# Evolution of the Pearl River and its Implication for East Asian Continental Landscape Reversion

ZHANG Hao[1], CUI Yuchi[1, 2, *], QIAO Peijun[1], ZHAO Meng[3] and XIANG Xuhong[4]

[1] *State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China*
[2] *Earth Dynamics Research Group, the Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, GPO Box U1987, Australia*
[3] *Tianjin Branch of China National Offshore Oil Corporation, Tianjin 300459, China*
[4] *Shenzhen Branch of China National Offshore Oil Corporation Ltd., Shenzhen 518054, China*

**Abstract:** As the link connecting the South China Continent and the northern South China Sea (SCS), the Pearl River is the focus of sedimentology and petroleum geology research. Its evolutionary process and controlling factors are of great significance in revealing the East Asian continental landscape reorganization during the Late Cenozoic. Based on published data, 'source-to-sink' provenance analyses allow systematic deliberation on the birth and evolutionary history of the Pearl River. Close to the Oligocene/Miocene boundary, an abrupt shift in the sedimentary composition indicates significant westward and northward expansion of the river's watershed area, followed by the establishment of a near-modern fluvial network. This sedimentary change generally concurred with a series of regional geological events, including the onset of the Yangtze throughflow, large-scale development of the loess plateau, and formation of the northwestern arid zone and Asian Monsoon system. These major changes in the geology-climate-ecoenvironment system are in close response to the process of the Cenozoic Xizang (Tibetan) Plateau uplift. Consequently, the East Asian continental landscape and most of mid-Cenozoic drainage systems underwent critical reversion into east-tilting, or east-flowing networks.

**Key words:** Oligocene–Miocene, landscape reversion, source to sink provenance analyses, East Asian continental landforms, Pearl River, South China

Citation: Zhang et al., 2021. Evolution of the Pearl River and its Implication for East Asian Continental Landscape Reversion. Acta Geologica Sinica (English Edition), 95(1): 66–76. DOI: 10.1111/1755-6724.14641

## 1 Introduction

The Pearl River is one of the most important rivers along the South China continental margin. It has been transporting a large amount of sediments to the northern South China Sea (SCS) since at least the mid-Cenozoic. As a result, large-scale deltas and submarine fans of were formed throughout the Oligocene–Miocene in the Pearl River Mouth Basin (Peng et al., 2004; Pang et al., 2007; Wang et al., 2012); here many oil and gas reservoirs have been explored. Research on the evolution of the Pearl River is significant not only for systematically understanding 'source-to-sink' sedimentary processes in the SCS, but also for petroleum exploration in this region.

East Asia is known as the third pole on the planet, where the world's highest plateau and numerous fluvial systems all develop. During the Cenozoic, plate collision led to the uplift of the Xizang (Tibetan) Plateau, and East Asia experienced drastic topographic reversion from east-high–west-low to west-high–east-low. Accordingly, the development and reorganization of the river systems can directly reflect the general geomorphic evolution (e.g., Zheng et al., 2017). The Pearl River originates from the southeastern margin of the Xizang (Tibetan) Plateau, and its evolutionary process has been under direct control from the East Asian topography. Earlier research demonstrated that the Pearl River experienced stepwise evolution into its modern continental scale, in close relation to the multi-phase topographic inversion caused by the Xizang (Tibetan) uplift and SCS expansion (Wang, 2005). ODP site 1148 revealed that the northern SCS was influenced from different provenances across the Oligocene/Miocene boundary with unconformities possibly formed by regional tectonic events (Clift et al., 2002; Li et al, 2003). Increasing lines of evidence confirm that the evolution of the northern SCS provenance has been closely linked with the continental-scale fluvial networks, such as the Pearl River (Shao et al., 2015, 2017, 2019a, b; Cao et al., 2018; Zhang et al., 2020). Apparently, the coupling relationship between the Pearl River evolution and the Xizang (Tibetan) uplift is significant for restoring the East Asian topography–geomorphology evolution.

In this paper, we use published data to make 'source-to-sink' provenance analyses with the aim of systematically deliberating the birth and evolutionary history of the Pearl River.

## 2 Geological Background

The northern SCS source-to-sink system is mainly

* Corresponding author. E-mail: cuiyuchi@tongji.edu.cn

composed of the South China continent (the source) and the Pearl River Mouth Basin (the sink). The Pearl River fluvial system initiates from the southeastern margin of the Xizang (Tibetan) Plateau (XTP) and flows across the extensive South China Block (Fig. 1). In addition to shaping regional topography, Asian monsoon and river systems, the XTP has also played an important role in controlling the sedimentary transport to the northern SCS (Clark et al., 2004; Zhang et al., 2012).

### 2.1 The Pearl River fluvial network

The Pearl River fluvial network stretches across a wide complex area, and its tributaries erode significantly different types of basement parent rocks (Fig. 1). Middle and lower reaches of the Xi River drainage basin are dominated by limestones, together with Paleozoic strata of quartz sandstones and shales and sporadic granite intrusions. The Liu and Gui rivers are tributaries from the middle reaches of the Xi River, which expose mainly Paleozoic strata, but rarely erode Mesozoic strata. The upper reaches of the Xi River, with the Nanpan and Beipan river tributaries, mainly expose Proterozoic parent rocks. The lower reaches of the Pearl River, represented by the Dong and Bei rivers, run mainly across the Mesozoic orogenic uplift of widespread granite and other volcanic rocks. Sediments from different parent rocks have been transported by the Pearl River tributaries and finally deposited in the offshore Pearl River Mouth Basin. Altogether these sedimentary records contribute greatly to understanding the evolution of the Pearl River based on the use of integrated source-to-sink provenance analyses.

### 2.2 Xizang (Tibetan) Uplift

Continuous uplift of the XTP has directly affected the formation and evolution of the Pearl River since the Middle Cenozoic. Numerous studies indicate that the XTP has experienced multiple-stage uplifting processes (Clark and Royden, 2000; Tapponnier et al., 2001; Rowley and Garzione, 2007; Wang et al., 2011; Li et al., 2020). Its central and southern parts were possibly uplifted first, followed by the Himalayan area, and finally the northern (northeastern) part (Tapponnier et al., 2001; Lu and Guo, 2013).

Although there are several classification schemes (three or more stages) for the Cenozoic XTP Uplift, a systematic reconstruction of the uplifting history is still required. By using lithofacies paleogeography analysis, apatite fission track thermochronology analysis and other compiled data, Zhang et al. (2013) recognized five uplifting intervals for the XTP, including ca. 58–53 Ma, ca. 45–30 Ma, ca. 25–20 Ma, ca. 13–7 Ma and ca. 5 Ma to present. Notably, these large-scale structural uplift and denudation stages with some geological synchroneity can be observed in certain regions of the XTP (Clift et al., 2008; Zhang et al., 2010). In general, the XTP was dominated by an east-high–west-low pattern geomorphology prior to the Oligocene. This topography was replaced during the Oligocene–Miocene by an uneven distribution of uplifting and

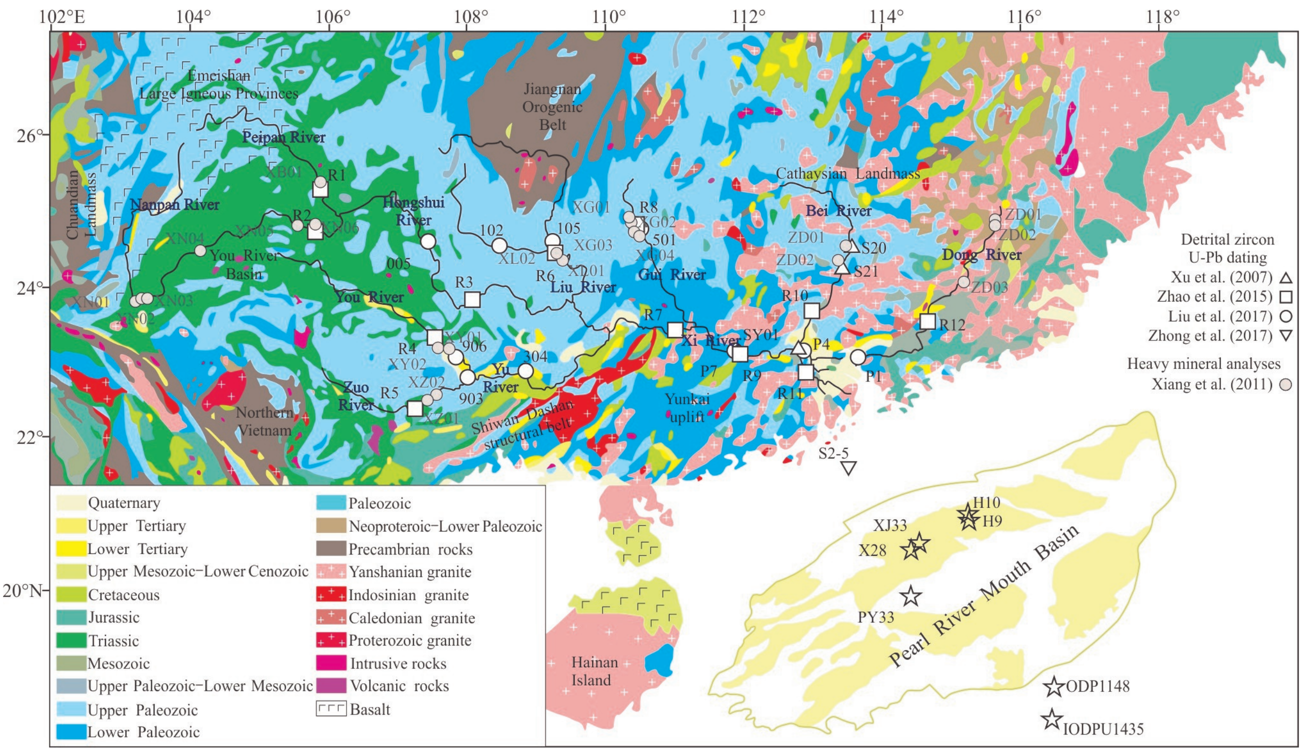


Fig. 1. Geological map of the Pearl River drainage areas and sampling locations from previous researches (modified from Cao et al., 2018).

U-Pb dating sample information: sample R1 to R12 according to Zhao et al., 2015, sample P1, P4, P7, 005, 102, 105, 304, 501, 903 and 906 according to Liu et al., 2017, sample S20, S21 and SY01 according to Xu et al., 2007, sample S2-5 according to Zhong et al., 2017, sample X28-4 to X28-9, H9-1 and H9-2 according to Cao et al., 2018, sample X28-1 and X28-2 according to Shao et al., 2016; Heavy minerals sample information: sample ZD01, ZD02, XG01 to XG04, XL01, XL02, XY01, XY02, XZ01, XZ02, XB01, and XN01 to XN06 according to Xiang et al., 2011; Elemental geochemistry sample information: sample ODP1148, XJ33 according to Shao et al., 2008, sample PY33, H9 according to Shao et al., 2013.

depression structures. Since the Late Miocene, the XTP eventually evolved into a west-high–east-low landform, which ended the drastic topographical and geomorphological reversion in this region (Zhang et al., 2010).

### 2.3 The Pearl River Mouth Basin

Since the Early Cenozoic, the South China continental margin has undergone long-term extension processes, leading to the formation of a series of grabens and faults along the border of SE South China and the northern SCS areas (Li and Li, 2007). As a representative faulted basin, the Pearl River Mouth Basin (PRMB) accumulated a thick Cenozoic sedimentary succession (Pang et al., 2009; Zhou et al., 2009; Zhang et al., 2019) overlying a Mesozoic basement of granites and sedimentary rocks (Li et al., 2012; Zhu et al., 2021). The oldest Cenozoic sediment sequences in the PRMB are of Early–Middle Eocene age (Fig. 2; Zhang et al., 2007, Zhang, 2010; Mi et al., 2018), interbedded with volcaniclastic strata (Wang et al., 2017). With the onset of the SCS spreading at ca. 34 Ma (Li et al., 2014; Huang et al., 2019), the PRMB was dominated by transitional sandstones during the Late Oligocene, and truncated by a sedimentary discontinuity of 2.5–3 Ma (Zhao, 2005; Jian et al., 2019). This marks the transition from rifting into depression. Since the Miocene, the PRMB has developed large-scale deltas and deep-water submarine fans, while patches of carbonate platforms were initiated in the submerging highlands (Wu, 2014).

## 3 Source-to-sink Analyses of the Pearl River System

Detrital zircon U-Pb dating has played an increasingly important part in provenance evolutionary analyses in recent years (Gehrels and Dickinson, 1995; Cao et al., 2015). However, due to the complexity of the actual ‘source-to-sink’ system, this method can be better utilized combined with elemental geochemistry, isotopic geochemistry, heavy mineral analysis, clay mineral analysis and other techniques (Fedo et al., 2003; Cao et al., 2018; Cui et al., 2019). This study aims to provide a comprehensive insight into the formation and evolution of the Pearl River based on detrital zircon U-Pb ages, heavy mineral assemblages and elemental geochemical variations.

### 3.1 Detrital zircon U-Pb age distribution patterns

In order to achieve a better coverage and representability for the complexity of the geological structure and bedrock types in the South China continent, our studied samples were mainly collected from different branches of the Pearl River in order to reflect lithological characteristics of the parent rocks and to minimize possible misinterpretations caused by the downstream mixing effect. The Pearl River Delta in the Zhu-I Depression, on the other hand, was sampled to conduct a source-to-sink comparative analysis.

#### 3.1.1 U-Pb age spectra of Pearl River tributaries

Detrital zircon U-Pb age histogram and Kernel Density

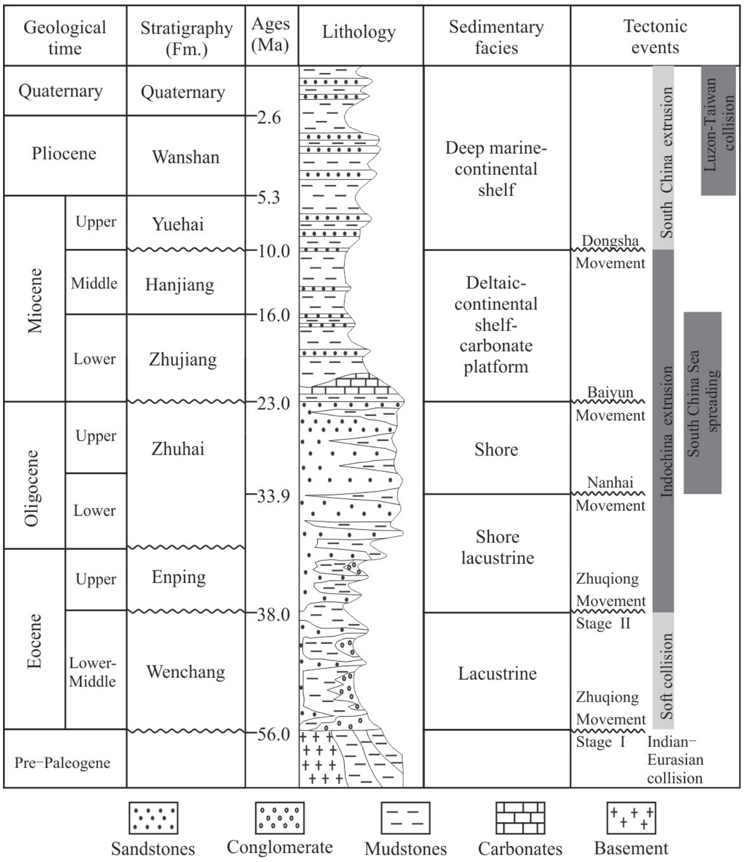


Fig. 2. Schematic stratigraphic column of the northern Pearl River Mouth Basin (modified from Shi et al., 2014; Mi et al., 2019).

Estimation (KDE) plots (Fig. 3) show clear distinctions between the different Pearl River tributaries. For example, in the upper reaches, represented by the Beipan River (sample R1) and the Nanpan River (sample R2), the results feature prominent Indosinian peaks (ca. 380–200 Ma) clustering at ca. 275 Ma and ca. 270 Ma, respectively, plus also discernible Caledonian (ca. 600–400 Ma) and Jinningian (ca. 1200–700 Ma) peaks. At the confluence flow of the Beipan and Nanpan rivers, in the Hongshui River samples (005 and R3) the U-Pb date exhibits a typical combination pattern of these two rivers. The Liu River samples (R6, 102 and 105) show a dominant Jinningian cluster (ca. 1200–700 Ma), with scattered zircons of other ages. The You River samples (R4 and 906) mainly comprise Indosinian (ca. 380–200 Ma) and Caledonian (ca. 600–400 Ma) populations, clustering around 270 Ma and 465 Ma, respectively. The Zuo River samples (R5 and 903) are also dominated by clear Indosinian (ca. 380–200 Ma) peaks centralized at ca. 250 Ma, accompanied by some Lvliangian zircons (ca. 2000–1800 Ma). Noteworthy is that the Caledonian peak in the Zuo River is less significant compared to that of the You River. Not surprisingly, the U-Pb age spectrum of the Yu River (sample 304) and its upstream Zuo and You rivers are similar. The Gui River samples (R8 and 501) are dominated by Caledonian (600–400 Ma) and Jinningian (1200–700 Ma) clusters, centralized at ca. 555 Ma and ca. 970 Ma, respectively, in addition to a small group of Archean zircons, which reflect the South China basement. On the other hand, the Bei River samples (S20, S21 and R10) display an apparent Yanshanian (ca. 200–80 Ma) peak and a secondary Caledonian (ca. 500–300 Ma) peak. Similarly, the Dong River samples (R12 and P1) also display Yanshanian (ca. 200–80 Ma) and Caledonian (500–300 Ma) clusters, with age peaks centralized around 100 Ma, 160 Ma, 240 Ma, and 450 Ma (Figs. 3, 4).

As the main western branch of the Pearl River, the Xi River lower reaches can be grouped into the upper, middle and lower sampling sections. The upper section (sample R7), including the Hongshui River upper reaches of the Nanpan and Beipan rivers, the Yu River upper reaches of the You and Zuo rivers, as well as the Liu River, is characterized by a mixed U-Pb age pattern of these tributaries. The middle section (samples P7 and R9) also represents the features of the aforementioned tributaries plus the Gui River. The lower section (samples P4 and R11) also includes all sediments from the upstream as well as from the Bei River, and reflects further mixing of different provenances. Finally, the modern Pearl River estuary sample (S2-5) shows a mixed provenance pattern of all tributaries, including the Dong River.

### 3.1.2 Source area division and basinal sedimentary responses

Potential source areas are determined by grouping samples with similar age combination and by linking them

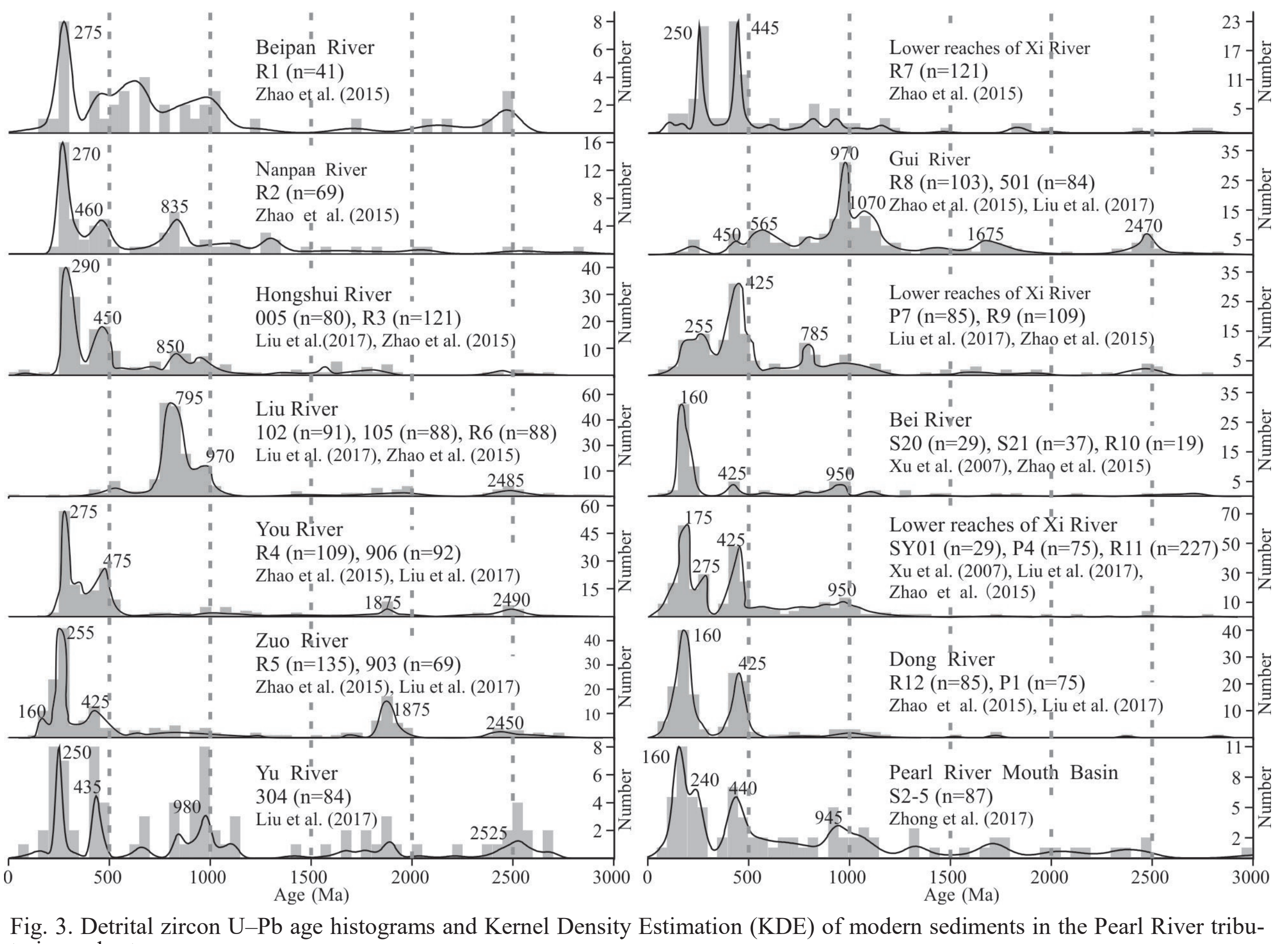


Fig. 3. Detrital zircon U–Pb age histograms and Kernel Density Estimation (KDE) of modern sediments in the Pearl River tributaries and estuary.

with regional lithological distribution and corresponding magmatic events. Therefore, the Pearl River fluvial system can be divided into seven provenances (Fig. 4), including the Hongshui River upstream (UHRP), Liu River (LRP), You River (YRP), Zuo River (ZRP), Gui River (GRP), Bei River (BRP) and Dong River (DRP) provenances.

UHRP is (samples R1 and R2) characterized by an Indosinian (ca. 380–200 Ma) cluster in addition to a small group of Proterozoic ages (Fig. 4). The middle reaches of the Pearl River are mainly the Liu and Gui rivers, which flow through the western Jiangnan Orogenic Belt and Paleozoic strata (Fig. 1). LRP (samples R6, 102 and 105) is characterized basically by a single peak of ca. 790 Ma (Fig. 4), whereas GRP (samples R8 and 501) features a dominant ca. 970 Ma age group and several small clusters of Mesozoic and Late Neoproterozoic–Early Paleozoic zircons. The upper reaches of the Yu River are mainly composed of the You and Zuo rivers, which flow southeast through the Youjiang Basin with intensive Upper Paleozoic carbonate rocks and Triassic deep-sea turbidites (Fig. 1). Accordingly, YRP (samples R4 and 906) mainly displays Caledonian and Hercynian ages, which are centralized at ca. 465 Ma and 270 Ma, respectively (Fig. 4). By contrast, the adjacent ZRP (samples R5 and 903) shows less significant Caledonian ages but more significant Paleoproterozoic, Indosinian (250–200 Ma) and early Yanshanian ages (Fig. 4). Presence of these Mesozoic age groups are closely related to the Jurassic–Cretaceous strata and Indosinian granites outcropping along the Shiwandashan orogenic belt (Fig. 1). The distribution patterns of lithology in the mainstream of the Xi River lower reaches and East China (Fig. 1) determine the contribution of different provenances. As indicated by sample R11 located near the Xi River estuary mouth, the provenance of the Xi River lower reaches highlights the combination of both BRP and DRP, with U-Pb age spectra markedly different from those of others from the Xi River lower reaches (samples P7, R9, SY01 and P4), but comparable to those of the Dong River samples (Figs. 3, 4). Both the Bei River and the Dong River flowed through the eastern Cathaysia landmass and erode bedrocks of Yanshanian (ca. 190–70 Ma) granites (Fig. 1). Thus, DRP (samples P1 and R12) shows two dominant peaks of ca. 160 Ma and ca. 450 Ma (Fig. 4), which are distinct from the overall U-Pb pattern of BRP. The Bei River upper reaches (sample S20) and lower reaches (samples S21 and R10) are slightly different, but they both lack Caledonian (ca. 500–400 Ma) and late Yanshanian age groups (Fig. 4).

The detrital zircon U-Pb age combination patterns (Shao et al., 2016; Cao et al., 2018) in different stratigraphic units of boreholes X28 and H9 from the Pearl River Mouth Basin (the ‘sink’ area) are largely comparable between the upper and lower samples of the same strata, with minor variations only in the proportion of their individual age peaks. Therefore, we combined samples of the same stratigraphic strata into a single analysis in our study (Fig. 4). Sample S2-5 from the surface sediment near the Pearl River estuary, on the other hand, was used as a modern representative in the source-to -sink analysis (Zhong et al., 2017).

Detrital zircon U-Pb age spectra show that the Lower and Upper Oligocene basinal samples are comparable in their age combination with a dominant Yanshanian peak and secondary Indosinian and Caledonian peaks (Fig. 4). However, differing from the Lower Oligocene samples, the Upper Oligocene samples feature more concentrated age clusters in their width and steepness, possibly indicating increasing sedimentary input as a result of the westward expansion of the drainage basin. In addition to the aforementioned age peaks, the Lower Miocene basinal samples begin to show apparent Jinningian (ca. 945 Ma) and other older age zircon populations. Moreover, the Yanshanian, Indosinian, and Caledonian peaks all changed significantly in their relative percentages and centralized ages (Fig. 4). In particular, the Caledonian and older age zircons (ca. 3000–500 Ma) increased abruptly from the Oligocene to Miocene, and continue to gain higher contents in the modern Pearl River estuary sediments.

Therefore, all the zircon age evidence indicates that the Pearl River fluvial system experienced drastic changes across the Oligocene/Miocene boundary, marking the most significant watershed change in its evolutionary history. After the Miocene, the Pearl River fluvial network developed into nearly its modern scale, as indicated by relatively stable U-Pb age spectra through to the present.

### 3.2 Heavy minerals

A heavy mineral assemblage combination is one of the robust proxies for reflecting potential provenances (Morton and Hallsworth, 1999). As shown in Figure 5a, the Apatite-Tourmaline index (ATi) and Gamet-Zircon index (GZi) ratios in the Pearl River tributaries differ significantly. Both the Dong River and the Bei River have extremely low ATi ratios whereas their GZi values vary greatly between 10 and 80, implying that the eroded parent rocks were predominantly acidic magmatic rocks and a small amount of low-degree contact metamorphic rocks. The Xi River upper reaches, including the Nanpan River, the Beipan River, the Hongshui River, and the middle reaches of the You River, have ATi values ranging broadly from 20 to 100, and extremely low GZi ratios, indicating that the parent bedrocks were rich with low-degree contact metamorphic rocks and basic magmatic bodies. The Xi River middle reaches, including the Zuo River, the Gui River, and the Liu River, commonly display negligible ATi and GZi values, indicating mainly clastic and carbonate parent rocks, which had undergone strong weathering processes and lacked stable heavy mineral assemblages (Xiang et al., 2011).

From the Oligocene to the Miocene, heavy minerals of the northern SCS sediments changed greatly, with an overall increase in compositional maturity likely because of a larger sedimentary input from further source areas (Fig. 5b). In the Lower Oligocene samples, for example, unstable minerals including apatites, epidotes, and garnets are relatively high in content (Fig. 5b), implying relatively short-distance transport of granite and metamorphic parental rocks. Upper Oligocene samples, on the other hand, contain more stable minerals like zircons, garnets and tourmalines, while their apatite and epidote contents decrease significantly (Fig. 5b). These heavy mineral

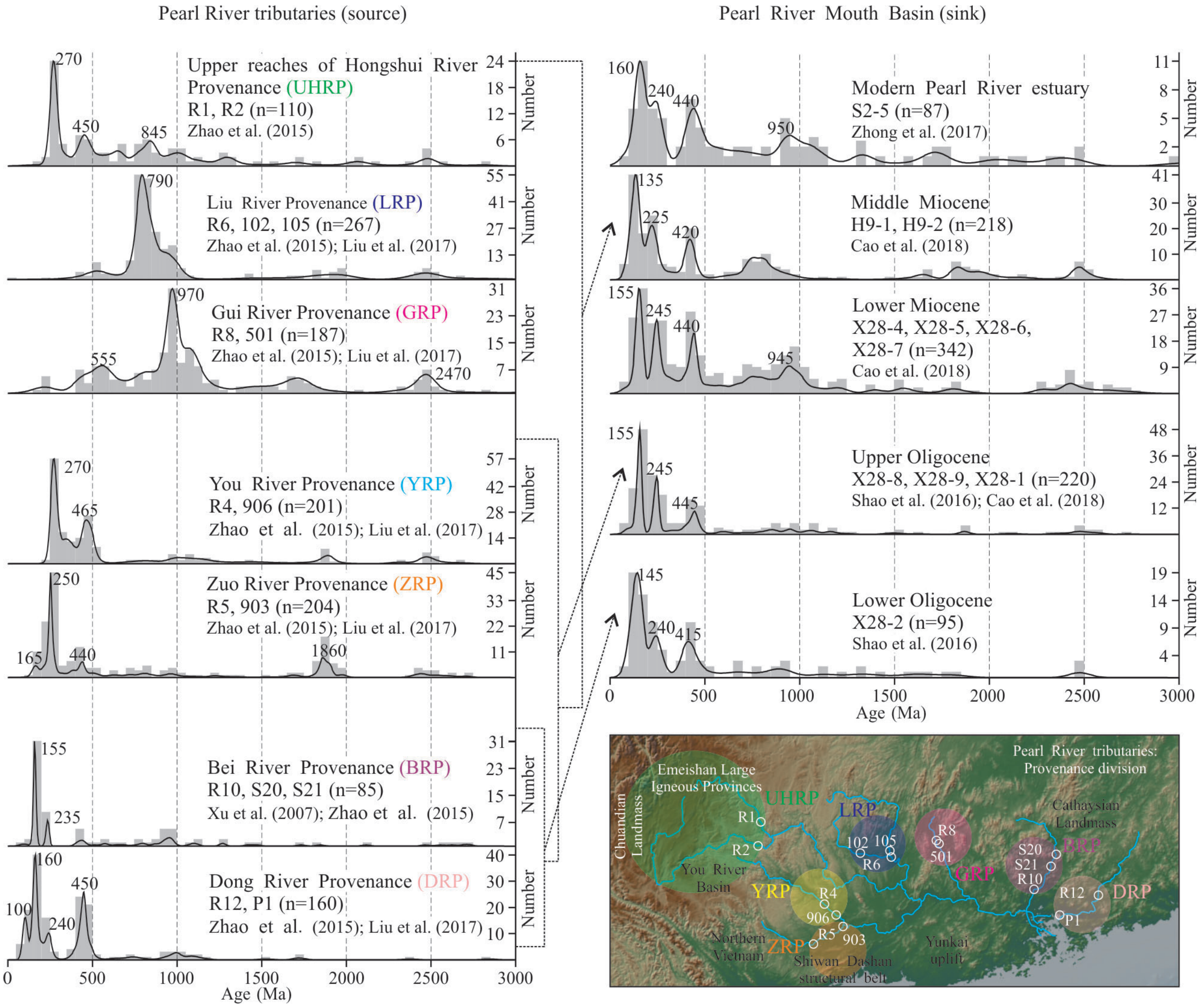


Fig. 4. Comparative analysis of the Pearl River drainages ('source') and the Pearl River Mouth Basin ('sink') areas (n indicates the number of zircons analyzed).

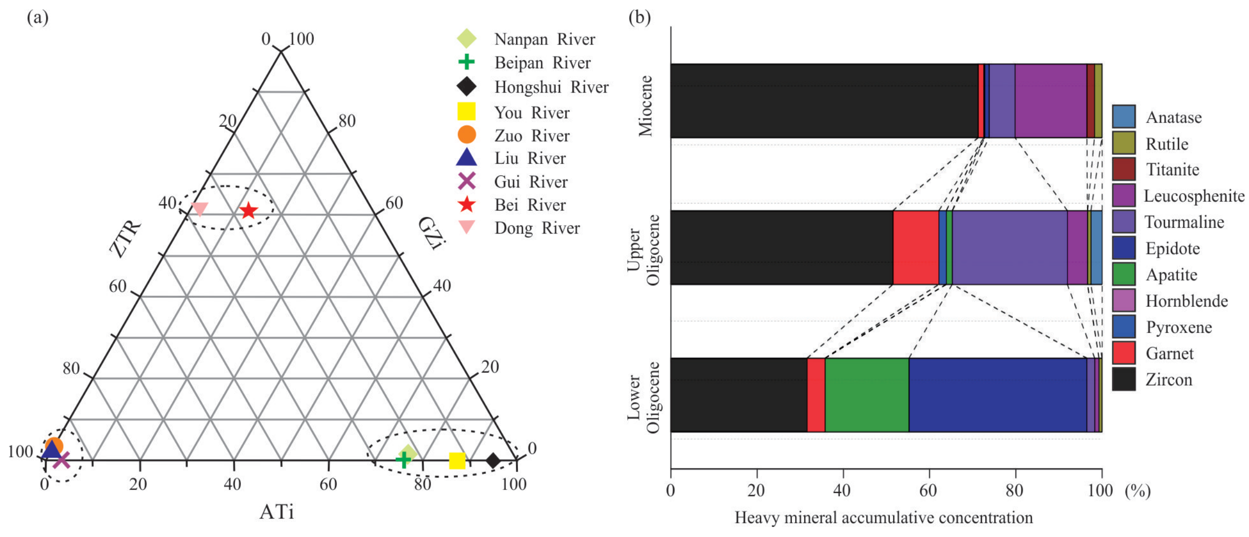


Fig. 5. Heavy mineral assemblage plots.

(a) ATi and GZi indexes for Pearl River heavy mineral components; (b) heavy mineral variations of H10, northern South China Sea.

changes strongly indicate the accumulation of Mesozoic granite, skarn metamorphic rocks and recycled sedimentary rocks during the Late Oligocene when the Pearl River drainage basin expanded further into the South China inland areas. The Miocene samples contain comparatively fewer types of heavy minerals, mainly such stable minerals as zircons (about 70%) and leucosphenites (about 15%), as well as <10% other heavy minerals (Fig. 5b). This evidence suggests that the Pearl River then most likely reached much further inland, resulting in a heavy mineral assemblage dominated by stable components like the zircon and leucosphenite due to long-distance transport.

### 3.3 Elemental geochemistry

Elemental geochemistry is of great significance in revealing the sedimentary composition variations in the northern SCS under the control from the Pearl River evolution. In general, CaO increase and $Al_2O_3$ decrease suggest more input of carbonate rocks and less input of silicates from parental source areas. The Chemical Index of Alteration (CIA) is a useful parameter widely used to measure the intensity of the chemical weathering processes, as higher CIA is often linked to greater intensity of chemical weathering. However, this parameter is also affected by the parent rock types, for example, a low CIA might be due to a high proportion of carbonate parent rocks.

Samples of ODP Site 1148 and boreholes PY33, XJ33 and H9 all show large elemental geochemistry variations across the Oligocene/Miocene boundary (ca. 23.8 Ma) (Fig. 6), as marked by CaO significantly increasing and $Al_2O_3$ decreasing during this time. The CIA index also displays an abrupt change around the stratigraphic boundary followed by a gradual decreasing trend upward. Apparently, the northern SCS was dominated by silicate sediments during the Oligocene, before being replaced by carbonate sediments during the Miocene. Combined with the eroded bedrocks discussed above, these elemental changes imply that the main sediment load transported by the Pearl River underwent a transition from the silicate rocks of coastal South China before the Miocene to the carbonate rocks of the Yunnan–Guizhou Plateau since the Miocene (Shao et al., 2013).

## 4 Coupling Relationship between the Pearl River and East Asian Topographic Evolution

During the Early Oligocene, the XTP might have partly experienced an uplifting process within the proto-Mount Gangdise area (Fig. 7a). This uplift, however, was likely a regional tectonic event that was too weak to greatly influence the evolution of the eastern fluvial network and Asian Monsoon system. At the same time, the northern SCS started to form deltas containing dominant Yanshanian zircons and secondary Indosinian and Caledonian zircon populations. The U-Pb age spectra of the northern SCS show consistency with those of the Bei River and the Dong River (Fig. 4). In addition, the Pearl River tributaries were composed of abundant unstable heavy mineral assemblages (Fig. 5b), which was likely influenced from the silicate source areas as implied by element geochemical indicators. Therefore, we infer that the Pearl River was fairly constrained during the Early Oligocene and mainly eroded the Mesozoic granites along the coastal South China area (Fig. 7b).

During the Late Oligocene, the central, northern and southern parts of the XTP all experienced accelerated uplift (Fig. 7a), which not only resulted in more significant changes in regional topography and geomorphology compared to the Early Oligocene (Bluisik et al., 2001; Specier et al., 2003; Rowley and Currie 2006; Wang et al., 2008; Deng et al., 2011), but also had greater impact in shaping the eastern river systems. Although the U–Pb age spectra between the Lower and Upper Oligocene sediments in the Pearl River Mouth Basin are similar, their distinctions in heavy mineral assemblages imply longer-distance sedimentary transport. Sedimentary composition changes and depositional input increase were likely caused by the formation and/or expansion of the Zuo River, the You River and a part of the Hongshui River drainages in the Pearl River system. During the Late Oligocene, the Pearl River network developed more tributaries and its catchment expanded to the wider inland area of South China (Fig. 7c).

Many scholars considered that the XTP Uplift occurred mainly in the Early–Middle Miocene (Yin, 2006; Royden et al., 2008; Molnar and Stock, 2009; Xu et al., 2013), thus the overall geomorphic pattern of the XTP was most likely formed at least during this time. The general geomorphology may have remained stable throughout this interval although local uplifting might have occasionally taken place since the Late Miocene (Lu and Guo, 2013). During the Early Miocene, the Pearl River Mouth Basin was characterized by major shelf delta deposits (Fig. 2) with a large number of Proterozoic and Archean zircons

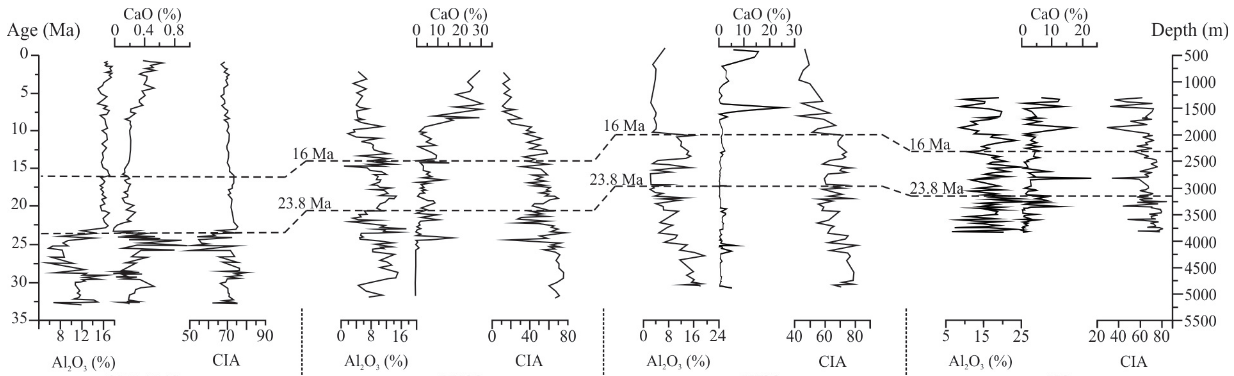


Fig. 6. Elemental geochemistry variations of the northern South China Sea borehole samples (modified from Shao et al., 2008, 2013).

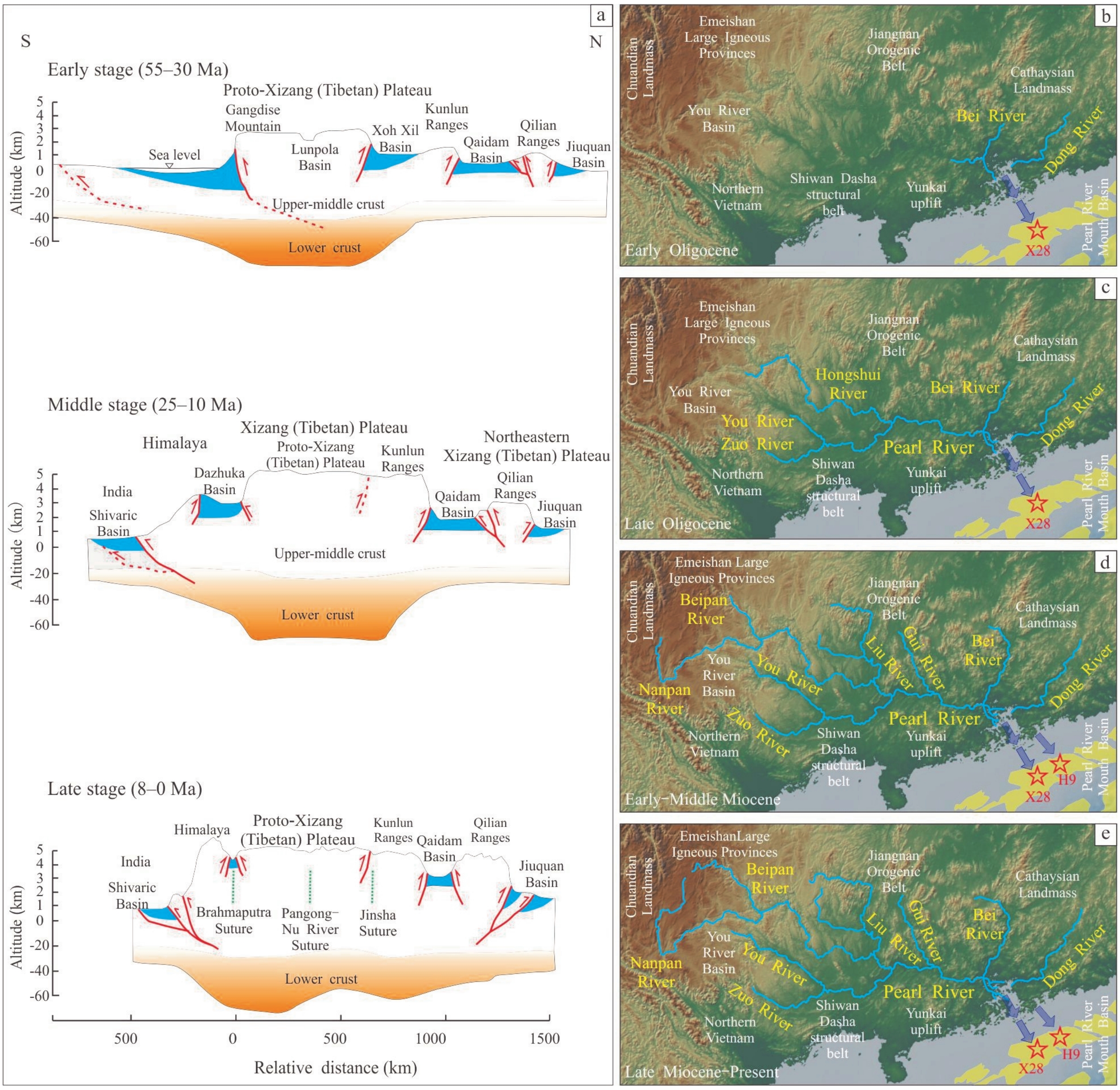


Fig. 7. Multi-stage evolution of the Xizang (Tibetan) Plateau (modified from Wang et al. 2008; Fang, 2017).
(a) Sketch map of the Cenozoic Xizang (Tibetan) Uplift; (b-e) schematic reconstructions for the Pearl River stepwise evolution.

present, indicating an abrupt expansion of the Pearl River into the Cathaysia hinterland and the Lower Yangtze region. During this period, the Gui River, the Liu River and the You River were included in the Pearl River system, in addition to the Nanpan and Beipan rivers of the Hongshui River upper reaches. Changes in the Pearl River tributary organization were completely coupled with the XTP Uplift (Fig. 7d). Similarly, as confirmed by elemental geochemistry indicators, the Pearl River started to erode carbonate rock source areas during the Early Miocene, while headwater erosion within the Pearl River upstream tributaries still occurred into the Late Miocene and since then subsequently developed into the present continental-scale river system (Fig. 7e).

## 5 Paleoenvironmental Responses to the East Asian Topographic Reversion

The multi-stage uplift of the XTP led to the complete reversion of the East Asian topography during the Cenozoic. In turn, it not only reshaped the paleogeography and paleogeomorphology, but also drastically affected the atmosphere, hydrosphere, and biosphere in the region. In particular, the East Asian topographic reversion has played a consistent influence on the formation of large river systems, development and strengthening of the monsoon climate, the generation of loess sediments, and changes in the marginal basin sedimentary composition. For a unique earth system perspective, a comprehensive understanding of their interactions over time necessarily requires integrated analyses on their roles.

The origination of many large rivers in Asia from the XTP itself strongly indicates the close relationship between the evolution of the large fluvial systems and the XTP Uplift. Under the control of this geomorphological change, for example, the birth and development of the Yangtze River marked by the connection of the Three Gorges, can be viewed as an optimal indicator for the initial establishment of the East Asian west-high–east-low landform close to the Oligocene/Miocene boundary (Zheng et al., 2013). In addition, the capture event of the Jinsha River upper reaches by the Yangtze might also have occurred during this period (Zheng et al., 2017). These discoveries show complete consistence with the contemporaneous abrupt provenance changes in the Pearl River network. Therefore, all these factors point to the strong impact of the East Asian topographic evolution on regional fluvial transporting systems.

Previous studies found the controlling role played by the XTP Uplift on the formation of the East Asian monsoon climate and arid zones within Central Asia. Cenozoic vegetation changes imply that arid zones of the Asian hinterland were possibly formed around the Late Oligocene/Early Miocene boundary (Sun and Wang, 2005). This timing coincided with the transition from a planetary to a monsoonal climate system in East Asia (Wang, 1990; Liu et al., 1998; Guo et al., 2008). Similar paleoenvironmental changes were also revealed in the records of the long-term loess sediments (Rea et al., 1998; Guo et al., 2002).

To sum up, East Asian geomorphology started to develop a west-high–east-low pattern during the Late Oligocene–Early Miocene due to the major uplift of the XTP. Prominent river systems, including the Pearl River and the Yangtze River, all started to flow eastward. Concomitantly, the East Asian topographic reversion also played the most important controlling role in the changes of the Asian monsoon system and the inland arid zones.

## 6 Conclusions

Prior to the Eocene, the Pearl River Mouth Basin mainly accumulated sediments from local paleo-uplifts under the influence of the general west-low–east-high topography without a meaningful Pearl River waterway. It was not until the close to the Eocene/Oligocene boundary that the Pearl River first developed, coinciding with the onset of the SCS spreading at ca. 34 Ma. During the Early Oligocene, the Pearl River remained as a relatively limited catchment, mainly eroding granite and other magmatic rocks from coastal South China. During the Late Oligocene, the Pearl River initially expanded westward into the frontal margin of the Yunnan–Guizhou Plateau. Since the Early Miocene, the Pearl River has reached further into the Yangtze Block and Cathaysian hinterland. The stepwise expansion of the Pearl River network was closely linked to the Xizang (Tibetan) Uplift (ca. 25–20 Ma), which marked the end of East Asian landform reversion into a west-high–east-low pattern. Since the Late Miocene, the Pearl River remained relatively stable in approaching the modern continental scale. In addition to its influence on river development and the ‘source to sink’ sedimentary process, this prominent landform reorganization is also of great significance in understanding the coupled relationship between the Indian-Eurasian plate collision, the Xizang (Tibetan) Uplift and the expansion of marginal oceans in the Asia-Pacific region.

We conclude that the East Asian continental landscape and most of drainage underwent critical reversion into east-tilting, or east-flowing networks across the Oligocene/Miocene boundary.

## Acknowledgements

We thank the China National Offshore Oil Corporation (CNOOC) for providing geological data and borehole samples from the northern SCS. Constructive and careful reviews by two referees are gratefully appreciated. This work was supported by the National Natural Science Foundation of China (grant Nos. 42076066, 92055203 and 41874076), the National Science and Technology Major Project of China (grant No. 2016ZX05026004-002), the National Key Research and Development Program of China (grant No. 2018YFE0202400).

Manuscript received May 22, 2020
accepted Nov. 7, 2020
associate EIC: ZHANG Gongcheng
edited by Susan TURNER and FANG Xiang

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## About the first author

ZHANG Hao, male, born in 1990 in Aksu City, Xinjiang Province; a PhD graduate in Tongji University. He is now interested in sedimentology and geochemistry. Email: zhanghao330@tongji.edu.cn; phone: 15801756280.

## About the corresponding author

CUI Yuchi, female, born in 1991 in Baoding City, Hebei Province; a PhD graduate in both Tongji University and Curtin University. She is now interested in sedimentology and tectonics. Email: cuiyuchi@tongji.edu.cn; phone: 15301756572.