysics, Geosystems**, 9(4): n/a-n/a.

992 Clift, P.D. and Sun, Z., 2006. The sedimentary and tectonic evolution of the
993 Yinggehai-Song Hong basin and the southern Hainan margin, South China Sea:
994 Implications for Tibetan uplift and monsoon intensification. **Journal of Geophysical
995 Research: Solid Earth**, 111(B6): n/a-n/a.

996 Clift, P.D., Wan, S. and Blusztajn, J., 2014. Reconstructing chemical weathering,
997 physical erosion and monsoon intensity since 25Ma in the northern South China Sea:
998 A review of competing proxies. **Earth-Science Reviews**, 130: 86-102.

999 Cui, Z., Schulz-Bull, D.E., Hou, Y., Xia, Z. and Waniek, J.J., 2016. Geochemical
1000 Characteristics and Provenance of Holocene Sediments (Core STAT22) in the Beibu
1001 Gulf, South China Sea. **Journal of Coastal Research**, 321: 1105-1115.

1002 Cui, Y., L. Shao, Z. Li, W. Zhu, P. Qiao, and X. Zhang, 2021. A Mesozoic Andean-
1003 type active continental margin along coastal South China: New geological records from
1004 the basement of the northern South China Sea. **Gondwana Research**, 99: 36-52.

1005 Cullers, R.L., 1995. The controls on the major-and trace-element evolution of
1006 shales, siltstones and sandstones of Ordovician to Tertiary age in the Wet Mountains
1007 region, Colorado, USA. **Chemical Geology**, 123(1-4): 107-131.

1008 Dickinson, W.R. and Gehrels, G.E., 2009. Use of U-Pb ages of detrital zircons to

1009 infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic
1010 database. **Earth and Planetary Science Letters**, 288(1-2): 115-125.

1011 Dou, Y., Li, J. and Li, Y., 2012. Rare earth element compositions and provenance
1012 implication of surface sediments in the eastern Beibu Gulf. **Geochimica, with English**
1013 **abstract**, (2): 147-158.

1014 Faure, M., Lepvrier, C., Nguyen, V.V., Vu, T.V., Lin, W. and Chen, Z., 2014. The
1015 South China block-Indochina collision: Where, when, and how? **Journal of Asian**
1016 **Earth Sciences**, 79: 260-274.

1017 Fyhn, M.B.W., Cuong, T.D., Hoang, B.H., Hovikoski, J., Olivarius, M., Tuan, N.Q.,
1018 Tung, N.T., Huyen, N.T., Cuong, T.X., Nytoft, H.P., Abatzis, I. and Nielsen, L.H., 2018.
1019 Linking Paleogene Rifting and Inversion in the Northern Song Hong and Beibuwan
1020 Basins, Vietnam, With Left-Lateral Motion on the Ailao Shan-Red River Shear Zone.
1021 **Tectonics**, 37(8): 2559-2585.

1022 Fyhn, M.B.W., Thomsen, T.B., Keulen, N., Knudsen, C., Rizzi, M., Bojesen-
1023 Koefoed, J., Olivarius, M., Tri, T.V., Phach, P.V., Minh, N.Q., Abatzis, I. and Nielsen,
1024 L.H., 2019. Detrital zircon ages and heavy mineral composition along the Gulf of Tonkin
1025 - Implication for sand provenance in the Yinggehai-Song Hong and Qiongdongnan
1026 basins. **Marine and Petroleum Geology**, 101: 162-179.

1027 Fyhn, M.B.W., Hoang, B.H., Anh, N.T., Hovikoski, J., Cuong, T.D., Dung, B.V.,
1028 Olivarius, M., Tuan, N.Q., Toan, D.M., Tung, N.T., Huyen, N.T., Cuong, T.X., Nytoft,
1029 H.P., Abatzis, I. and Nielsen, L.H., 2020. Eocene-Oligocene syn-rift deposition in the

1030 northern Gulf of Tonkin, Vietnam. **Marine and Petroleum Geology**, 111: 390-413.

1031 Fu, C., S. Li, S. Li, and J. Xu, 2021a, Spatial and temporal variability of sediment
1032 infilling and episodic rifting in the North Pearl River Mouth Basin, South China Sea:
1033 **Journal of Asian Earth Sciences**, 211: 104702.

1034 Fu, C., S. Li, S. Li, and J. Xu, 2021b, Source-to-sink transformation processes
1035 between closed setting, semiopen setting, and opening setting: A case study of the
1036 West-East China Sea from the Paleocene to the Eocene: **Marine Geology**, 442:
1037 106640.

1038 Fu, C., X. Yu, W. Chen, G. Ren, and D. Liu, 2021c, Strata Architectural Variability
1039 and Facies Distribution in Structural Transfer Zone: A Case Study of Fushan Sag,
1040 Northern South China Sea: **Acta Geologica Sinica-English Edition**, 95(6):
1041 1998~2015

1042 Gaillardet, J., Dupré, B. and Allègre, C.J., 1999. Geochemistry of large river
1043 suspended sediments: silicate weathering or recycling tracer? **Geochimica et**
1044 **Cosmochimica Acta**, 63(23): 4037-4051.

1045 Garzanti, E., 2016. From static to dynamic provenance analysis—Sedimentary
1046 petrology upgraded. **Sedimentary Geology**, 336: 3-13.

1047 Gilley, L.D. et al., 2003. Direct dating of left-lateral deformation along the Red
1048 River shear zone, China and Vietnam. **Journal of Geophysical Research: Solid**
1049 **Earth**, 108(B2).

1050 Gong, Y., V. Pease, H. Wang, H. Gan, E. Liu, Q. Ma, S. Zhao, and J. He, 2021,

1051 Insights into evolution of a rift basin: Provenance of the middle Eocene-lower
1052 Oligocene strata of the Beibuwan Basin, South China Sea from detrital zircon:
1053 **Sedimentary Geology**, 419: 105908.

1054 Gong, Z., 2004. Neotectonics and petroleum accumulation in offshore Chinese
1055 basins. **Earth Science-Journal of China University of Geosciences, with English**
1056 **abstract**, 29(5): 513-517.

1057 Halpin, J. A., H. T. Tran, C. Lai, S. Meffre, A. J. Crawford, and K. Zaw., 2016. U-
1058 Pb zircon geochronology and geochemistry from NE Vietnam: A 'tectonically
1059 disputed' territory between the Indochina and South China blocks. **Gondwana**
1060 **Research**, 34: 254-273.

1061 He, J., Garzanti, E., Cao, L. and Wang, H., 2020. The zircon story of the Pearl
1062 River (China) from Cretaceous to present. **Earth-Science Reviews**, 201: 103078.

1063 He, L., Xiong, L. and Wang, J., 2002. Heat flow and thermal modeling of the
1064 Yinggehai Basin, South China Sea. **Tectonophysics**, 351(3): 245-253.

1065 Helland-Hansen, W., Steel, R.J. and Somme, T.O., 2012. Shelf genesis revisited.
1066 **Journal of Sedimentary Research**, 82(3): 133-148.

1067 Hinderer, M., 2012. From gullies to mountain belts: A review of sediment budgets
1068 at various scales. **Sedimentary Geology**, 280: 21-59.

1069 Hoang, B. H., M. B. W. Fyhn, T. D. Cuong, N. Q. Tuan, W. J. Schmidt, L. O.
1070 Boldreel, N. T. K. Anh, N. T. Huyen, and T. X. Cuong., 2020. Paleogene structural
1071 development of the northern Song Hong Basin and adjacent areas: Implications for the

1072 role of extrusion tectonics in basin formation in the Gulf of Tonkin. **Tectonophysics**,
1073 789: 228522.

1074 Holbrook, J. and Wanas, H., 2014. A Fulcrum Approach To Assessing Source-To-
1075 Sink Mass Balance Using Channel Paleohydrologic Parameters Derivable From
1076 Common Fluvial Data Sets With An Example From the Cretaceous of Egypt. **Journal**
1077 **of Sedimentary Research**, 84(5): 349-372.

1078 Holeman, J.N., 1968. The sediment yield of major rivers of the world. **Water**
1079 **resources research**, 4(4): 737-747.

1080 Hoskin, P. and Black, L.P., 2000. Metamorphic zircon formation by solid - state
1081 recrystallization of protolith igneous zircon. **Journal of metamorphic Geology**, 18(4):
1082 423-439.

1083 Hoskin, P.W. and Ireland, T.R., 2000. Rare earth element chemistry of zircon and
1084 its use as a provenance indicator. **Geology**, 28(7): 627-630.

1085 Hu, L., Cawood, P.A., Du, Y., Xu, Y., Xu, W. and Huang, H., 2015. Detrital records
1086 for Upper Permian-Lower Triassic succession in the Shiwandashan Basin, South
1087 China and implication for Permo-Triassic (Indosinian) orogeny. **Journal of Asian**
1088 **Earth Sciences**, 98: 152-166.

1089 Huang, Y., Yao, G. and Zhou, F., 2016. Provenance analysis and petroleum
1090 geological significance of shallow-marine gravity flow sandstone for Huangliu
1091 Formation of Dongfang Area in Yinggehai Basin, the South China Sea. **Earth Science-**
1092 **Journal of China University of Geosciences, with English abstract**, 41(9): 1526-

1093 1538.

1094 Liu, Y., Z. Wu, L. Liu, S. Yan, L. Hu, M. Ping, and M. Zhang, 2021, Cenozoic
1095 structure and tectonics of North subbasins in Beibu Gulf Basin, northern South China
1096 Sea: **Tectonophysics**, 812: 228912.

1097 Jian, W., Yingchang, C. and Junliang, L., 2012. Sequence structure and non-
1098 structural traps of the Paleogene in the Weixi'nan Sag, Beibuwan Basin. *Petroleum*
1099 *Exploration and Development*, 39(3): 325-334.

1100 Jolivet, M., L. Barrier, S. Dominguez, L. Guerit, G. Heilbronn, and B. Fu., 2014.
1101 Unbalanced sediment budgets in the catchment–alluvial fan system of the Kuitun River
1102 (northern Tian Shan, China): Implications for mass-balance estimates, denudation and
1103 sedimentation rates in orogenic systems. ***Geomorphology***, 214: 168-182.

1104 Jolivet, M., Roger, F., Xu, Z.Q., Paquette, J.L. and Cao, H., 2015. Mesozoic–
1105 Cenozoic evolution of the Danba dome (Songpan Garzê, East Tibet) as inferred from
1106 LA-ICPMS U–Pb and fission-track data. ***Journal of Asian Earth Sciences***, 102: 180-
1107 204.

1108 Le, T.P.Q., Garnier, J., Gilles, B., Sylvain, T. and Van Minh, C., 2007. The
1109 changing flow regime and sediment load of the Red River, Viet Nam. ***Journal of***
1110 ***Hydrology***, 334(1-2): 199-214.

1111 Lei, C., J. Ren, P. D. Cliff, Z. Wang, X. Li, and C. Tong., 2011. The structure and
1112 formation of diapirs in the Yinggehai–Song Hong Basin, South China Sea. ***Marine and***
1113 ***Petroleum Geology***, 28(5): 980-991.

1114 Lei, C., J. Ren, P. Sternai, M. Fox, S. Willett, X. Xie, P. D. Clift, J. Liao, and Z.
1115 Wang, 2015, Structure and sediment budget of Yinggehai–Song Hong basin, South
1116 China Sea: Implications for Cenozoic tectonics and river basin reorganization in
1117 Southeast Asia. **Tectonophysics**, 655: 177-190.

1118 Lei, C., J. Ren, J. Pei, B. Liu, X. Zuo, J. Liu, and S. Zhu, 2021, Tectonics of the
1119 offshore Red River Fault recorded in the junction of the Yinggehai and Qiongdongnan
1120 Basins: **Science China Earth Sciences**, 64(11): 1893-1908.

1121 Li, J., G. Zhao, S. T. Johnston, S. Dong, Y. Zhang, Y. Xin, W. Wang, H. Sun, and
1122 Y. Yu., 2017. Permo-Triassic structural evolution of the Shiwandashan and Youjiang
1123 structural belts, South China. **Journal of Structural Geology**, 100: 24-44.

1124 Lin, T., S. Chung, H. Chiu, F. Wu, M. Yeh, M. P. Searle, and Y. Iizuka., 2012.
1125 Zircon U–Pb and Hf isotope constraints from the Ailao Shan–Red River shear zone on
1126 the tectonic and crustal evolution of southwestern China. **Chemical Geology**, 291: 23-
1127 37.

1128 Liu, C., P. D. Clift, A. Carter, P. Böning, Z. Hu, Z. Sun, and K. Pahnke., 2017.
1129 Controls on modern erosion and the development of the Pearl River drainage in the
1130 late Paleogene. **Marine Geology**, 394: 52-68.

1131 Liu, E., H. Wang, Y. Li, W. Zhou, N. D. Leonard, Z. Lin, and Q. Ma., 2014.
1132 Sedimentary characteristics and tectonic setting of sublacustrine fans in a half-graben
1133 rift depression, Beibuwan Basin, South China Sea. **Marine and Petroleum Geology**,
1134 52: 9-21.

1135 Liu, E., H. Wang, Y. Feng, S. Pan, Z. Jing, Q. Ma, H. Gan, and J. Zhao., 2020.
1136 Sedimentary architecture and provenance analysis of a sublacustrine fan system in a
1137 half-graben rift depression of the South China Sea. ***Sedimentary Geology***, 409:
1138 105781.

1139 Liu, Z., Y. Zhao, C. Colin, K. Stattegger, M. G. Wiesner, C. Huh, Y. Zhang, X. Li,
1140 P. Sompongchaiyakul, C. You, C. Huang, J. T. Liu, F. P. Siringan, K. P. Le, E.
1141 Sathiamurthy, W. S. Hantoro, J. Liu, S. Tuo, S. Zhao, S. Zhou, Z. He, Y. Wang, S.
1142 Bunsomboonsakul, and Y. Li., 2016. Source-to-sink transport processes of fluvial
1143 sediments in the South China Sea. ***Earth-Science Reviews***, 153: 238-273.

1144 Liu, Y., Z. Wu, L. Liu, S. Yan, L. Hu, M. Ping, and M. Zhang, 2021, Cenozoic
1145 structure and tectonics of North subbasins in Beibu Gulf Basin, northern South China
1146 Sea: ***Tectonophysics***, 812: 228912.

1147 Luo, X., Dong, W., Yang, J. and Yang, W., 2003. Overpressuring mechanisms in
1148 the Yinggehai basin, south China sea. ***AAPG bulletin***, 87(4): 629-645.

1149 Lyu, C., C. Li, G. Chen, G. Zhang, M. Ma, Y. Zhang, Z. Sun, and Q. Zhou, 2021.
1150 Zircon U–Pb age constraints on the provenance of Upper Oligocene to Upper Miocene
1151 sandstones in the western Qiongdongnan Basin, South China sea. ***Marine and***
1152 ***Petroleum Geology***, 126: 104891.

1153 Martin, J., Paola, C., Abreu, V., Neal, J. and Sheets, B., 2009. Sequence
1154 stratigraphy of experimental strata under known conditions of differential subsidence
1155 and variable base level. ***AAPG Bulletin***, 93(4): 503-533.

1156 Maruyama, S., Isozaki, Y., Kimura, G. and Terabayashi, M., 1997.
1157 Paleogeographic maps of the Japanese Islands: Plate tectonic synthesis from 750 Ma
1158 to the present. *Island arc*, 6(1): 121-142.

1159 McLennan, S.M., 1989. Rare earth elements in sedimentary rocks: influence of
1160 provenance and sedimentary processes. *Geochemistry and Mineralogy of Rare Earth*
1161 *Elements, Reviews in Mineralogy* 21: 169-200.

1162 Miao, W., Shao, L. and Pang, X., 2008. REE geochemical characteristics in the
1163 Northern South China Sea since the Oligocene. *Marine Geology & Quaternary*
1164 *Geology, with English abstract*, 28(2): 71-78.

1165 Miller, K. G., J. V. Browning, W. J. Schmelz, R. E. Kopp, G. S. Mountain, and J.
1166 D. Wright., 2020. Cenozoic sea-level and cryospheric evolution from deep-sea
1167 geochemical and continental margin records. *Science advances*, 6(20): eaaz1346.

1168 Miluch, J., A. Osadczuk, P. Feldens, J. Harff, Ł. Maciag, and H. Chen., 2021.
1169 Seismic profiling-based modeling of geometry and sedimentary architecture of the Late
1170 Pleistocene delta in the Beibu Gulf, SW of Hainan Island (South China Sea). *Journal*
1171 *of Asian Earth Sciences*, 205: 104611.

1172 Moecher, D.P. and Samson, S.D., 2006. Differential zircon fertility of source
1173 terranes and natural bias in the detrital zircon record: Implications for sedimentary
1174 provenance analysis. *Earth and Planetary Science Letters*, 247(3-4): 252-266.

1175 Morley, C.K., 2012. Late Cretaceous–Early Palaeogene tectonic development of
1176 SE Asia. *Earth-Science Reviews*, 115(1-2): 37-75.

1177 Morley, C.K., 2016. Major unconformities/termination of extension events and
1178 associated surfaces in the South China Seas: Review and implications for tectonic
1179 development. **Journal of Asian Earth Sciences**, 120: 62-86.

1180 Morton, A.C. and Hallsworth, C., 1994. Identifying provenance-specific features of
1181 detrital heavy mineral assemblages in sandstones. **Sedimentary Geology**, 90(3-4):
1182 241-256.

1183 Morton, A.C. and Hallsworth, C.R., 1999. Processes controlling the composition
1184 of heavy mineral assemblages in sandstones. **Sedimentary geology**, 124(1-4): 3-29.

1185 Morton, A.C., Whitham, A.G. and Fanning, C.M., 2005. Provenance of Late
1186 Cretaceous to Paleocene submarine fan sandstones in the Norwegian Sea: integration
1187 of heavy mineral, mineral chemical and zircon age data. **Sedimentary Geology**,
1188 182(1-4): 3-28.

1189 Müller, R. D., M. Seton, S. Zahirovic, S. E. Williams, K. J. Matthews, N. M. Wright,
1190 G. E. Shephard, K. T. Maloney, N. Barnett-Moore, and M. Hosseinpour., 2016. Ocean
1191 basin evolution and global-scale plate reorganization events since Pangea breakup.
1192 **Annual Review of Earth and Planetary Sciences**, 44: 107-138.

1193 Nyberg, B., W. Helland-Hansen, R. L. Gawthorpe, P. Sandbakken, C. H. Eide, T.
1194 Sømme, F. Hadler-Jacobsen, and S. Leiknes., 2018. Revisiting morphological
1195 relationships of modern source-to-sink segments as a first-order approach to scale
1196 ancient sedimentary systems. **Sedimentary Geology**, 373: 111-133.

1197 Nyberg, B. and Howell, J.A., 2016. Global distribution of modern shallow marine

1198 shorelines. Implications for exploration and reservoir analogue studies. **Marine and**
1199 **Petroleum Geology**, 71: 83-104.

1200 Paola, C. and Martin, J.M., 2012. Mass-Balance Effects In Depositional Systems.
1201 **Journal of Sedimentary Research**, 82(6): 435-450.

1202 Peltzer, G. and Tapponnier, P., 1988. Formation and evolution of strike - slip faults,
1203 rifts, and basins during the India - Asia Collision: An experimental approach. **Journal**
1204 **of Geophysical Research Solid Earth**, 93(B12): 15085-15117.

1205 Pigott, J.D. and Ru, K., 1994. Basin superposition on the northern margin of the
1206 South China Sea. **Tectonophysics**, 235(1): 27-50.

1207 Rangin, C., Klein, M., Roques, D., Le Pichon, X. and Le Van Trong, 1995. The
1208 Red River fault system in the Tonkin Gulf, Vietnam. **Tectonophysics**, 243(3): 209-222.

1209 Rizzi, M., M. B. W. Fyhn, N. H. Schovsbo, C. Korte, J. Hovikoski, M. Olivarius, T.
1210 B. Thomsen, N. Keulen, N. T. T. Thuy, B. H. Hoang, B. V. Dung, D. M. Toan, I. Abatzis,
1211 and L. H. Nielsen., 2020. Hinterland setting and composition of an Oligocene deep rift-
1212 lake sequence, Gulf of Tonkin, Vietnam: Implications for petroleum source rock
1213 deposition. **Marine and Petroleum Geology**, 111: 496-509.

1214 Roger, F., Maluski, H., Lepvrier, C., Vu Van, T. and Paquette, J., 2012. LA-ICPMS
1215 zircons U/Pb dating of Permo-Triassic and Cretaceous magmatisms in Northern
1216 Vietnam – Geodynamical implications. **Journal of Asian Earth Sciences**, 48: 72-82.

1217 Ru, K. and Pigott, J.D., 1986. Episodic rifting and subsidence in the South China
1218 Sea. **AAPG bulletin**, 70(9): 1136-1155.

1219 Schärer, U., Zhang, L. and Tapponnier, P., 1994. Duration of strike-slip
1220 movements in large shear zones: The Red River belt, China. **Earth and Planetary**
1221 **Science Letters**, 126(4): 379-397.

1222 Schoenbohm, L.M., Burchfiel, B.C., Liangzhong, C. and Jiyun, Y., 2006. Miocene
1223 to present activity along the Red River fault, China, in the context of continental
1224 extrusion, upper-crustal rotation, and lower-crustal flow. **GSA bulletin**, 118(5-6): 672-
1225 688.

1226 Shao, L., P. Qiao, M. Zhao, Q. Li, M. Wu, X. Pang, and H. Zhang., 2016.
1227 Depositional characteristics of the northern South China Sea in response to the
1228 evolution of the Pearl River. **Geological Society, London, Special Publications**,
1229 429(1): 31-44.

1230 Shao, L., Y. Cui, K. Stattegger, W. Zhu, P. Qiao, and Z. Zhao., 2018. Drainage
1231 control of Eocene to Miocene sedimentary records in the southeastern margin of
1232 Eurasian Plate. **GSA bulletin**, 131(3-4): 461-478.

1233 Sun, Z., Zhou, D., Zhong, Z., Zeng, Z. and Wu, S., 2003. Experimental evidence
1234 for the dynamics of the formation of the Yinggehai basin, NW South China Sea.
1235 **Tectonophysics**, 372(1-2): 41-58.

1236 Sun, X., X. Zhang, G. Zhang, B. Lu, J. Yue, and B. Zhang, 2014. Texture and
1237 tectonic attribute of Cenozoic basin basement in the northern South China Sea.
1238 **Science China Earth Sciences**, 57(6): 1199-1211.

1239 Syvitski, J.P.M. and Milliman, J.D., 2007. Geology, Geography, and Humans

1240 Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean. **The**
1241 **Journal of Geology**, 115(1): 1-19.

1242 Tang, S., Shao, L. and Zhao, Q., 2004. Characteristics of clay mineral in South
1243 China Sea since Oligocene and its significance. **Acta Sedimentologica Sinica, with**
1244 **English abstract**, 2(22): 337-342.

1245 Tang, X., Yang, S. and Hu, S., 2020. Provenance of the Paleogene sediments in
1246 the Pearl River Mouth Basin, northern South China Sea: Insights from zircon U-Pb and
1247 fission track double dating. **Journal of Asian Earth Sciences**, 200: 104494.

1248 Tang, Y., J. Liu, M. Tran, Z. Song, W. Wu, Z. Zhang, Z. Zhao, and W. Chen., 2013.
1249 Timing of left-lateral shearing along the Ailao Shan-Red River shear zone: constraints
1250 from zircon U-Pb ages from granitic rocks in the shear zone along the Ailao Shan
1251 Range, Western Yunnan, China. **International Journal of Earth Sciences**, 102(3):
1252 605-626.

1253 Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R. and Cobbold, P., 1982.
1254 Propagating extrusion tectonics in Asia: New insights from simple experiments with
1255 plasticine. **Geology**, 10(12): 611.

1256 Teipel, U., R. Eichhorn, G. Loth, J. Rohrmüller, R. Höll, and A. Kennedy., 2004.
1257 U-Pb SHRIMP and Nd isotopic data from the western Bohemian Massif (Bayerischer
1258 Wald, Germany): implications for upper Vendian and lower Ordovician magmatism.
1259 **International Journal of Earth Sciences**, 93(5): 782-801.

1260 Thanh, N. X., T. T. Hai, N. Hoang, V. Q. Lan, S. Kwon, T. Itaya, and M. Santosh.,

1261 2014. Backarc mafic-ultramafic magmatism in Northeastern Vietnam and its regional
1262 tectonic significance. **Journal of Asian Earth Sciences**, 90: 45-60.

1263 van Hoang, L., Wu, F., Clift, P.D., Wysocka, A. and Swierczewska, A., 2009.
1264 Evaluating the evolution of the Red River system based on in situ U-Pb dating and Hf
1265 isotope analysis of zircons. **Geochemistry, Geophysics, Geosystems**, 10(11): 1-20.

1266 Vermeesch, P., 2013. Multi-sample comparison of detrital age distributions.
1267 **Chemical Geology**, 341: 140-146.

1268 von Blanckenburg, F., 2005. The control mechanisms of erosion and weathering
1269 at basin scale from cosmogenic nuclides in river sediment. **Earth and Planetary
1270 Science Letters**, 237(3-4): 462-479.

1271 Wang, C., X. Liang, Y. Xie, C. Tong, J. Pei, Y. Zhou, Y. Jiang, J. Fu, and S. Wen.,
1272 2015. Late Miocene provenance change on the eastern margin of the Yinggehai-Song
1273 Hong Basin, South China Sea: Evidence from U-Pb dating and Hf isotope analyses of
1274 detrital zircons. **Marine and Petroleum Geology**, 61: 123-139.

1275 Wang, C., X. Liang, D. A. Foster, Y. Xie, C. Tong, J. Pei, J. Fu, Y. Jiang, C. Dong,
1276 Y. Zhou, and S. Wen., 2016. Zircon U-Pb geochronology and heavy mineral
1277 composition constraints on the provenance of the middle Miocene deep-water
1278 reservoir sedimentary rocks in the Yinggehai-Song Hong Basin, South China Sea.
1279 **Marine and Petroleum Geology**, 77: 819-834.

1280 Wang, C., X. Liang, D. A. Foster, X. Liang, C. Tong, and P. Liu., 2019. Detrital
1281 zircon ages: A key to unraveling provenance variations in the eastern Yinggehai-Song

1282 Hong Basin, South China Sea. **AAPG bulletin**, 103(7): 1525-1552.

1283 Wang, C. et al., 2019. Linking source and sink: Detrital zircon provenance record
1284 of drainage systems in Vietnam and the Yinggehai–Song Hong Basin, South China
1285 Sea. **GSA bulletin**, 131(1-2): 191-204.

1286 Wang, C., X. Liang, D. A. Foster, X. Liang, L. Zhang, and M. Su., 2019.
1287 Provenance and Drainage Evolution of the Red River Revealed by Pb Isotopic Analysis
1288 of Detrital K - Feldspar. **Geophysical Research Letters**, 46(12): 6415-6424.

1289 Wang, C., Zeng, L., Lei, Y., Su, M. and Liang, X., 2020. Tracking the Detrital Zircon
1290 Provenance of Early Miocene Sediments in the Continental Shelf of the Northwestern
1291 South China Sea. **Minerals**, 10(9): 752.

1292 Wang, J., A. Yin, T. M. Harrison, M. Grove, Y. Zhang, and G. Xie., 2001. A tectonic
1293 model for Cenozoic igneous activities in the eastern Indo–Asian collision zone. **Earth
1294 and Planetary Science Letters**, 188(1): 123-133.

1295 Wang, P., S. Li, Y. Suo, L. Guo, M. Santosh, X. Li, G. Wang, Z. Jiang, B. Liu, J.
1296 Zhou, S. Jiang, X. Cao, and Z. Liu, 2021, Structural and kinematic analysis of Cenozoic
1297 rift basins in South China Sea: A synthesis: **Earth-Science Reviews**, 216: 103522.

1298 Wang, Y., L. M. Schoenbohm, B. Zhang, D. E. Granger, R. Zhou, J. Zhang, and
1299 J. Hou., 2017. Late Cenozoic landscape evolution along the Ailao Shan Shear Zone,
1300 SE Tibetan Plateau: Evidence from fluvial longitudinal profiles and cosmogenic erosion
1301 rates. **Earth and Planetary Science Letters**, 472: 323-333.

1302 Wang, Y., Fan, W., Zhao, G., Ji, S. and Peng, T., 2007. Zircon U–Pb

1303 geochronology of gneissic rocks in the Yunkai massif and its implications on the
1304 Caledonian event in the South China Block. ***Gondwana Research***, 12(4): 404-416.
1305 Wang, Z., B. Xian, J. Liu, C. Fan, H. Li, J. Wang, X. Zhang, H. Huang, J. Tan, P.
1306 Chen, and J. Liu, 2021, Large-scale turbidite systems of a semi-enclosed shelf sea:
1307 The upper Miocene of Eastern Yinggehai Basin, South China Sea: ***Sedimentary***
1308 ***Geology***, 425: 106006.
1309 Wissink, G.K., Hoke, G.D., Garzione, C.N. and Liu-Zeng, J., 2016. Temporal and
1310 spatial patterns of sediment routing across the southeast margin of the Tibetan Plateau:
1311 Insights from detrital zircon. ***Tectonics***, 35(11): 2538-2563.
1312 Xia, Z., J. Lin, K. Liang, S. Zhang, Y. Pan, Y. Shi, X. Huang, and T. Chen., 2017.
1313 Distribution and provenance significance of detrital minerals in surfac sediments under
1314 typical coastal water areas, Guangxi. ***Geological Survey of China, with English***
1315 ***abstract***, 4(2): 66-72.
1316 Xu, X., S. Y. O Reilly, W. L. Griffin, X. Wang, N. J. Pearson, and Z. He., 2007. The
1317 crust of Cathaysia: Age, assembly and reworking of two terranes. ***Precambrian***
1318 ***Research***, 158(1-2): 51-78.
1319 Xu, Z., Y. Wang, Y. Li, F. Ma, F. Zhang, and C. Ye., 2010. Sediment transport
1320 patterns in the eastern Beibu Gulf based on grain-size multivariate statistics and
1321 provenance analysis. ***Acta Oceanologica Sinica, with English abstract***, 32(3): 68-
1322 78.
1323 Xue, E., W. Wang, M. Zhou, M. K. Pandit, S. Huang, and G. Lu., 2020. Late

1324 Neoproterozoic– early Paleozoic basin evolution in the Cathaysia Block, South China:
1325 Implications of spatio-temporal provenance changes on the paleogeographic
1326 reconstructions in supercontinent cycles. **GSA Bulletin**.

1327 Yao, Y., S. Guo, H. Zhu, Y. Huang, H. Liu, and X. Wang 2021. Source-to-sink
1328 characteristics of the channelized submarine fan system of the Huangliu formation in
1329 the Dongfang block, Yinggehai basin, south China sea. **Journal of Petroleum**
1330 **Science and Engineering**, 206: 109009.

1331 Yan, Q., Metcalfe, I. and Shi, X., 2017. U-Pb isotope geochronology and
1332 geochemistry of granites from Hainan Island (northern South China Sea margin):
1333 Constraints on late Paleozoic-Mesozoic tectonic evolution. **Gondwana Research**, 49:
1334 333-349.

1335 Yan, Y., B. Huang, J. Zhao, D. Zhang, X. Liu, P. Charusiri, and A.
1336 Veeravananakul., 2017. Large southward motion and clockwise rotation of
1337 Indochina throughout the Mesozoic: Paleomagnetic and detrital zircon U–Pb
1338 geochronological constraints. **Earth and Planetary Science Letters**, 459: 264-278.

1339 Yan, Y., Carter, A., Palk, C., Brichau, S. and Hu, X., 2011. Understanding
1340 sedimentation in the Song Hong-Yinggehai Basin, South China Sea. **Geochemistry,**
1341 **Geophysics, Geosystems**, 12(6): n/a-n/a.

1342 Yan, Z., Y. Tian, R. Li, P. Vermeesch, X. Sun, Y. Li, M. Rittner, A. Carter, C. Shao,
1343 H. Huang, and X. Ji., 2019. Late Triassic tectonic inversion in the upper Yangtze Block:
1344 Insights from detrital zircon U-Pb geochronology from south-western Sichuan Basin.

1345 **Basin Research**, 31(1): 92-113.

1346 Yang, C., H. Dang, X. Zhou, H. Zhang, X. Wang, Y. Wang, P. Qiao, X. Jiang, and
1347 Z. Jian, 2021, Upper ocean hydrographic changes in response to the evolution of the
1348 East Asian monsoon in the northern South China Sea during the middle to late Miocene.
1349 **Global and Planetary Change**, 201: 103478.

1350 Ye, Q., L. Mei, H. Shi, G. Camanni, Y. Shu, J. Wu, L. Yu, P. Deng, and G. Li.,
1351 2018. The Late Cretaceous tectonic evolution of the South China Sea area: An
1352 overview, and new perspectives from 3D seismic reflection data. **Earth-Science**
1353 **Reviews**, 187: 186-204.

1354 Yuan, X., Yao, G., Jiang, P. and Lu, J., 2017. Provenance Analysis for Liushagang
1355 Formation of Wushi Depression, Beibuwan Basin, the South China Sea. **Earth**
1356 **Science-Journal of China University of Geosciences, with English abstract**,
1357 11(42): 2040-2054.

1358 Zeng, Y., Liu, W., Cheng, H., Zheng, R., Zhang, J., Li, X. and Jiang, T., 1995.
1359 Evolution of Sedimentation and Tectonics of the Youjiang Composite Basin, South
1360 China. **Acta Geologica Sinica, English edition**, 8(4): 358-371.

1361 Zhang, C., Wang, Z., Sun, Z., Sun, Z., Liu, J. and Wang, Z., 2013. Structural
1362 differences between the western and eastern Qiongdongnan Basin: evidence of
1363 Indochina block extrusion and South China Sea seafloor spreading. **Marine**
1364 **Geophysical Research**, 34(3-4): 309-323.

1365 Zhang, P., Najman, Y., Mei, L., Millar, I., Sobel, E.R., Carter, A., Barfod, D.,

1366 Dhuime, B., Garzanti, E., Govin, G., Vezzoli, G. and Hu, X., 2019. Palaeodrainage
1367 evolution of the large rivers of East Asia, and Himalayan-Tibet tectonics. **Earth-**
1368 **Science Reviews**, 192: 601-630.

1369 Zhao, M., Shao, L. and Qiao, P., 2015. Characteristics of Detrital Zircon U-Pb
1370 Geochronology of the Pearl River Sands and its Implication on Provenances. **Journal**
1371 **of Tongji University (Natural Science), with English abstract**, 43(6): 915-923.

1372 Zhao, M., Shao, L., Liang, J. and Li, Q., 2015. No Red River capture since the late
1373 Oligocene: Geochemical evidence from the Northwestern South China Sea. **Deep Sea**
1374 **Research Part II: Topical Studies in Oceanography**, 122: 185-194.

1375 Zhao, Y., Wang, H., Yan, D., Jiang, P., Chen, S., Zhou, J., Ma, J., Qin, C., He, J.
1376 and Zhao, Y., 2020. Sedimentary characteristics and model of gravity flows in the
1377 eocene Liushagang Formation in Weixi'nan depression, South China Sea. **Journal of**
1378 **Petroleum Science and Engineering**, 190: 107082.

1379 Zhao, Z., Sun, Z., Huang, H. and Sun, L., 2020. The Red River sediment budget
1380 in the Yinggehai and Qiongdongnan basins, northwestern South China Sea, and its
1381 tectonic implications. **International geology review**, 62(7-8): 1019-1035.

1382 Zheng, H., Wen, S., Pang, C., Bryan, K. and He, P., 2020. Provenance of beach
1383 sands on Weizhou Island, Beibu Bay: Implications for source to sink provenance
1384 interpretation. **Geochimica, with English abstract**, 5(49): 1-17.

1385 Zhong, L., Li, G., Yan, W., Xia, B., Feng, Y., Miao, L. and Zhao, J., 2017. Using
1386 zircon U-Pb ages to constrain the provenance and transport of heavy minerals within

1387 the northwestern shelf of the South China Sea. ***Journal of Asian Earth Sciences***,
1388 134: 176-190.

1389 Zhou, X., Gao, G., Lü, X., Zhao, L., Dong, Y., Xu, X. and Gan, J., 2019. Petroleum
1390 source and accumulation of WZ12 oils in the Weixi'nan sag, south China sea, China.
1391 ***Journal of Petroleum Science and Engineering***, 177: 681-698.

1392 Zhu, M., Graham, S. and McHargue, T., 2009. The Red River Fault zone in the
1393 Yinggehai Basin, South China Sea. ***Tectonophysics***, 476(3-4): 397-417.

1394