Early and late Holocene paleoenvironmental reconstruction of the Pearl River estuary, South China Sea using foraminiferal assemblages and stable carbon isotopes

Chen, Huixian; Wang, Jianhua; Khan, Nicole S.; Waxi, Lali; Wu, Jiaxue; Zhai, Yanhui; Zhang, Yunbo; Horton, Benjamin Peter

2019

Chen, H., Wang, J., Khan, N. S., Waxi, L., Wu, J., Zhai, Y., . . . Horton, B. P. (2019). Early and late Holocene paleoenvironmental reconstruction of the Pearl River estuary, South China Sea using foraminiferal assemblages and stable carbon isotopes. *Estuarine, Coastal and Shelf Science*, 222, 112-125. doi:10.1016/j.ecss.2019.04.002

<https://hdl.handle.net/10356/143795>

<https://doi.org/10.1016/j.ecss.2019.04.002>

© 2019 Elsevier Ltd. All rights reserved. This paper was published in *Estuarine, Coastal and Shelf Science* and is made available with permission of Elsevier Ltd.

Downloaded on 26 Apr 2023 23:28:13 SGT

**Early and late Holocene paleoenvironmental reconstruction
of the Pearl River estuary, South China Sea using
foraminiferal assemblages and stable carbon isotopes**

Huixian Chen^{1,2}, Jianhua Wang*^{1,2}, Nicole S. Khan³, Lali Waxy⁴, Jiaxue Wu*^{2,5},
Yanhui Zhai⁵, Yunbo Zhang^{5,6}, Benjamin P. Horton^{3,7}

1 School of Earth Science and Engineering, Sun Yat-Sen University, Guangzhou,
China.

2 Southern Laboratory of Ocean Science and Engineering, Guangdong, Zhuhai, 5190
00, China.

3 Asian School of the Environment, Nanyang Technological University, Singapore.

4 Guangdong Provincial Transportation Planning and Research Centre, Guangzhou
510101, China.

5 School of Marine Science, Sun Yat-Sen University, Guangzhou, China.

6 Guangdong Sea Star Ocean Science and Technology Company Limited, Guangzhou,
China.

7 Earth Observatory of Singapore, Nanyang Technological University, Singapore.

*Corresponding authors (e-mail: adswjh@mail.sysu.edu.cn;

wujiaxue@mail.sysu.edu.cn)

Abstract

Proxy reconstructions of estuarine evolution provide perspectives on regional to global environmental changes, including relative sea-level changes, climatic changes, and agricultural developments. Here, we present a new benthic foraminiferal record along with $\delta^{13}\text{C}$ and C/N, and lithological data from a sediment core in the Pearl River estuary (Lingding Bay) adjacent to the South China Sea. The core has relatively thick Holocene sediments (>40 m) due to its location in the paleo-valley of the Pearl River. The lithologic and foraminiferal record reveal an evolution in paleoenvironment from fluvial, inner estuary to middle estuary between 11300 and 8100 cal a BP in response to rapid sea-level rise. $\delta^{13}\text{C}$ and C/N data indicate high freshwater discharge from 10500 to 8100 cal a BP driven by a strong Asian monsoon. The middle Holocene (8100 - 3300 cal a BP) sediment is absent in the core due to subaqueous erosion resulting from the unique geomorphology of the Pearl River Delta. In the late Holocene from 3300 cal a BP to the present, the lithology and foraminiferal assemblages suggest a further evolution from outer estuary, middle estuary channel, to middle estuary shoal, resulting from deltaic progradation under stable relative sea levels. In the last 2000 years, $\delta^{13}\text{C}$ and C/N values reveal the intensive development of agriculture coupled with the reduction of freshwater input derived from a weakening Asian monsoon.

Key words: Benthic foraminifera, $\delta^{13}\text{C}$ and C/N, Paleoenvironment, Sea-level changes, Pearl River estuary, monsoon, Hiatus

42

43 **1. Introduction**

44 As transitional zones, estuarine sediments record fluctuations of freshwater and
45 seawater inputs with a high sedimentation rate, and thus provide detailed archives of
46 paleoenvironmental changes (e.g., Zong et al., 2009b; Weckström et al., 2017).
47 Investigations of Holocene estuarine sediments reveal important information about
48 changes in sea level, climate and human activities (e.g., Atahan et al., 2008; Leorri et
49 al., 2006; McGann, 2008; Oldfield et al., 2003; Rolett et al., 2011; Wang et al., 2012),
50 which elucidate the patterns of natural variability and thus provide a background to
51 compare against the increasing environmental stresses from human activities of the 20th
52 and 21st century (e.g., Kemp et al., 2011).

53

54 Holocene paleoenvironments have been comprehensively reconstructed using a multi-
55 proxy approach (e.g., Barnett et al., 2017; Di Rita et al., 2011; Sen and Bhadury, 2017).
56 For example, benthic foraminifera contained within estuarine sediments are vital
57 indicators of environmental change because they are sensitive to salinity and inhabit a
58 wide range of sedimentary environments from brackish to fully marine (e.g., Murray,
59 1991; Leorri et al., 2006; Pilarczyk et al., 2014). In addition, bulk-sediment organic
60 stable carbon isotopes ($\delta^{13}\text{C}$) and the ratio of total organic carbon to total nitrogen ratios
61 (C/N) can be used to differentiate terrestrial and marine sources in estuarine sediments
62 (e.g., Da Cruz Miranda et al., 2009; Kemp et al., 2017; Sen and Bhadury, 2017) and

enables interpretation of paleoenvironmental change where poor preservation or absence limits the utility of microfossils (e.g., Khan et al., 2015; Mackie et al., 2007; Wilson et al., 2005).

Many Holocene paleoenvironmental reconstructions have focused on the deltaic plain of the Pearl River due to its large size, high-volume discharge, and location in the most economically developed region of southern China (e.g., Zong et al., 2009a,b; 2012). Sea-level change and fluvial processes are two main driving mechanisms that contribute to the formation of Pearl River deltaic landforms (Zong et al., 2009a). Previous studies of fossil foraminifera show that an estuarine environment developed between ~9650 and 8000 cal a BP in the Pearl River Delta following the Holocene transgression (e.g., Alberti et al., 2013; Dong et al., 2007; Wu et al., 2015; Liu et al., 2008; Zhuang et al., 2013). As sea-level rise slowed following deglaciation of the Eurasian and North American ice sheets (e.g., Lambeck et al., 2014), a fluvial plain began to form with the onset of deltaic progradation after ~7000-6000 cal a BP (e.g., Wei and Wu, 2011; Zong et al., 2009a). In addition to the influence of sea-level changes, $\delta^{13}\text{C}$ values of the estuarine sediments reveal variations in the Asian monsoon have resulted in the fluctuation of freshwater input into the Pearl River Delta during the Holocene, with increased discharge from 8500 to 6000 cal a BP and decreasing discharge from 6000 cal a BP to present (Yang et al., 2011; Yu et al., 2012; Zong et al., 2006).

Here, we use benthic foraminifera, $\delta^{13}\text{C}$ and C/N within a chronological framework from an estuarine sediment core (ZK19), which is located in the paleo-valley of the Lingding Bay, to understand estuarine evolution and monsoonal discharge changes in the Pearl River estuary. We extend the chronology beyond previous studies to 11300 cal a BP to incorporate a period of rapidly rising sea level (e.g., Xiong et al., 2018a) and stronger Asian monsoon (e.g., Dykoski et al., 2005). We also place focus on the most recent 3300 years, a period of intensifying impacts from human activities (e.g., Zong et al., 2013a) due to early agriculture from 2000 cal a BP to the present day.

2. The Pearl River estuary and Lingding Bay

The Pearl River estuary lies between $21^{\circ}20' - 23^{\circ}30'$ and $112^{\circ}40' - 114^{\circ}50'$ (Fig 1). The Pearl River estuary is in a transitional region between tropical and subtropical zones, with the mean annual temperature ranging from 14 to 22°C across the basin and the annual precipitation ranging from 1200 to 2200 mm (Zhang et al., 2008). The drainage basin is under the influence of the humid summer monsoon (June – September) from the south and the dry winter monsoon (December - February) from the north (e.g., Zong et al., 2006).

The drainage basin of the Pearl River formed from the uplift of the Tibetan Plateau during the Tertiary and Quaternary periods (Huang et al., 1982; Li et al., 1990). The Pearl River estuary, where the Pearl River flows into the South China Sea, is a bell-

shaped, semi-enclosed estuary. The major bay – Lingding Bay – is separated from the South China Sea by Lantau Island and Neilingding Island and is crossed by deep channels east and west (Wu et al., 2010). Previous stratigraphic studies indicate two paleo-valleys pass through Lingding Bay (Fig 1b). We sampled the deeper channel, which extends from the Jiaomen and Hongqili to Neilingding Island and then to Guishan Island before it reaches the inner shelf (Wang, 2004; Wei and Wu, 2011). The west side of the deeper paleo-valley location was targeted for sampling to investigate a longer paleoenvironmental record of the Pearl River estuary.

Three main rivers (East River, West River and North River) drain into the estuary through eight outlets, most of which are separated by rock-bound gorges called the “gates” (Wu et al., 2010). The total annual sediment load delivered to the Pearl River estuary, mainly from these three rivers, is 89×10^9 kg (Wei and Wu, 2011). The Pearl River estuary is microtidal, with a tidal range that increases from 0.89 m in the open bay to 1.69 m at the Humen gate due to tidal amplification in the bell-shaped estuary (Mao et al., 2004; Zhao, 1989; Zhang et al., 2013). The estuary exhibits a strong northwest-southeast salinity gradient resulted from the mixing of freshwater from the Pearl River via the west channel and high-salinity water intruded from the South China Sea via the east deep-water channels (Mao et al., 2004). Salinity patterns change significantly with the seasons due to the influence of monsoon precipitation (Fig 1c, d). For example, in summer, high precipitation generates a strong freshwater flux into the

estuary, lowering water salinity below 1 psu at the inner estuary, while in winter, surface water salinity is approximately 5 psu at the inner estuary and increases gradually seaward, approaching average seawater salinity at Lantau Island (Dong et al., 2004). Based on surface sediment particle size and salinity, the Pearl River estuary can be divided into four estuarine zones: (1) inner estuary; (2) middle estuary; (3) outer estuary environments; and (4) marine environment (Fig 1c; Fyfe et al., 1997; Owen, 2005; Zong et al., 2009a).

3. Material and Methods

Sediment core ZK19 (22°20.9302'N, 113°41.9147'E) was collected from Lingding Bay within the middle estuary zone (Fig 1) and was retrieved by the Marine Geological Survey of Guangzhou with a rotating drilling system at a water depth of 5.0 m (measured by multiple-beam system, R2Sonic 2024) in spring 2013. The core was 62.6 m long and transported to the laboratory at Sun Yat-Sen University for cold storage (4°C). In the laboratory, the core was split, photographed, and described. Subsamples were taken for radiocarbon (Section 3.1), grain size (Section 3.2), foraminiferal (Section 3.3) and $\delta^{13}\text{C}$ and C/N (Section 3.4) analyses. The sediment in core ZK19 comprised two marine units and two terrestrial units and spanned the late Pleistocene and the Holocene. In this study, we only focused on the Holocene section in the upper 40.8 m of the core.

3.1 Chronology and age depth model

The chronology of core ZK19 was established based on 12 accelerator mass spectrometry (AMS) ^{14}C dates from mollusc shells and plant fragments. The AMS ^{14}C dates were measured at the Beta Analytic Laboratory, USA. All results are presented on a calibrated age scale before present (cal a BP), with the present being AD 1950 (Table 1). The ages were calibrated with the program CALIB v. 7.10 (Stuiver and Reimer, 2018) using the IntCal13 curve for terrestrial materials and the Marine13 curve for marine shells with a local marine reservoir correction (ΔR) of -128 ± 40 (Southon et al., 2002; Zong et al., 2010b). The age-depth model was established using the statistical package Bchron 3.1 (Parnell et al., 2008) in R based on 12 radiocarbon dates. Two separate age models were developed for the top 0 - 16.4 m and the lower 16.4 - 40.8 m of the core due to the presence of a hiatus at 16.4 m in the core (see section 4.2 and 5.3 for further details). Sedimentation rates were also calculated using Bchron (Haslett and Parnell, 2008). We report the median and 95% credible intervals for ages and sedimentation rates estimated by Bchron (Fig 2).

3.2 Sediment stratigraphy and grain size

The stratigraphy of core ZK19 was described using the Shepard classification (1954), and further supported by grain size analysis (Fig 2, 4). Three hundred and seventy-three samples were selected every 10 cm down the core for grain size analysis. Approximately 1 g of each dried sample was pretreated with 10 ml of 20% H_2O_2 for at

least 12 hours to remove organic matter and soaked in 10 ml of 10% HCl to remove carbonates. Deionized water was used to rinse the sediment to neutralize the pH. Subsequently, the residual sample was dispersed in 10 ml of 0.1 M (NaPO₃)₆ before analysis. The grain size analysis was performed using a Malvern Mastersizer 2000 laser grain size analyzer with a measurement range of 0.02 - 2000 µm. The grain size designation into gravel (>1000 µm), sand (63-1000 µm), silt (4-63 µm), and clay (<4 µm) was based on the Wentworth size classification (Wentworth, 1922).

3.3 Foraminifera and cluster analyses

We selected seventy-four samples every 50 cm down core ZK19 for foraminiferal analyses (Fig 3). The sediment samples were dried at 60°C, soaked in deionized water for 24 hours, wet sieved with tap water through stacked 150 µm and 63 µm screens, and dried again. Identification was performed under a binocular microscope; where possible, at least 150 foraminiferal individuals were counted from the >150 µm fraction. Foraminiferal taxonomy followed Li (1985), Li et al. (2011), Wang et al. (1988) and Garrett (2010). We identified *Elphidium nakanokawaense* (Li, 1985; Li et al., 2011) as *Haynesina* sp. (Garrett, 2010). We combined all the species from the genus *Ammonia* to *Ammonia* spp. (e.g., Horton and Edwards, 2006). The representative specimens from core ZK19 were photographed using a scanning electron microscope (Plates 1, 2). We calculated the foraminiferal density (the number of the specimens normalized to 50 g of dry sediment sample), the diversity (estimated by species richness, or the number of

taxa in each sample), and the relative abundance of each taxa. The data are provided in Appendix 1.

The ecological interpretations of the foraminiferal assemblages followed modern foraminiferal distribution studies in the Pearl River estuary (Garrett, 2010; Li, 1985; Li et al., 2011; Wu et al., 2015). The modern distribution of foraminifera in the Pearl River estuary is mainly controlled by salinity, although water depth and substrate are also very important factors to account for the distribution patterns (Garrett, 2010; Li et al., 2015; Tao et al., 2011). Therefore, we summarized the modern foraminiferal assemblages from different studies according to the sedimentary facies from which the modern sample was collected. We define five sedimentary facies – inner estuary, middle estuary, outer estuary, shallow marine environment, tidal channel – based on salinity and surface sediment grain size (Table 2). This classification scheme is a well-established convention for the Pearl River estuary, and is also used to describe the distribution of diatoms (Zong et al., 2009a).

We classified the foraminiferal assemblages (species with >2% abundance in at least one sample) in core ZK19 into groups using stratigraphically-constrained CONISS (Constrained Incremental Sums of Squares; Grimm, 1987) cluster analysis. Because of the chronological hiatus, we applied cluster analysis to the lower (34.8 - 16.4 m) and upper parts (16.4 - 0 m) separately.

210

211 **3.4 $\delta^{13}\text{C}$ and C/N ratios**

212 We selected seventy-four samples every 50 cm down core for geochemical analysis.
213 All samples were initially acidified with 5% HCl to dissolve all carbonates, then rinsed
214 with deionized water until the pH was neutral. This acid pre-treatment may possibly
215 alter C/N and $\delta^{13}\text{C}$ values of sediments (Brodie et al., 2011; Schlacher and Connolly,
216 2014); however, this alteration is very small when compared to the ranges of elemental
217 and isotopic values observed in estuarine settings, and thus should not affect
218 environmental interpretations (Craven et al., 2013). Subsequently, sediment samples
219 were dried at 50°C for 24 hours and then ground to fine powder using an agate mortar
220 and pestle following the procedure suggested by Yu et al. (2012). Two aliquots were
221 prepared for each sample. Approximately 20 mg of sample were wrapped in silver
222 capsules to measure total organic carbon (TOC) and total nitrogen (TN) using a Vario
223 EL cube elemental analyzer. C/N ratios were calibrated with an acetanilide standard
224 and are given as a weight percentage. Replicate analysis of well-mixed samples
225 indicated a precision of $< \pm 0.1\%$ (1 SD). 2 mg of sediment were used for stable carbon
226 isotope analysis. $^{13}\text{C}/^{12}\text{C}$ analysis was performed by an EA Flash 2000 Elemental
227 Analyzer online to a Delta V Advantage mass spectrometer at the Isotope Laboratory
228 of Sun Yat-Sen University, Guangzhou. The values were converted to the VPDB scale
229 using a within-run laboratory standard calibrated against NBS-18. Replicate analysis of

well-mixed samples indicated a precision of $\pm 0.03\%$. The data are provided in Appendix 2.

We applied the modern $\delta^{13}\text{C}$ values and C/N ratios of vegetation and sediments from the Pearl River estuary from Yu et al. (2012) to interpret the sources of sediments in the core.

4. Results

4.1 Chronology of core ZK19

The ages of the 12 AMS ^{14}C dating materials from core ZK19 ranged from 10775 ± 139 cal a BP to 496 ± 37 cal a BP (Table 1), with two outliers at 16.0 m and 19.0 m. The ages obtained from depths between 34.6 m and 17.0 m range from 10775 ± 139 to 8126 ± 123 cal a BP, while the ages obtained from depths of 16.0 m to 2.0 m are in the range of 2823 ± 105 to 496 ± 37 cal a BP. The distribution of ages implies a ~5300 year long hiatus from ~8100 to 2800 cal a BP. The Bchron age-depth model provides the median and 95% credible interval of age estimates and sedimentation rates every 10 cm (Fig 2). The model extrapolated the age at the base of the core at 40.8 m to be ~11300 cal a BP and interpolated an age of 3300 cal a BP at the depth of hiatus 16.4 m. The sedimentation rates were variable above and below the hiatus (Fig 2). In the early Holocene, rates were relatively high ($\sim 0.6 \pm 0.8$ cm/a on average) and decreased

through time. In the late Holocene, the sedimentation rate was $\sim 0.4 \pm 0.5$ cm/a on average, increasing from an average of 0.2 ± 0.4 cm/a during 3300 - 2000 cal a BP to an average of 0.4 ± 0.63 cm/a during 2000 - 700 cal a BP, and finally to $\sim 1.5 \pm 2.0$ cm/a from 700 cal a BP to present.

4.2 Grain size and lithology of Core ZK19

Seven lithologic zones were recognized based on the color, grain size and sedimentary structure of sediments in core ZK19 (Fig 2). Zone G (40.8 - 34.8 m) consisted of yellow-gray medium-coarse sand without any fossils. The median grain size ranged between 78 - 624 μm (avg. 261 μm). At 36.8 m, the sediment fraction of sand decreased and transitioned to a brown to light gray silty fine sand with horizontal bedding.

Zone F (34.8 - 31.4 m) the sediment changed from dark gray silty sand to clayey silt with a general upward-fining sequence and intercalated yellow coarse sand layers containing shell debris at ~ 0.1 - 0.2 m intervals. The median grain size ranged between 10 - 480 μm (avg. 149 μm).

Zone E (31.4 - 21.6 m), a 0.6 m-thick dark gray silty-coarse sand layer containing shell debris was found from 31.4 - 30.8 m. From 30.7 - 21.6 m, dark gray clayey silt was deposited intercalating with 0.1 - 1 cm-thick gray silty to fine-sand laminae, and 3 - 5

270 cm-diameter yellow sandy pockets scattered within the silty matrix at depths of 30.15
271 m, 24.8 m and 24.6 m. The median grain size ranged between 12 - 178 μ m (avg. 25 μ m).

272

273 Zone D (21.6 - 16.4 m), dark gray clayey silt was intercalated with ~1 - 2 cm gray fine-
274 sand laminae containing abundant shell debris and exhibiting horizontal bedding. The
275 median grain size ranged between 14 - 49 μ m (avg. 27 μ m). We defined the boundary
276 at 16.4 m due to the chronological hiatus. Although the grain size shows little change
277 at this depth, we identified variations in water content, with higher water content above
278 16.4 m.

279

280 Zone C (16.4 - 9.8 m) contained dark gray clayey silt intercalated with dark sandy silt
281 or silty sand layers. Isolated intact gastropods and bivalves were found at depths of 16.1
282 - 15.5 m. The median grain size ranged between 15 - 42 μ m (avg. 23 μ m).

283

284 Zone B (9.8 - 3.8 m) consisted of gray clayey silt with several sandy silt laminae
285 containing sporadic pieces of degraded wood and burrow structures filled with sand.
286 The median grain size ranged between 13 - 21 μ m (avg. 16 μ m).

287

288 Zone A (3.8 m - top) contained homogeneous brown gray clayey silt devoid of
289 macrofossils. The median grain size ranged between 8 - 39 μ m (avg. 15 μ m).

290

4.3 Fossil foraminifera from core ZK19

Foraminifera were present from 34.8 m to the top of core ZK19. A total of 57 species from 23 genera were identified. The brackish taxa *Ammonia* spp. and *Quinqueloculina akeriana* accounted for more than 80% of the assemblages in most of the samples, except the upper section of the core (3.8 to 0 m), which was dominated by agglutinated species *Haplophragmoides canariensis* and *Ammobaculites agglutinans* (Figure 3). The foraminiferal diversity ranged from 0 to 20, and the density of foraminifera in samples ranged between 0 and 7600 individuals per 50 g (Figure 3).

Six clusters were recognized by the CONISS cluster analysis (Figure 3). The foraminiferal clusters 1 - 6 compared well with the lithologic zones A - F, except for the boundary dividing lithological zones D and E. The lithological boundary was defined at 21.6 m, whereas the equivalent foraminiferal cluster boundary was at 24.5 m. The additional zone in the lithology (zone G) is the section of the core devoid of foraminifera.

Cluster 6 (34.8 - 31.4 m) contained sparse (2 individuals per 50 g) foraminifera with only a few broken tests of a monospecific *Ammonia* spp. assemblage. The appearance of broken and low-density foraminiferal tests suggested a dynamic environment where tests may have been transported or mechanically reworked (Murray, 1991). The

appearance of foraminifera in this unit indicates the onset of marine influence and a transition from the underlying fluvial facies (40.8 - 34.6 m) devoid of foraminifera.

Cluster 5 (31.4 - 24.5 m) mainly contained *Ammonia* spp. (70%), accompanied by *Haynesina* sp. (5%) and *Triloculina* sp. (15%). The average foraminiferal density was 217 individuals per 50 g, and the diversity was 1-11 (avg. 5.4). This assemblage is comparable to that of the modern inner estuary assemblage (Table 2).

Cluster 4 (24.5 - 16.4 m) had an average density of 663 individuals per 50 g. The average diversity rose to 14.4 due to the increase of the calcareous taxa *Quinqueloculina* spp., *Spiroloculina* spp. and the appearance of *Rotalinoides annectens*, *Elphidium advenum*. Overall, the assemblage is characterized by *Ammonia* spp. and *Quinqueloculina akeriana*, which accounted for approximately 40% and 20 - 40% of the assemblage, respectively. This assemblage contains most species present in the modern middle estuary assemblage (Table 2). However, fewer agglutinated taxa and a higher percentage of porcellaneous tests are observed in Cluster 4. This discrepancy may be due to the differential loss of tests during the taphonomic process. Agglutinated tests have poor preservation potential because they have fragile structure and organic cements that may easily be destroyed by bacterial degradation in subtropical regions (Buzas-Stephens et al., 2014; Goldstein and Watkins, 1999; Wang et al., 2001). Drying

the samples during the pretreatment process might also contribute to agglutinated test loss (Schönfeld et al., 2012).

Cluster 3 (16.4 - 9.8 m) had remarkably higher foraminiferal densities than the underlying zones and reached 2410 individuals per 50 g. The diversity was also the highest in this section (avg. 15.4). The foraminiferal assemblage was similar to that of zone 4, with *Ammonia* spp. and *Quinqueloculina akeriana* (70% and 10 - 20%, respectively) dominant. The high salinity species *Pararotalia nipponica* and the planktonic species *Globorotalia neoflexuosa* first appeared in zone 3. Foraminiferal assemblages showed close correspondence to the modern outer estuary assemblage (Table 2) and have much higher density and diversity than cluster 4.

Cluster 2 (9.8 - 3.8 m) had a low density (average of 310 individuals per 50 g) and diversity (average of 7.2), and was dominated by *Quinqueloculina akeriana* (60%) with *Ammonia* spp. (25%) and *Haynesina* sp. (10%). There was no counterpart in the modern estuary. The lower density and diversity of foraminifera could imply test destruction of agglutinated species (similar to that observed in Cluster 4), or accumulation of sediments in a more near shore environment than the outer estuary environment of Cluster 3, such as a middle estuary environment. *Quinqueloculina akeriana* was found abundantly in the high-salinity bottom waters of the modern tidal channels of the middle estuary (Luo et al., 2001),

352

353 Cluster 1 (3.8 - 0 m) substantially differed from the previous clusters. The density
354 decreased to 100 individuals per 50 g, and the diversity ranged between 3 - 12 (avg.
355 6.8). This zone was characterized by agglutinated species, such as *Haplophragmoides*
356 *canariensis* and *Ammobaculites agglutinans* (~10 - 70% of the assemblage), although
357 *Ammonia* spp. was still dominant (~40%). This assemblage resembles the modern
358 middle estuary shoal, which is also characterized by agglutinated species (Table 2).

359

360 4.4 $\delta^{13}\text{C}$ and C/N ratios

361 The $\delta^{13}\text{C}$ and C/N ratios were described across the foraminiferal cluster zones. The $\delta^{13}\text{C}$
362 values beneath Zone 6, increased substantially from 40.8 m (-29.6‰) to 34.8 m (-
363 24.8‰). C/N ratios (1.7 - 5.6) were the lowest throughout the entire core, suggesting
364 microbial alteration of source $\delta^{13}\text{C}$ and C/N values (Lamb et al., 2006). Bacterial action
365 can introduce N to the sediment and thus decrease C/N ratios (e.g. Rice and Hanson,
366 1984). The $\delta^{13}\text{C}$ may also be altered by high rates of microbial activity (e.g. Ember et
367 al., 1987; Cloern, 2002; Coffin et al., 1989). Similar $\delta^{13}\text{C}$ values and C/N ratios ($\delta^{13}\text{C}$
368 between -19‰ and -22‰; C/N < 5) have been observed in Holocene paleosols from
369 the Yangtze Delta (Zhan et al., 2012), which further suggested the sediments
370 accumulated in a pedogenic, subaerial environment that introduced higher microbial
371 activity (Fig 4, 5).

372

373 The $\delta^{13}\text{C}$ values in Zone 6 decreased from -27.2‰ to -28.1‰ (avg. -27.8‰), while the
374 C/N ratios decreased from 11.4 to 9.8. Together these values suggested a mixed source
375 from freshwater POC and C_3 terrestrial plants (Lamb et al, 2006; Fig 5c). In addition,
376 the trend from bottom to top in this section indicated an increase in freshwater aquatic
377 organic matter inputs, which have lower C/N values but similar $\delta^{13}\text{C}$ values (from -26‰
378 to -30‰) to C_3 terrestrial plants (e.g., Meyers, 1994; Bianchi and Canuel, 2011).

379

380 The $\delta^{13}\text{C}$ values in Zone 5 fluctuated between -28.8‰ and -26.6‰ (avg. -27.8‰), with
381 a slightly increasing upward trend. The C/N ratio varied between 10 and 12 (avg. 11.3).

382 The $\delta^{13}\text{C}$ values and C/N ratios from Zone 5, similar to Zone 6, indicated a mixture of
383 C_3 terrestrial plants and freshwater POC (Lamb et al., 2006; Fig 5c).

384

385 The $\delta^{13}\text{C}$ values in Zone 4 ranged from -28.3‰ to -26.8‰ (avg. -27.9‰), and the C/N
386 ratio ranged from 10.4 to 12.8 (avg. 11.9). The $\delta^{13}\text{C}$ values and C/N ratios were
387 relatively stable between Zone 5 and Zone 4 and indicated a similar terrestrial end-
388 member associated with high freshwater input.

389

390 The $\delta^{13}\text{C}$ values in Zone 3 increased from -28.2‰ to -25.8‰ (avg. -27.0‰), whereas
391 the C/N ratio, ranging from 10.2 to 12.0 (avg. 10.8), showed a slight decreasing trend.
392 Although this range in values suggested a predominant mixed C_3 terrestrial plants and

freshwater POC source (Fig 5d), the increasing $\delta^{13}\text{C}$ values suggested increasing marine influence (e.g., Middelburg and Nieuwenhuize, 1998; Meyers, 1994; Hu et al., 2006).

The $\delta^{13}\text{C}$ values in Zone 2 continued to increase from -24.6‰ to -22.4‰ (avg. -23.5‰), while the C/N ratio decreased from 11.8 to 9.0 (avg. 10.0). A mix of marine POC, reworked agricultural soil, or outer estuary sediments may have contributed to the $\delta^{13}\text{C}$ and C/N values of this zone (Fig 5d; Lamb et al., 2006; Yu et al., 2012; Owen and Lee, 2004).

The $\delta^{13}\text{C}$ values in Zone 1 increased from -22.4‰ to the highest value of -21.4‰ (avg. -21.9‰); the C/N ratio decreased from 10.3 to 8.7 (avg. 9.4). Marine POC or reworked agricultural soil could have contributed to the increased $\delta^{13}\text{C}$ and decreased C/N values of this zone (Fig 5d; Lamb et al., 2006; Yu et al., 2012; Owen and Lee, 2004).

5. Discussion

5.1 The influence of sea-level rise and strong monsoon during the early Holocene

Paleo-valleys of the Pearl River estuary were formed as the river incised the late Pleistocene marine sequence during the last glacial period when the sea level was ~40 - 50 m lower than present and the shoreline extended further seaward to the edge of the continental shelf (e.g., Chen et al., 1990; Huang and Xu, 1995; Zong et al., 2009b; Zong

et al., 2012; Yim et al., 2006). At the beginning of the Holocene, fluvial deposits began accumulating in the paleo-valley at 11300 cal a BP. Gravel and coarse sand carried by river discharge were deposited on the top of the old marine sequence. The $\delta^{13}\text{C}$ and C/N values indicative of bacterially-degraded freshwater POC deposited in a fluvial environment suggested that the river sediment was subaerially exposed periodically prior to the marine transgression. Foraminifera were absent in this section of the core, further supporting a fluvial environment.

The core location was influenced by the Holocene transgression between ~10800 and ~10500 cal a BP (Fig 6; 7 a, b, c). Rapidly rising sea level caused an increase in water depth and estuarine accommodation space, causing a transition in depositional environment from tidal channel to inner estuary based on the first appearance of foraminiferal tests. This transition is also reflected in a fining-upward sequence with a very high sedimentation rate averaging ~1.3 cm/a between 10794 cal a BP (depth 34.8 m) and 10535 cal a BP (depth 31.4 m) over a period of ~260 years. $\delta^{13}\text{C}$ and C/N values of -27.2‰ to -28.1‰ and 9.8 to 11.4 indicated high amounts of terrigenous organic matter and an increase of freshwater aquatic plant input (e.g., Meyers, 1994), which further supports this transition. This transitional zone represented the initial phase of marine influence in the Pearl River Delta, which was limited to the incised channel locations in early Holocene (Fig 8 a,b). The similar zone was recorded around 10600 cal a BP in core HKUV12 at -52.1 m mean sea level (MSL) and 10040 cal a BP in core

HKUV11 at -43.3 m MSL along a paleo-incised channel south of the Lantau Island. In these cores, the transgression was marked by a low abundance of brackish diatoms and high TOC indicative of a terrigenous organic matter source, and suggested a transition to an estuarine-river-mouth environment (Xiong et al., 2018b). Comparatively, the timing of the initial marine phase of the other cores located in the paleo-interfluvium is later than paleo-incised channel cores, recording a transgression generally between 9000 - 7000 cal a BP (Fig 8 a, c; Zong et al., 2009b; Zong et al., 2010b; Shi et al., 2015). This difference in timing provides evidence that early Holocene sea-level rise first influenced the low-lying paleo-valley (Wei et al., 2016).

Foraminiferal assemblages indicated increased salinity as the local environment gradually evolved from an inner to a middle estuary at ~9650 cal a BP driven by sea-level rise. Local sea-level records indicated a rapid rise occurred from 10500 cal a BP (~16.4 mm/a) to 7500 cal a BP (~1.7 mm/a), with an accelerated sea-level rise (~33 mm/a) at 9500 cal a BP (Xiong et al., 2018a), consistent with changes observed in sea level across the Chinese coast (Fig 6; Liu et al., 2004; Zong, 2013b). This apparent increase in marine influence across the Pearl River Delta has been attributed to a phase of accelerated rise in sea level, which resulted in shoreline retreat and estuary expansion with a relative increase in salinity (Xiong et al., 2018a; Zong et al., 2009a; Zong et al., 2010b).

455 $\delta^{13}\text{C}$ and C/N values (-28.8‰ to -26.6‰ and 10 to 12.8) indicated a high contribution
456 of terrestrial vascular plants to estuarine sediments from 10500 to 8100 cal a BP,
457 suggesting strong freshwater discharge. A similar trend in $\delta^{13}\text{C}$ was observed in core
458 HK-UV11 from 10350 to 7000 cal a BP (Wu et al., 2017). In cores further inland in the
459 paleo-valley, freshwater benthic diatoms dominated the corresponding unit (Fig 8 a, b;
460 Phase I in cores SS0901 and SDZK01), indicating a shallow depositional environment
461 influenced strongly by freshwater discharge (Zong et al., 2012). The increase in
462 terrestrial-derived sediments and freshwater discharge during this time is coincident
463 with a period of strong monsoons and humid, warm climate during the early Holocene
464 optimum from ~10000 to 6000 cal a BP observed in numerous high-resolution
465 paleoclimate studies of stalagmite and geochemical records from southern China (Fig
466 7 e, f, g; Dong et al., 2010; Dykoski et al., 2005; Jia et al., 2015; Strong et al., 2013;
467 Zhou et al., 2004; Zong et al., 2006). The climate optimum may also have been
468 responsible for thriving vegetation and greater production and delivery of terrestrial
469 vascular plant input in the early Holocene, indicated by greater diversity and an
470 increased number of tree species in regional pollen records (e.g., Sheng et al., 2017;
471 Wang et al., 2007). The paleo-valley location of ZK19 may also play a role in
472 magnifying the monsoonal freshwater sedimentation. Freshwater outflows may have
473 been restricted in relatively narrow valleys, limiting the area over which these terrestrial
474 sediments may be dispersed (Zong et al., 2012). Conversely, import of marine organic
475 matter from rapid sea-level rise may have suppressed the monsoonal signature in ZK19

sediment, which shows a smaller amplitude of $\delta^{13}\text{C}$ and C/N changes compared with the Southern China monsoon records (Fig 7g, h).

5.2 Hiatus in the middle Holocene of the Pearl River Delta

The chronology of ZK19 shows a large gap in time between radiocarbon ages of 8127 and 2226 cal a BP at 17.0 m and 16.0 m, respectively. If we were to assume continuous sedimentation in the core, then the 1.0 m-thick sediment layer would represent nearly 5000 a of deposition, with a sedimentation rate of ~ 0.02 cm/a. This rate is much slower than those in the modern estuary or continental shelf of the South China Sea (Liu et al., 2014). Therefore, we interpret this gap in ages as a middle Holocene sedimentary hiatus. Although the grain size and foraminiferal assemblages show little change at this depth, subtle changes of water content and sedimentary texture were observed at 16.4 m (see core photograph; Fig S1). Analyses of core ZK19 presented in Waxi (2016) also show changes in trace element geochemistry (V/Sc) of sediments at 16.4 m.

Sedimentary hiatuses are commonly observed in Pearl River deltaic sediments. Core ZK3, located northward of the Lingding Bay also reported a hiatus from 7600 to 2900 cal a BP (unpublished core, Fig S2 and Table S1); Cores PRD 18 and core PRD 15 located near “the gates,” a series of rocky islands outside the lower bay, also exhibited a hiatus in sedimentation from 6000 to 3000 cal a BP and from 7925 to 1226 cal a BP, respectively (Fig 9 a, b; Wei et al., 2011). We can conclude that the discontinuity occurred in the middle Holocene after the early Holocene sediment infilling the paleo-

497 valley reached the old, pre-Holocene surface (Fig 8b, c ; Zong et al., 2012) and regional
498 sea levels reached near modern level (Zong, 2004). The geomorphology of the paleo-
499 Pearl River estuary may have played an important role in causing these sedimentary
500 hiatuses. Rocky islands were scattered across the paleo-estuary and divided the paleo-
501 Pearl River estuary into two distinct depositional environments. The upper part
502 developed into a semi-enclosed inner bay in connection with mainland rivers, and the
503 lower part remained an outer bay connected to the oceans (Fig 9a; Wei and Wu, 2011;
504 Wu et al., 2010). A combination of two conditions in the outer bay, where ZK19 is
505 located, make the observed ~6000 year hiatus possible. First, the sedimentation rate
506 decreased in the lower bay as the shoreline retreated during the transgression maximum,
507 and sedimentation was concentrated in the landward part of the delta plain (upper bay)
508 (Zong et al., 2009a). Second, the extensive transgression led to the intensification of
509 tidal influx at the rocky gorges. This strong influx and convergence of paleo-tidal
510 energy at the gorges created a bi-directional jet system, which caused the formation of
511 tidal channels and enhanced seafloor erosion near the rocky gorges and lower bay of
512 the paleo estuary (Wu et al., 2010). A simulation of ebb tide flow fields between 6000
513 - 2500 cal a BP shows that the area with highest velocity is near the “gates” and in the
514 lower bay (Wei, 2010), consistent with the locations of cores showing a depositional
515 hiatus (Fig 9a). Together, these two factors likely caused deposition to cease or
516 sediments to be reworked. This scenario is further supported by seismic stratigraphy,
517 showing a tidal ravinement surface characterized by strong erosion and channel

formation in the lower zone of the paleo-estuary between a depth of 16 - 24 m (Fig 9 c,d). The tidal ravinement surface occurs close above the old, pre-Holocene surface (e.g., L2; Fig 8c), likely forming between ~8000-6000 cal a BP when sea-level rise began to slow (Fig 8c; Tang et al., 2010).

5.3 Asian monsoon, delta progradation and human activities in late Holocene

In the past 3300 cal a BP, the development of the Pearl River Delta is a combined effect of deltaic progradation, declined Asian monsoon and intensified human activities. Deltaic progradation became the main feature of paleoenvironmental change during a period of relative sea-level stability in the late Holocene (e.g., Zong, 2004; Zong et al., 2009a, 2012). Foraminiferal assemblages indicated an outer estuary environment with the highest density and diversity of foraminifera within core ZK19 between 3300 cal a BP and 1670 cal a BP. A transition to a middle estuary environment occurred at ~1670 cal a BP as a result of deltaic progradation. Previous studies show that the shoreline advanced ~20 km from 4500 to 2000 cal a BP based on archaeological evidence (Zong et al., 2012; Wei et al., 2016). Delta progradation in Lingding Bay may have caused an apparent increase in proximity to freshwater discharge from the Pearl River. However, $\delta^{13}\text{C}$ values increased from -28.2‰ to -25.8‰ across the transition at 1670 cal a BP in core ZK19, indicating decreasing freshwater discharge or impact from anthropogenic factors. A reduction of freshwater discharge at this time is consistent with multiple records across the region that indicated a weakening monsoon from 3300 cal a BP to

present. Near Lantau Island, the increase of $\delta^{13}\text{C}$ values and diatom assemblages with decreasing salinity preference in core V37 (Fig 1c) has been attributed to the reduction of freshwater discharge associated with a decrease in precipitation from the weakening monsoon (Zong et al., 2006). An increase of $\delta^{13}\text{C}$ values in tropical Lake Huguangyan in Zhanjiang and stalagmite records from the Dongge Cave in southern China also demonstrate that the Asian monsoon declined during the last 3300 years (Fig 1a; Fig 7f, g, h; Dong et al., 2010; Wang, 2005).

Between ~1670 cal a BP to present, foraminiferal assemblages indicated a lateral development of shoal-channels in the submerged delta, reflecting continuing delta progradation. From ~1670 to 550 cal a BP, high proportions of *Quinqueloculina akeriana* are associated with subtidal channel development. An assemblage typical of a middle estuarine environment appeared from 550 cal a BP to present. Shoreline advance accelerated in the last 2000 years (Wei and Wu, 2011; Wei et al., 2016; Zong et al., 2012; Zong et al., 2013a). The encroaching shoreline (possibly causing the west river channel avulsion that directly discharged into Lingding Bay) and the increase of Pearl River sediment load flux resulting from intensive reclamation of land and deforestation accelerated the deltaic progradation, together likely contributed to a doubling of sedimentation rate from 0.21 cm/a to 0.42 cm/a in Lingding Bay during this time (Fig 2c). The increase in anthropogenic influence in core ZK19 can also be observed in the increase in $\delta^{13}\text{C}$ values (-26.5‰ to -21.4‰) from ~2000 cal a BP to

present (Fig 7e) due to a change in composition of the terrestrial material delivered to the Pearl River Delta. A similar change in $\delta^{13}\text{C}$ values has been observed in core HK-UV1 (Fig 7f); paired leaf wax $\delta^{13}\text{C}$ analysis, which reflects changes in the source of terrestrial organic matter rather than relative inputs of marine and terrestrial organic matter, indicated the shift in $\delta^{13}\text{C}$ values is due to an increase in C_4 terrestrial vegetation contribution (Strong et al., 2013).

These terrestrial vegetation changes likely resulted from local, anthropogenic cultivation ~2000 years ago (Strong et al., 2013; Zong et al., 2010a, 2013a). Agricultural activity developed ~4000 - 3000 cal a BP in the Pearl River Delta region with the transition from hunting-gathering to wet rice farming (Zheng et al., 2004; Zheng et al., 2009). Agricultural activity further increased during the Han Dynasty (220 BC - 206 AD; 2170 - 1950 cal a BP) when advanced cultivation techniques were introduced from north China (Zong et al., 2009a, 2010a, 2013a). The increase of charcoal in mountainous peat cores in southern subtropical China at ~2000 cal a BP provides evidence for significant deforestation and biomass burning that may be associated with enhanced agriculture and population growth (Ma et al., 2016). Secondary grasses (e.g., *Dicranopteris*, *Poaceae*), which developed subsequently after deforestation and also covered the newly formed delta plain, and agricultural crops (e.g., sugarcane) all have high proportions of C_4 plants (Strong et al., 2013; Yu et al., 2010); therefore, the terrestrial organic matter transported to the estuary had much higher $\delta^{13}\text{C}$

values. This scenario is also supported by pollen records that show increasing proportions of *Poaceae*, *Cyperaceae* and *Dicranopteris* in the last 2000 years (Peng et al., 2015; Wang et al., 2009; Huang et al., 2016; Zheng et al., 2004) and a synchronous increase of heavy metal elements Pb, Fe and Cu introduced by the use of metal tools in agricultural activity (Waxi et al., 2016; Zong et al., 2010a).

Conclusion

The sediment core ZK19 provided a high resolution early and late Holocene paleoenvironmental record from a paleo-incised valley in Lingding Bay. The lithology and geochemistry and the absence of foraminifera suggested a fluvial environment from approximately 11300 to 10800 cal a BP. Rapid sea-level rise contributed to marine transgression of Lingding Bay from a fluvial to an estuarine environment from 10800 to 10500 cal a BP. From 10500 to 8100 cal a BP, foraminiferal assemblages in the core indicated increasing marine influence as the sedimentary environment evolved from an inner estuary to middle estuary. However, $\delta^{13}\text{C}$ and C/N values of sediments within the core indicated greater delivery of terrestrial material from freshwater discharge, which implied an enhanced monsoon with high precipitation. A sedimentary hiatus was observed in the core from 8100 to 3300 cal a BP, likely due to subaqueous erosion resulting from the local geomorphology of the Pearl River Delta. In the late Holocene (3300 cal a BP to present), the foraminiferal assemblages revealed a change in sedimentary facies from outer estuary to middle estuary due to continued deltaic progradation under stable relative sea levels. During this time, an increase in $\delta^{13}\text{C}$ and

decrease in C/N values suggested a weakening monsoon, although in the last 2000 years, the early development of agriculture likely introduced a higher proportion of C₄ plants that contributed to the increase in $\delta^{13}\text{C}$ values. Our study extended the record of the paleoenvironmental response of the Pearl River estuary to sea level and climatic changes to the early Holocene, a period characterized by more extreme rates of sea-level rise and enhanced Asian monsoon in comparison with the rest of the Holocene, and contributes to the understanding of how climatic and anthropogenic changes influenced the evolution of Pearl River Delta.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grants NO. 41276079). Professor Huang Kangyou was thanked for his assistance in improving the English. This work was supported by the following grants: the National Natural Science Foundation of China (NSFC: 41661144003). NSK and BPH were funded by the Singapore Ministry of Education Academic Research Fund MOE2018-T2-1-030, the National Research Foundation Singapore, and the Singapore Ministry of Education, under the Research Centres of Excellence initiative. This article is a contribution to PALSEA2 (Palaeo-Constraints on Sea-Level Rise) and International Geoscience Program (IGCP) Project 639, “Sea Level Change from Minutes to Millennia”. This work is Earth Observatory of Singapore contribution 243.

References:

- 623 1. Alberti, M., Hethke, M., Fürsich, F.T., Liu, C.L., 2013. Macro- versus microfauna:
624 resolution potential of bivalves, gastropods, foraminifera and ostracods in reconstructing
625 the Holocene palaeoenvironmental evolution of the Pearl River delta, China. *Palaeobio*
626 *Palaeoenv.* 93, 327-353.
- 627 2. Atahan, P., Itzstein-Davey, F., Taylor, D., Dodson, J., Qin, J., Zheng, H., Brooks, A., 2008.
628 Holocene-aged sedimentary records of environmental changes and early agriculture in the
629 lower Yangtze, China. *Quat. Sci. Rev.* 27, 556-570.
- 630 3. Barnett, R.L., Bernatchez, P., Garneau, M., Juneau, M.N., 2017. Reconstructing late
631 Holocene relative sea-level changes at the Magdalen Islands (Gulf of St. Lawrence,
632 Canada) using multi-proxy analyses. *J. Quat. Sci.* 32, 380-395.
- 633 4. Bianchi, T.S., Canuel, E.A., 2011. *Chemical Biomarkers in Aquatic Ecosystems*. Princeton
634 University Press. Chapter 3.
- 635 5. Brodie, C.R., Casford, J.S.L., Lloyd, J.M., Leng, M.J., Heaton, T.H.E., Kendrick, C.P.,
636 Zong, Y., 2011. Evidence for bias in C/N, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of bulk organic matter,
637 and on environmental interpretation, from a lake sedimentary sequence by pre-analysis
638 acid treatment methods. *Quat. Sci. Rev.* 30, 3076-3087.
- 639 6. Buzas-Stephens, P., Livsey, D.N., Simms, A.R., Buzas, M.A., 2014. Estuarine
640 foraminifera record Holocene stratigraphic changes and Holocene climate changes in
641 ENSO and the North American monsoon: Baffin Bay, Texas. *Palaeogeogr. Palaeoclimatol.*
642 *Palaeoecol.* 404, 44-56.
- 643 7. Chen, X.S., Bao L.Y., Chen, J.R., Zhao, X.T., 1990. Discovery of lowest sea level in late
644 Quaternary at the continental shelf off Pearl River mouth. *Journal of Tropical*
645 *Oceanography.* 9, 74-77 (in Chinese, with English abstract).
- 646 8. Cloern, J.E., 2002. Stable Carbon and Nitrogen Isotope Composition of Aquatic and
647 Terrestrial Plants of the San Francisco Bay Estuarine System. *Limnology & Oceanography*
648 47, 713-729.
- 649 9. Coffin, R.B., Fry, B., Peterson, B.J., Wright, R.T., 1989. Carbon isotopic compositions of
650 estuarine bacteria. *Limnology & Oceanography* 34, 1305-1310.
- 651 10. Craven, K.F., Edwards, R.J., Goodhue, R., Rocha, C., 2013. Evaluating the influence of
652 selected acid pre-treatment methods on c/n and $\delta^{13}\text{C}$ of temperate inter-tidal sediments for
653 relative sea level reconstruction. *Irish Journal of Earth Sciences.* 31, 25-42.
- 654 11. Da Cruz Miranda, M.C., De Fátima Rossetti, D., Carlos Ruiz Pessenda, L., 2009.
655 Quaternary paleoenvironments and relative sea-level changes in Marajó Island (Northern
656 Brazil): Facies, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C/N. *Palaeogeography, Palaeoclimatology,*
657 *Palaeoecology* 282, 19-31.
- 658 12. Di Rita, F., Simone, O., Caldara, M., Gehrels, W.R., Magri, D., 2011. Holocene
659 environmental changes in the coastal Tavoliere Plain (Apulia, southern Italy): A
660 multiproxy approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 310, 139-151.
- 661 13. Dong, L., Su, J., Wong, L., Cao, Z., Chen, J., 2004. Seasonal variation and dynamics of
662 the Pearl River plume. *Cont Shelf Res.* 24, 1761-1777.

14. Dong, J.G., Wang, Y.J., Cheng, H., Hardt, B., Edwards, R.L., Kong, X.G., Wu, J.Y., Chen, S.T., Liu, D.B., Jiang, X.Y., Zhao, K., 2010. A high-resolution stalagmite record of the Holocene East Asian monsoon from Mt Shennongjia, central China. *Holocene*. 20, 257-264.
15. Dong, Y.X., Liu, C.L., Yin, J.R., Yang, X.Q., Fürsich, F.T., Gao, F.L., 2007. Late Quaternary microfaunas and paleoenvironmental changes recorded in core sediment of the Pearl River Delta, South China. *Vertebrata Palasiatica*. 45, 161-172. (in Chinese, with English abstract)
16. Dykoski, C.A., Edwards, R.L., Cheng, H., Yuan, D., Cai, Y., Zhang, M., Lin, Y., Qing, J., An, Z., Revenaugh, J., 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. *Earth & Planetary Science Letters*. 233, 71-86.
17. Ember, L.M., Williams, D.F., Morris, J.T., 1987. Processes that influence carbon isotope variations in salt marsh sediments. *Mar. Ecol. Prog* 36, 33-42.
18. Fyfe, J.A., Selby, I.C., Shaw, R., James, J.W.C., Evans, C.D.R., 1997. Quaternary sea-level change on the continental shelf of Hong Kong. *J. Geol. Soc. London*. 154, 1031-1038.
19. Garrett, E., 2010. The contemporary distribution of benthic foraminifera in the Pearl River estuary, southeast China, and their use in reconstructing mid-to late-Holocene fluvial flux. Master's Thesis, Durham University.
20. Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Comput. Geosci* 13, 13-35.
21. Goldstein, S.T., Watkins, G.T., 1999. Taphonomy of salt marsh foraminifera: an example from coastal Georgia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 149, 103-114.
22. Haslett, J., Parnell, A., 2008. A Simple Monotone Process with Application to Radiocarbon-Dated Depth Chronologies. *Journal of the Royal Statistical Society* 57, 399-418.
23. Horton, B., Edwards, R., 2006. Quantifying Holocene Sea Level Change Using Intertidal Foraminifera: Lessons from the British Isles. Philadelphia University. Cushman Foundation for Foraminiferal Research, Special Publication, Volume 40, 2006, 97pp.
24. Hu, J., Peng, P., Jia, G., Mai, B., Zhang, G., 2006. Distribution and sources of organic carbon, nitrogen and their isotopes in sediments of the subtropical Pearl River estuary and adjacent shelf, Southern China. *Mar. Chem.* 98, 274-285.
25. Huang, Z.G., Li, P.R., Zhang, Z.Y., Li, K.H., Qiao, P.N., 1982. Zhujiang (Pearl) Delta. General Scientific Press, Guangzhou, p. 274 (in Chinese).
26. Huang, Z.G., Xu, Q.H., 1995. On the lowest sea level during the culmination of the latest glacial period in South China. *Acta Geogr. Sin.* 50, 385-393 (in Chinese, with English abstract).
27. Huang, K., Jiahui, H.E., Zong, Y., Zheng, Z., Zhang, G., Cao, L., 2016. Holocene Paleoenvironment Reconstruction Based on Pollen Data in the Sanshui Basin, Northern Pearl River Delta. *Tropical Geography* (in Chinese, with English abstract).
28. Jia, G., Bai, Y., Yang, X., Xie, L., Wei, G., Ouyang, T., Chu, G., Liu, Z., Peng, P., 2015. Biogeochemical evidence of Holocene East Asian summer and winter monsoon variability

- from a tropical maar lake in southern China. *Quat. Sci. Rev.* 111, 51-61.
29. Kemp, A.C., Horton, B.P., Donnelly, J.P., Mann, M.E., Vermeer, M., Rahmstorf, S., 2011. Climate related sea-level variations over the past two millennia. *Proc Natl Acad Sci USA* 108, 11017-11022.
 30. Kemp, A.C., Horton, B.P., Nikitina, D., Vane, C.H., Potapova, M., Weber Bruya, E., Culver, S.J., Repkina, T., Hill, D.F., 2017. The distribution and utility of sea-level indicators in Eurasian sub-Arctic salt marshes (White Sea, Russia). *Boreas*. 46,562-584.
 31. Khan, N.S., Vane, C.H., Horton, B.P., Hillier, C., Riding, J.B., Kendrick, C.P., 2015. The application of $\delta^{13}\text{C}$, TOC and C/N geochemistry to reconstruct Holocene relative sea levels and paleoenvironments in the Thames Estuary, UK. *J. Quat. Sci.* 30, 417-433.
 32. Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}\text{C}$ and C/N ratios in organic material. *Earth-Science Rev.* 75, 29-57.
 33. Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proc Natl Acad Sci USA* 111, 15296-15303.
 34. Leorri, E., Martin, R., McLaughlin, P., 2006. Holocene environmental and parasequence development of the St. Jones Estuary, Delaware (USA): Foraminiferal proxies of natural climatic and anthropogenic change. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 241, 590-607.
 35. Li, S.L., 1985. Distribution of the foraminiferal thanatocoenosis of Pearl River estuary. *Marine Geology and Quaternary Geology*. 5, 83-104 (in Chinese, with English abstract).
 36. Li, P., Qiao, P., Zheng, H., Fang, G., Huang, G., 1990. The Environmental Evolution of the Pearl River Delta in the Last 10,000 years. China Ocean Press, Beijing. (in Chinese).
 37. Li, T., Xiang, R., Li, T.J., 2011. Benthic foraminiferal distribution in surface sediments of zhujiang estuary and its environmental implications. *Marine Geology and Quaternary Geology*. 31, 91-98 (in Chinese, with English abstract).
 38. Liu, J.P., Milliman, J.D., Gao, S., Cheng, P., 2004. Holocene development of the Yellow River's subaqueous delta, North Yellow Sea. *Mar Geol.* 209, 45-67.
 39. Liu, C.L, Franz, T.F.R., Dong. Y.X., Che, X.G., Chen, L., Zhuang, C., 2008. High resolution ostracod records of borehole PRD05 and the Late Quaternary palaeoenvironment in Pearl River Delta. *Journal of Palaeogeography*. 10, 313-322 (in Chinese, with English abstract).
 40. Liu, Y., Gao, S., Wang, Y.P., Yang, Y., Long, J., Zhang, Y., Wu, X., 2014. Distal mud deposits associated with the Pearl River over the northwestern continental shelf of the South China Sea. *Mar. Geol.* 347, 43-57.
 41. Luo, X.L, Li, C.C, Mou, C.J., 2001. Difference in environmental explanation from analysis of living and dead foraminifera in the Lingdingyang estuary. *Acta Oceanol. Sinica*. 23, 69-75 (in Chinese, with English abstract).
 42. Mackie, E.A.V., Lloyd, J.M., Leng, M.J., Bentley, M.J., Arrowsmith, C., 2007. Assessment of $\delta^{13}\text{C}$ and C/N ratios in bulk organic matter as palaeosalinity indicators in Holocene and Lateglacial isolation basin sediments, northwest Scotland. *J. Quat. Sci.* 22,

- 747 579-591.
- 748 43. Mao, Q.W., Shi, P., Yin, K.D., Gan, J. P., Qi, Y.q., 2004. Tides and tidal currents in the
749 Pearl River Estuary. *Cont. Shelf. Res.*, 24(16), 1797-1808.
- 750 44. Ma T., Zheng, Z., Man, M.L., Li J., Peng, H.H., Han, A.Y., Huang, K.Y., 2016. Holocene
751 Fire History in Relation to Climate Changes and Human Activities in Southern Subtropical
752 China. *Tropical Geography*. 36, 486-494 (in Chinese, with English abstract).
- 753 45. Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of
754 sedimentary organic matter. *Chem. Geol.* 144, 289-302.
- 755 46. McGann, M., 2008. High-Resolution Foraminiferal, Isotopic, and Trace Element Records
756 from Holocene Estuarine Deposits of San Francisco Bay, California. *J. Coast. Res.* 24,
757 1092-1109.
- 758 47. Middelburg, J.J., Nieuwenhuize, J., 1998. Carbon and nitrogen stable isotopes in
759 suspended matter and sediments from the Schelde Estuary. *Mar. Chem.* 60, 217-225.
- 760 48. Murray, J.W., 1991. Ecology and Palaeoecology of Benthic Foraminifera. *Journal of the*
761 *Marine Biological Association of the United Kingdom*. 71, 1-916.
- 762 49. Oldfield, F., Asioli, A., Accorsi, C.A., Mercuri, A.M., Juggins, S., Langone, L., Rolph, T.,
763 Trincardi, F., Wolff, G., Gibbs, Z., 2003. A high resolution late Holocene palaeo
764 environmental record from the central Adriatic Sea. *Quat. Sci. Rev.* 22, 319-342.
- 765 50. Owen, R.B., Lee, R., 2004. Human impacts on organic matter sedimentation in a proximal
766 shelf setting, Hong Kong. *Cont. Shelf. Res.* 24, 583-602.
- 767 51. Owen, R.B., 2005. Modern fine-grained sedimentation—spatial variability and
768 environmental controls on an inner pericontinental shelf, Hong Kong. *Mar. Geol.* 214, 1-
769 26.
- 770 52. Parnell, A.C., Haslett, J., Allen, J.R.M., Buck, C.E., Huntley, B., 2008. A flexible approach
771 to assessing synchronicity of past events using Bayesian reconstructions of sedimentation
772 history. *Quaternary. Sci. Rev.* 27, 1872-1885.
- 773 53. Peng, H.H., Zheng, Z., Zheng, Y.W., Huang, K.Y., Wei, J.H., 2015. Holocene vegetation
774 changes and human activities revealed by a peat sediment core in Gaoyao, Zhaoqing.
775 *Quaternary Sciences*. 35, 742-754 (in Chinese, with English abstract).
- 776 54. Pilarczyk, J.E., Dura, T., Horton, B.P., Engelhart, S.E., Kemp, A.C., Sawai, Y., 2014.
777 Microfossils from coastal environments as indicators of paleo-earthquakes, tsunamis and
778 storms. *Palaeogeogr. Palaeocl.* 413, 144-157.
- 779 55. Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E.,
780 Cheng, H., Edwards, R.L., Friedrich, M., 2013. IntCal13 and Marine13 Radiocarbon Age
781 Calibration Curves 0-50,000 Years cal BP. *Radiocarbon*. 55, 1869-1887.
- 782 56. Rice, D.L., Hanson, R.B., 1984. A Kinetic Model for Detritus Nitrogen: Role of the
783 Associated Bacteria in Nitrogen Accumulation. *B Mar Sci.* 35, 326-340.
- 784 57. Rolett, B.V., Zheng, Z., Yue, Y., 2011. Holocene sea-level change and the emergence of
785 Neolithic seafaring in the Fuzhou Basin (Fujian, China). *Quat. Sci. Rev.* 30, 788-797.
- 786 58. Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., Spezzaferri, S., 2012. The
787 FOBIMO (FORaminiferal BIO-MONitoring) initiative—Towards a standardised protocol
788 for soft-bottom benthic foraminiferal monitoring studies. *MAR MICROPALAEONTOLOGY* 94-

- 789 95, 1-13.
- 790 59. Schlacher, T.A., Connolly, R.M., 2014. Effects of acid treatment on carbon and nitrogen
791 stable isotope ratios in ecological samples: a review and synthesis. *Methods. Ecol. Evol.*
792 5, 541-550.
- 793 60. Sen, A., Bhadury, P., 2017. Intertidal foraminifera and stable isotope geochemistry from
794 world's largest mangrove, Sundarbans: Assessing a multiproxy approach for studying
795 changes in sea-level. *Estuarine. Coast. Shelf .Sci.* 192, 128-136.
- 796 61. Sheng, M., Wang, X., Zhang, S., Chu, G., Su, Y., Yang, Z., 2017. A 20,000-year high-
797 resolution pollen record from Huguangyan Maar Lake in tropical–subtropical South China.
798 *Palaeogeogr. Palaeocl.* 472, 83-92.
- 799 62. Shepard, F., 1954. Nomenclature based on sand-silt-clay ratios. *Jour. sediment. petrol* 24,
800 151-158.
- 801 63. Shi C., Gan H. Y., Ma S. Z., Xia Z., Lin J. Q. Late Quaternary evolution and sequence
802 stratigraphy of the Lingdingyang Estuary in South China. 2015. *Marine Geology Frontiers.*
803 31, 8-18. (in Chinese, with English abstract)
- 804 64. Southon, J., Kshgarian, M., Fontugne, M., Metibier, B., Yim, W.W.-S., 2002. Marine
805 reservoir corrections for the Indian Ocean and Southeast Asia. *Radiocarbon* 44, 167-180.
- 806 65. Strong, D., Flecker, R., Valdes, P.J., Wilkinson, I.P., Rees, J.G., Michaelides, K., Zong,
807 Y.Q., Lloyd, J.M., Yu, F.L., Pancost, R.D., 2013. A new regional, mid-Holocene
808 palaeoprecipitation signal of the Asian Summer Monsoon. *Quat. Sci. Rev.* 78, 65-76.
- 809 66. Stuiver, M., Reimer, P.J., and Reimer, R.W., 2018, CALIB 7.1 [WWW program] at
810 <http://calib.org>, accessed 2018-7-20
- 811 67. Tang, C., Zhou, D., Endler, R., Lin, J.Q., Harff, J., 2010. Sedimentary development of the
812 Pearl River Estuary based on seismic stratigraphy. *J. Mar. Syst.* 82, S3-S16.
- 813 68. Waxi, L.L., Wang, J.H., Chen H.X., Wu J.X., Tao, H., 2016. Major and trace elements
814 geochemistry and paleoenvironmental implications of borehole ZK19 in the Lingdingyang
815 bay of the Pearl River estuary. *Tropical Geography.* 36, 343-354 (in Chinese, with English
816 abstract).
- 817 69. Wang, P.X., Zhang, J.J., Zhao, Q.H., Min, Q.B., Bian, Y.H., Zheng, L.L., Cheng, X.R.,
818 Chen, R.H., 1988. Foraminifera and Ostracoda in bottom sediments of the East China Sea.
819 Ocean Press, Peking, pp 339-402 (in Chinese).
- 820 70. Wang, P.X., Chappell, J., 2001. Foraminifera as Holocene environmental indicators in the
821 South Alligator River, Northern Australia. *Quat. Int.* 83-85, 47-62.
- 822 71. Wang W.J., 2004. Probe into the traces of buried ancient valley in the Pearl River Estuary.
823 *Pearl River.* 4, 4-6. (in Chinese, with English abstract)
- 824 72. Wang, Y., Cheng, H., Edwards, R.L., He, Y.Q., Kong, X.G., An, Z.S., Wu, J.Y., Kelly,
825 M.J., Dykoski, C.A., Li, X.D., 2005. The Holocene Asian Monsoon: Links to Solar
826 Changes and North Atlantic Climate. *Science.* 308, 854-857.
- 827 73. Wang, S.Y., Houyuan, L., Liu, J.Q., Negendank, J.F.W., 2007. The early Holocene
828 optimum inferred from a high-resolution pollen record of Huguangyan Maar Lake in
829 southern China. *Chin. Sci. Bull.* 52, 2829-2836.
- 830 74. Wang, J.H., Wang, X.J., Cao, L.L., Zheng, Z., Yang, X.Q., Yang, J., 2009. The Holocene

- sporopollen characteristics and their paleoenvironmental significance of Core GZ- 2 in Pearl River Delta. *Journal of Palaeogeography*. 6, 661-669 (in Chinese, with English abstract).
75. Wang, Z., Zhuang, C., Saito, Y., Chen, J., 2012. Early mid-Holocene sea-level change and coastal environmental response on the southern Yangtze delta plain, China: implications for the rise of Neolithic culture. *Quat. Sci. Rev.* 35, 51-62.
 76. Weckström, K., Saunders, K.M., Gell, P.A., Skilbeck, C.G., 2017. *Applications of Paleoenvironmental Techniques in Estuarine Studies*. Springer Netherlands.
 77. Wei Xing, 2010. A study of the Holocene sedimentary evolution pattern of the Zhujiang River Delta. Doctoral's Thesis, Sun Yat-Sen University. P 132-135.
 78. Wei, X., Wu, C.Y., 2011. Holocene delta evolution and sequence stratigraphy of the Pearl River Delta in South China. *Sci China Earth Sci.* 54, 1523-1541.
 79. Wei, X., Mo W.Y., Wu C.Y., 2011. Analysis on the Sedimentation Rates and Depositional Environment of the Pearl River Delta Area since Holocene. *Acta Sedimentologica Sinica* 29, 328-335. (in Chinese with English abstract)
 80. Wei, X., Wu, C., Ni, P., Mo, W., 2016. Holocene delta evolution and sediment flux of the Pearl River, southern China. *J. Quat. Sci.* 31, 484-494.
 81. Wentworth, C.K., 1922. A Scale of Grade and Class Terms for Clastic Sediments. *J Geol.* 30, 377-392.
 82. Wilson, G.P., Lamb, A.L., Leng, M.J., Gonzalez, S., Huddart, D., 2005. $\delta^{13}\text{C}$ and C/N as potential coastal palaeoenvironmental indicators in the Mersey Estuary, UK. *Quat. Sci. Rev.* 24, 2015-2029.
 83. Wu, C.Y., Wei, X., Ren, J., Bao, Y., He, Z.G., Lei, Y.P., Shi, H.Y., Zhang, W.Y., 2010. Morphodynamics of the rock-bound outlets of the Pearl River estuary, South China -- A preliminary study. *J. Mar. Syst.* 82, S17-S27.
 84. Wu, J., Liu, C.L., Fürsich, F.T., Yang, T.T., Yin, J., 2015. Foraminifera as environmental indicators and quantitative salinity reconstructions in the Pearl River estuary, South China. *J. Foraminifer. Res.* 45, 205-219.
 85. Wu, M.S., Zong, Y., Mok, K.M., Cheung, K.M., Xiong, H., Huang, G., 2017. Holocene hydrological and sea surface temperature changes in northern coast of the South China Sea. *J. Asian Earth. Sci.* 135, 268-280.
 86. Xiong, H., Zong, Y., Qian, P., Huang, G., Fu, S., 2018a. Holocene sea-level history of the northern coast of South China Sea. *Quat. Sci. Rev.* 194, 12-26.
 87. Xiong, H., Zong, Y., Huang, G., Fu, S., 2018b. Sedimentary responses to Holocene sea-level change in a shallow marine environment of southern China. *J ASIAN EARTH SCI* 166, 95-106
 88. Yang, S., Tang, M., Yim, W.S., Zong, Y., Huang, G., Switzer, A.D., Saito, Y., 2011. Burial of organic carbon in Holocene sediments of the Zhujiang (Pearl River) and Changjiang (Yangtze River) estuaries. *Mar. Chem.* 123, 1-10.
 89. Yim, W. W. S., Huang, G., Fontugne, M.R., Hale, R.E., Paterne, M., Pirazzoli, P.A., Ridley Thomas, W.N., 2006. Postglacial sea-level changes in the northern South China Sea continental shelf: Evidence for a post-8200 calendar yr BP meltwater pulse. *Quat. Int.*

- 873 145-146, 55-67.
- 874 90. Yu, F.L., Zong, Y.Q., Lloyd, J.M., Huang, G.Q., Leng, M.J., Kendrick, C., Lamb, A.L.,
875 Yim, W.W.S., 2010. Bulk organic $\delta^{13}\text{C}$ and C/N as indicators for sediment sources in the
876 Pearl River delta and estuary, southern China. *Estuarine. Coast. Shelf. Sci.* 87, 618-630.
- 877 91. Yu, F.L., Zong, Y.Q., Lloyd, J.M., Leng, M.J., Switzer, A.D., Yim, W.W.S., Huang, G.Q.,
878 2012. Mid-Holocene variability of the East Asian monsoon based on bulk organic $\delta^{13}\text{C}$
879 and C/N records from the Pearl River estuary, southern China. *Holocene.* 22, 705-715.
- 880 92. Zhao, H.T., 1989. Hydrological and sedimentary characteristics of the Pearl River
881 Estuary. *Tropical Geography.* 9, 201-212. (in Chinese, with English abstract)
- 882 93. Zhan, Q., Wang, Z.H., Xie, Y., Xie, J.L., He, Z.F., 2012. Assessing C/N and $\delta^{13}\text{C}$ as
883 indicators of Holocene sea level and freshwater discharge changes in the subaqueous
884 Yangtze delta, China. *Holocene.* 22, 697-704.
- 885 94. Zhang, S., Lu, X.X., Higgitt, D.L., Chen, C.A., Han, J., Sun, H., 2008. Recent changes of
886 water discharge and sediment load in the Zhujiang (Pearl River) Basin, China. *Global*
887 *planet change.* 60, 365-380.
- 888 95. Zhang, W., Zheng, J., Ji, X., Hoitink, A.J.F., Vegt, M.V.D., Zhu, Y., 2013. Surficial
889 sediment distribution and the associated net sediment transport pattern in the Pearl River
890 Estuary, South China. *Cont. Shelf. Res.* 62, 41-51.
- 891 96. Zheng, Z., Deng, Y., Zhang, H., Yu, R., Chen, Z., 2004. Holocene environmental changes
892 in the tropical and subtropical areas of the south China and the relation to human activities.
893 *Quat. Sci.* 24, 387-393.
- 894 97. Zheng Z., Huang K.Y., Wei J.H., Tan H.Z., Xiao Y.T., Bi L.S., 2009. The relationship
895 between environmental changes and human activities since Neolithic age in Pearl River
896 Delta. The 10th National Congress of Palaeontological Society of China. Nanjing, Jiangsu,
897 China, 266-267.
- 898 98. Zhou, W., Yu, X., Timothy, J.A.J., Burr, G., Xiao, J.Y., Lu, X., Feng, X., 2004. High-
899 resolution evidence from southern China of an early holocene optimum and a mid-
900 Holocene dry event during the Past 18,000 Years. *Quaternary Res.* 62, 39-48.
- 901 99. Zhuang, C., Liu, C.L., Wu, J., Yang, T.T., Yin, J., 2013. Microfossil records of Borehole
902 PRD16 and palaeoenvironment since the late Pleistocene in the Pearl River Delta. *Acta*
903 *Sci. Nat. Univ. Sunyatseni.* 52, 128-132 (in Chinese, with English abstract).
- 904 100. Zong, Y.Q., 2004. Mid-Holocene sea-level highstand along the Southeast Coast of China.
905 *Quat. Int.* 117, 55-67.
- 906 101. Zong, Y.Q., Lloyd, J.M., Leng, M.J., Yim, W.W.S., Huang, G.Q., 2006. Reconstruction
907 of Holocene monsoon history from the Pearl River Estuary, southern China, using diatoms
908 and carbon isotope ratios. *Holocene.* 16, 251-263.
- 909 102. Zong, Y.Q., Huang, G.Q., Switzer, A.D., Yu, F.L., Yim, W.W.S., 2009a. An evolutionary
910 model for the Holocene formation of the Pearl River delta, China. *Holocene.* 19, 129-142.
- 911 103. Zong, Y.Q., Yim, W.W.S., Yu, F.L., Huang, G.Q., 2009b. Late Quaternary environmental
912 changes in the Pearl River mouth region, China. *Quat. Int.* 206, 35-45.
- 913 104. Zong, Y.Q., Yu, F.L., Huang, G.Q., Lloyd, J.M., Yim, W.W.S., 2010a. Sedimentary
914 evidence of Late Holocene human activity in the Pearl River delta, China. *Earth Surf.*

915 Process. Landf. 35, 1095-1102.

916 105. Zong, Y., Yu, F., Huang, G., Lloyd, J.M., Yim, W.W.S., 2010b. The history of water

917 salinity in the Pearl River estuary, China, during the Late Quaternary. Earth. Surf. Proc.

918 Land. 35, 1221-1233.

919 106. Zong, Y.Q., Huang, K.Y., Yu, F.L., Zheng, Z., Switzer, A.D., Huang, G.Q., Wang, N.,

920 Tang, M., 2012. The role of sea-level rise, monsoonal discharge and the palaeo-landscape

921 in the early Holocene evolution of the Pearl River delta, southern China. Quat. Sci. Rev.

922 54, 77-88.

923 107. Zong, Y.Q., Zheng, Z., Huang, K.Y., Sun, Y.Y., Wang, N., Tang, M., Huang, G.Q., 2013a.

924 Changes in sea level, water salinity and wetland habitat linked to the late agricultural

925 development in the Pearl River delta plain of China. Quat. Sci. Rev. 70, 145-157.

926 108. Zong, Y., 2013b. SEA-LEVELS, LATE QUATERNARY | Late Quaternary Relative Sea-

927 Level Changes in the Tropics. Encyclopedia of Quaternary Science. 4, 495-502.

928

Tables

Table 1 Summary information of Accelerator Mass Spectrometry (AMS) ^{14}C dating of core ZK19.

All dates are calibrated to calendar years before present (cal yr BP relative to 1950 AD) using program CALIB v. 7.1 with the calibration dataset INTCAL13 for plant fragment and Marine13 for shells (Reimer et al., 2013). TP: small (<1 cm) dense of plant fragment; SI: single, large (3 cm) intact mollusk shell (*Bursa rana*); SL: single, large (3 cm) broken mollusk shell; SS: small intact (1 - 2 cm) mollusk shells.

Sample ID	Laboratory code	Depth (m)	Material	Material matrix	$\delta^{13}\text{C}$ (‰)	^{14}C Age (a)	Calibrated age (cal a BP)
19-C02	Beta-378385	3.0	TP	plant frag.	-31.3	440±30	496±36
19-C04	Beta-378386	4.8	SI	gastropods	-0.9	810±30	551±78
19-C06	Beta-378387	7.1	SS	shell	-1.4	1380±30	1056±121
19-C08	Beta-378388	11.0	SS	shell	-5.9	2200±30	1954 ±133
19-C09	Beta-378389	13.1	SS	shell	+1.0	2910±30	2823±105
19-C11	Beta-378390	16.0	SL	shell	-1.8	2440±30	*2226±118
19-CB01	Beta-383041	17.0	SS	shell	-2.6	7620±30	8126±123
19-CB02	Beta - 383042	19.0	SS	shell	-7.9	8640±30	*9421±101
19-C13	Beta-378391	20.1	TP	plant frag.	-30.3	7990±30	8874±124
19-C14	Beta-378392	23.0	TP	plant frag.	-28.9	8410±40	9459±63
19-C19	Beta-378394	30.4	SS	shell	-12.2	9470±30	10474±103
19-C22	Beta-378395	34.6	SS	shell	-8.8	9700±30	10775±139

* outlier dates

Table 2 Summary of the foraminiferal species' preference to the modern estuarine environment.

Four estuarine zones are divided: 1. inner estuary; 2. middle estuary; 3. outer estuary environments; 4. shallow marine environment. The different gray scale of circle represent different proportion of the species in the assemblage: ● >50%, ● 20-40%, ○ 10-20%, ○ 5-10%.

[illegible]

Fig 1 (a) The location of the Pearl River estuary and its drainage basin in southern China. Published records of Asian monsoon variability derived from stalagmites from Dongge cave (purple triangle) (Dykoski et al., 2005) and biogeochemical proxy from Huguangyan Lake (green triangle) (Jia et al., 2015). (b) Location of the paleo- (darker blue) and modern (lighter blue) Pearl River estuary. The paleo-estuarine extent at ~6800 cal a BP is shown, when the rise in sea level stabilized and the shoreline retreated to its landward-most position. The location of paleo-valleys (dotted lines) are shown (revised after Zong et al., 2009a). (c) The modern Pearl River estuary, divided into the four deltaic facies zones defined by Fyfe et al. (1997): 1) inner estuary, 2) middle estuary, 3) outer estuary, and 4) shallow marine. The locations of sediment core ZK19 (this study), published Asian monsoon proxy records from sediment core HK-UV1 (Strong et al., 2013), and previous stratigraphic analyses from cores V37, BVC, HK-UV11, (Zong et al., 2006; 2009b; Wu, 2017) (orange triangle). (d) Salinity distribution in the Pearl River estuary during the dry season and (e) the wet season bottom water (Dong et al., 2004).

Fig 2 (a) Lithology and stratigraphic division (7 zones) of core ZK19 with calibrated ^{14}C ages shown. Age-depth model (b) and sedimentation rates (c) generated using Bchron (Parnell et al., 2008). A hiatus is estimated between ~8160 cal a BP and 3300 cal a BP at depth of 16.4 m. The outliers of radiocarbon age are marked in red. CI: credible interval.

Fig 4 Downcore variations of sediment size fractions (%), median grain size (ϕ), organic stable carbon isotopes ($\delta^{13}\text{C}$) (‰), TOC/TN ratio, TOC (%) and TN (%) in sediment core ZK19. Calibrated radiocarbon age, zones (followed the foraminiferal zones) and interpretation of sediment source (derived by comparison with end-member values shown on the binary diagrams of Fig 5) are shown. Md: median diameter of grain size. The dark gray bar indicates the depth of the hiatus.

Fig 5 Binary diagrams of $\delta^{13}\text{C}$ and C/N showing (a) modern vegetation and surface samples from the Pearl River estuary from Yu et al. (2012) (shallow marine, pro-delta, river mouth and delta front, agricultural soil, riverbank soil, riverine, sugarcane, and C_3 and C_4 terrestrial plants; the numbers by each entry in the legend indicate the number of replicates for each group) and typical ranges end-member organic matter sources (marine and freshwater algae, particulate organic carbon (POC) and bacteria) recorded in different coastal environments after Lamb et al. (2006); (b) same as (a) with a change in axes to show the differences between Pearl River estuary organic matter sources; (c) as in (b) with early Holocene samples from zone 7 - 4 (40.8 - 16.4 m) plotted in comparison with end-member values; and (d) late Holocene samples from zone 3 - 1 (16.4 - 0 m) in comparison with end-member values.

Fig 6 Chronological comparison of (a) foraminiferal diversity, (b) foraminiferal density, (c) the sediment size fraction of silt (7 point moving average) from core ZK19 in this study with (d) the sea-level curves derived from the Pearl River delta (Xiong et al., 2018) (dark blue line); data compiled from the Bonaparte Gulf, north Australia, the Sunda Shelf, and the Strait of Malacca (Zong et al., 2013 and references therein) (orange line); and the western Pacific using brackish-marine sediment, coastal marsh peat, mangrove sea-level indicators (Liu et al., 2004 and references therein) (blue line).

Fig 7 (a) Relative changes of sea level and freshwater discharge qualitatively estimated in this study based on the relative changes of the proxies from core ZK19. Chronological comparison of the (b) foraminiferal diversity; (c) foraminiferal density; (d) total organic carbon and total nitrogen ratios; (e) organic $\delta^{13}\text{C}$ values from sediment core ZK19; (f) organic $\delta^{13}\text{C}$ value from Hong Kong UV1 core of the Pearl River estuary (the bold black line) (Yu et al., 2012) to signal Asian monsoon from the same core and a new biomarker method (Stanol(C₂₉)/(C₂₉+C₂₈ brassica-sterol) to differentiate sources of organic matter (blue circles) (Strong et al., 2013); (g) the isotopic difference between C₃₁ and C₂₉ n-alkanes in tropical-subtropical Huguangyan Maar Lake (Jia et al., 2015); and (h) the stalagmite $\delta^{18}\text{O}$ record from Dongge Cave in Southern China (dark blue) and average summer insolation for 25°N (grey blue) (Dykoski et al., 2005).

Fig 8 (a) The locations of sediment cores forming the stratigraphy transects from previous investigations. (b) Stratigraphy of core ZK19 compared to the stratigraphic transects (shown in a) along the paleo-valley from the apex to the mouth region of the Pearl River Delta showing the early Holocene infill (marine transgressive unit) and the middle-late Holocene deltaic progradation (deltaic regressive unit) proposed by Zong et al. (2012). (c) Stratigraphy across Lingding Bay, revised after Zong et al., (2009a).

Fig 9 (a) Paleo-landforms of the Pearl River estuary before 6000 years ago (revised after Wei and Wu, 2011) showing the locations of sediment cores shown in (b) exhibiting a hiatus and the location of seismic profiles shown in (c) and (d). The ebb tide flow field showing areas of high velocity (>60 m/s) (revised after Wei, 2010). (b) Age-depth models for sediment cores PRD 15, PRD18 (Wei xing, 2010), ZK3 (our unpublished core), and ZK19 (this study) with a depositional hiatus in the middle Holocene. (c, d) Seismic profiles near cores NZ2 (c) and L2 (d) indicating a tidal ravinement surface between the depths of 16 - 24 m (Tang et al., 2010). The tidal ravinement surface are marked in red shading.

Plate 1. Scale bar=100 μm . 1,2. *Ammonia beccarii* (spiral and umbilical views) 3. *Elphidium advenum* (lateral view) 4. *Quinqueloculina akeriana* (lateral view) 5. *Nonion akitaense* 6,7. *Ammonia pauciloculata* (spiral and umbilical views) 8. *Haynesina* sp. 9,10. *Ammonia tepida* (spiral and umbilical views) 11,12. *Rotalinoides annectens* (spiral and umbilical views) 13,14. *Pararotalia nipponica* (spiral and umbilical views) 15,16. *Rosalina bradyi* (spiral and umbilical views) 17,18. *Cancris auriculus* (spiral and umbilical views) 19. *Miliolinella chukchiensis* (lateral view)

Plate 2. Scale bar=100 μm . 1. *Haplophragmoides canariensis* 2. *Ammobaculides agglutinans* 3. *Protelphidium tuberculatum*. (lateral view) 4. *Miliolinella* sp. (lateral view) 5. *Miliolinella webbiana* 6,7. *Triloculina* sp. (lateral view views) 8. *Spiroloculina laevigata* (lateral view)