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# Limited Effect of the Pearl River on the Pearl River Mouth Basin Before the Early Miocene

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## ABSTRACT

The Pearl River has received particular attention with respect to its links to the growth of the Tibetan Plateau and associated landscape evolution. However, controversy still surrounds the issues of when the present-day Pearl River became established, and how landscape deformation may have triggered the formation of the Pearl River. In this study, new and published zircon U–Pb ages from the late Oligocene Pearl River Mouth Basin (PRMB) and potential source areas are used to conduct a systematic provenance analysis with a view to reconstructing the drainage pattern in the South China Block. The results suggest that the PRMB was fed by multiple major sources during the late Oligocene, exhibiting significant spatial provenance variability. The paleo-Pearl River had a limited effect on the northern and southern PRMB during the late Oligocene, and there was an overlooked Yunkai Massif source which made a significant contribution to the western and southern PRMB. We infer that, compared to the early Miocene or the present day, a paleo-Nanduhe River with a larger catchment area flowed through the Yunkai Massif into the PRMB in the late Oligocene, and the paleo-Pearl River only drained the less extensive Cathaysia Block during this time. In the early Miocene, the westward expansion of the paleo-Pearl River and the capture of the upstream part of the paleo-Nanduhe River by the paleo-Pearl River, which are attributed to the growth of the Tibetan Plateau and the exhumation of the Yunkai Massif, respectively, resulted in the present-day Pearl River configuration with its dominant impact on the PRMB.

## 1 | Introduction

The dynamics of drainage systems have been intimately linked to tectonically induced landscape deformations and topographic changes, as reflected in drainage capture and reorganisation (Hoorn et al. 1995; Brookfield 1998; Clark et al. 2004; Clift, Carter, et al. 2006; Clift, Blusztajn, et al. 2006; Clift, Long, et al. 2008; Clift et al. 2020; Yan et al. 2018; Zhao et al. 2023). The Pearl River, currently flowing from the southeastern Tibetan Plateau into the northern South China Sea (SCS), has attracted particular attention due to its potential links to the growth of the Tibetan Plateau and the opening of the SCS (Figure 1A) (Cao et al. 2018; Jin et al. 2022; Liu, Stockli, et al. 2022; Cheng et al. 2023; Zhang et al. 2023). Numerous provenance studies have been conducted on sediments in the northern SCS margin to constrain the evolution of the Pearl River. There is a broad agreement that the Pearl River has a multi-stage evolutionary history (Ma et al. 2019; He et al. 2020; Zhang et al. 2022; Hu et al. 2023). The paleo-Pearl River only drained the Cathaysia Block (i.e., the northeastern catchment of the Pearl River; Figure 1A) and subsequently expanded westwards into the Yangtze Block and southeastern Tibetan Plateau (i.e., the western catchment of the Pearl River; Figure 1A), forming the present-day course of the Pearl

**Summary**

- The late Oligocene sediments in the Pearl River Mouth Basin display pronounced spatial provenance variability.
- A late Oligocene River draining the Yunkai Massif made a hitherto overlooked contribution to the Pearl River Mouth Basin.
- Early Miocene drainage reorganisation resulted in the Pearl River playing a dominant role in the Pearl River Mouth Basin.

River. Nevertheless, it is still debated whether the westward expansion and the development of the modern Pearl River occurred in the early Oligocene, the late Oligocene, or the early Miocene (Cao et al. 2018; He et al. 2020; Jin et al. 2022; Cheng et al. 2023; Hu et al. 2023; Zhang et al. 2023). These different views are partly related to the area where analyses have been carried out. Cao et al. (2018) suggested an early Miocene formation of the Pearl River based on samples from the northern Pearl River Mouth Basin (PRMB). Data acquired in the south and the southwest of the PRMB suggested an early or late Oligocene formation (Jin et al. 2022; Cheng et al. 2023; Hu et al. 2023; Zhang et al. 2023). These studies have subconsciously attributed the provenance changes in the northern SCS margin to the evolution of the Pearl River, without assessing whether other potential drainage systems fed the PRMB from the South China Block at that time.

The PRMB, located in front of the Pearl River estuary, has received abundant sediments from the Pearl River and holds the key to revealing the history of the Pearl River as well as other drainage systems in the South China Block (Figure 1A). It is noteworthy that sediments in the northern PRMB, in proximity to the Pearl River estuary, exhibit greater sensitivity to the Pearl River evolution than sediments in the southern part. The Pearl River sediments can be traced back as early as the Cretaceous in the northern SCS margin (He et al. 2020), and the Pearl River is thought to have played a significant role in the PRMB fill (Zeng et al. 2019; Tang et al. 2020; Li et al. 2023; Wang et al. 2023). Researchers widely accept that the present-day Pearl River had already formed in the early Miocene (Cao et al. 2018; Shao et al. 2019; Liu, Chen, et al. 2022). For the controversial drainage pattern before the early Miocene, especially in the Oligocene, zircon U–Pb geochronology has been widely applied in the PRMB. Zircon provenance studies on the Oligocene PRMB have mainly concentrated on the evolution of the Pearl River or paleo-Pearl River (Cao et al. 2018; Wang et al. 2018; He et al. 2020; Hu et al. 2023; Li et al. 2023), with a degree of attention being given to the processes of continental margin rifting (Shao et al. 2016; Wang et al. 2017). In addition, some studies have identified significant Caledonian (Ordovician-Devonian) age zircons in the Oligocene of the southern PRMB, and these zircons have been interpreted as having been fed into the basin by the paleo-Xiangjiang River connected to the paleo-Pearl River (Yan et al. 2018), or by the Kontum-Ying-Qiong River draining Central Vietnam (Shao et al. 2019). However, recent evidence from the southern PRMB indicates a southeastward sediment dispersal pathway in the late Oligocene (Tang et al. 2024), probably suggesting a source to the northwest rather than the paleo-Pearl River to the north or the Kontum-Ying-Qiong River to the west. A general overview of the provenance of the late Oligocene PRMB, considering the whole basin and not just a part of it, is of great significance for understanding the drainage pattern in the South China Block, which may differ from that of the early Miocene or present day.

In this study, we use zircon U–Pb ages obtained from the PRMB and potential source areas, and employ a visual comparison and statistical analysis of these ages for provenance interpretation. We aim to (1) determine the source areas for different units of the late Oligocene PRMB, (2) assess the varying effects of source areas on the late Oligocene PRMB, and (3) provide insights into the history of the Pearl and Nanduhe Rivers in relation to the evolution of the landscape.

## 2 | Geological Setting

### 2.1 | Pearl River Mouth Basin

Widespread extension along the South China margin has resulted in a series of rift basins in the northern SCS (Taylor and Hayes 1980; Su et al. 1989; Clift and Lin 2001; Morley 2016). As the largest Cenozoic continental margin basin in the northern SCS, the Eocene PRMB was dominated by strong rifting and terrestrial deposits (Wang et al. 2015; Jiang et al. 2022; Li et al. 2023). Following the continental rifting, several separate sags formed, separated by uplifts and faulted blocks (Figure 1B). In response to the onset of the seafloor spreading of the SCS at ca. 33 ~ 32 Ma (Barckhausen et al. 2014; Sibuet et al. 2016), the PRMB entered into a post-rift stage. Deposited sediments indicate the passage of a continental to marine environment during the Oligocene with a marine environment that has been maintained since the Miocene (Taylor and Hayes 1983; Su et al. 1989). Before being submerged by the sea water, the intrabasinal uplifts played an important role in sediment contribution to the PRMB (Wang et al. 2017; Shao et al. 2019; Li et al. 2023). Igneous rocks of the intrabasinal basement are dated to the Yanshanian (Jurassic-Cretaceous) with an age peak at ca. 153 Ma (Figure 2E; Xu et al. 2016; Liu et al. 2023; Wang et al. 2023). Apart from the igneous basement, Mesozoic sedimentary rocks have also been identified beneath the eastern PRMB (Sun et al. 2014). The sedimentary basement made an obvious contribution to the eastern PRMB during the middle Eocene, but ceased to do so after the late Eocene (Li et al. 2024).

### 2.2 | South China Block

The South China Block consists of the Yangtze Block in the northwest and the Cathaysia Block in the southeast (Figure 1A), which have experienced multi-phase orogeny and magmatism since the Neoproterozoic. The Yangtze Block has an Archean to Proterozoic basement. The Cathaysia Block contains a Proterozoic basement and is subdivided into the West Cathaysia Block and the East Cathaysia Block. The West Cathaysia Block experienced strong Caledonian and Indosinian (Permo-Triassic) magmatism, while the East Cathaysia Block was overprinted

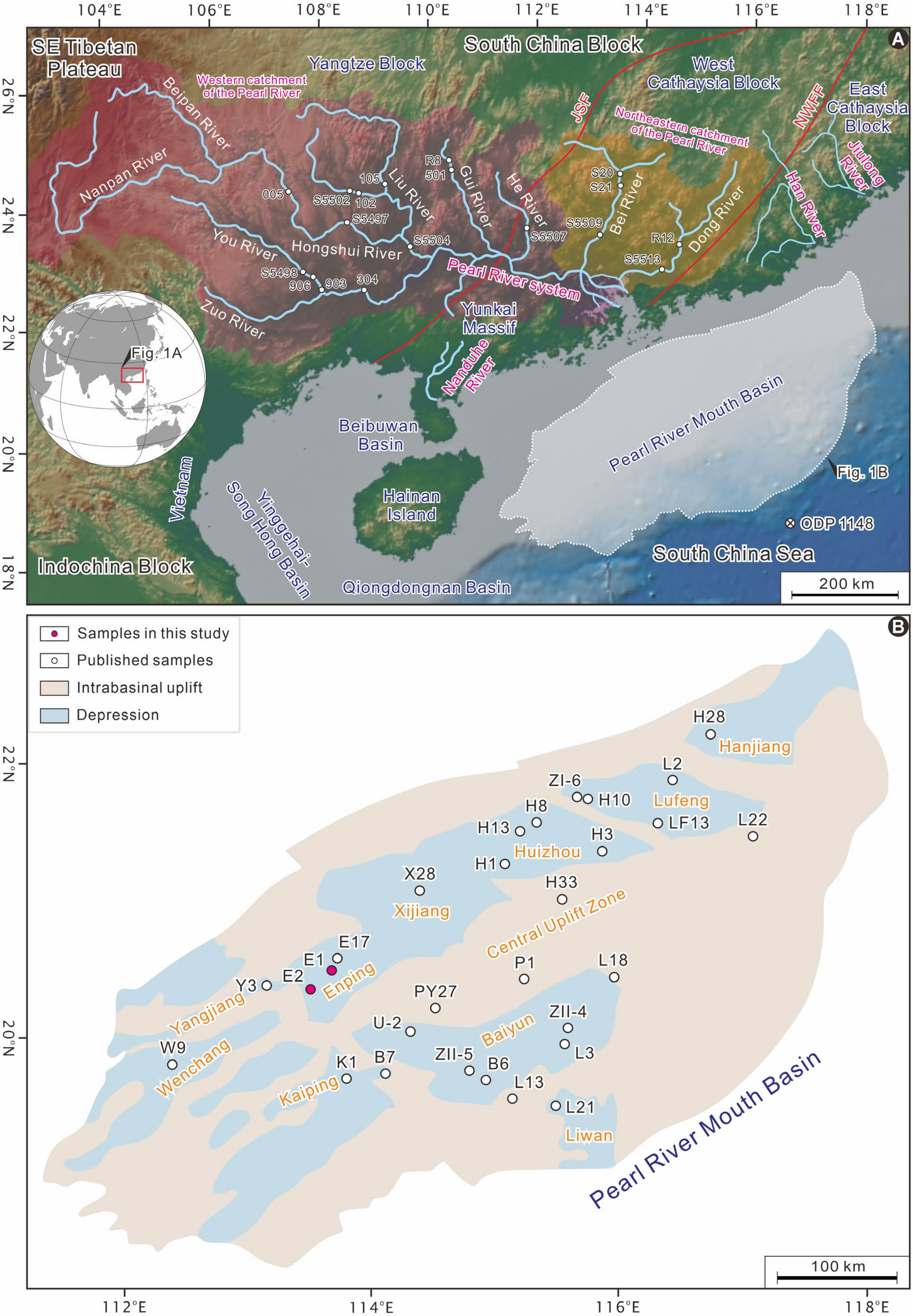


**FIGURE 1** | Legend on next page.

**FIGURE 1** | (A) Topographic map with geological units in the South China Block showing drainage systems flowing from the South China Block into the South China Sea (Xu et al. 2007; Lin et al. 2018). The northeastern and western catchments of the Pearl River are shaded with different colours, and the locations of previously published samples of modern Pearl River sands used in this study are also shown (Xu et al. 2007; Zhao et al. 2015; Liu et al. 2017; He et al. 2020). (B) Geological map of the Pearl River Mouth Basin (PRMB) showing locations of the late Oligocene zircon samples used in this study. The western PRMB contains the Yangjiang and Wenchang Sags; the southern PRMB contains the Baiyun, Kaiping, and Liwan Sags; the northern PRMB contains the Huizhou, Xijiang and Enping Sags; the eastern PRMB contains the Lufeng and Hanjiang Sags. JSF, Jiangshan-Shaoxing Fault; NWFF, Northwest Fujian Fault.

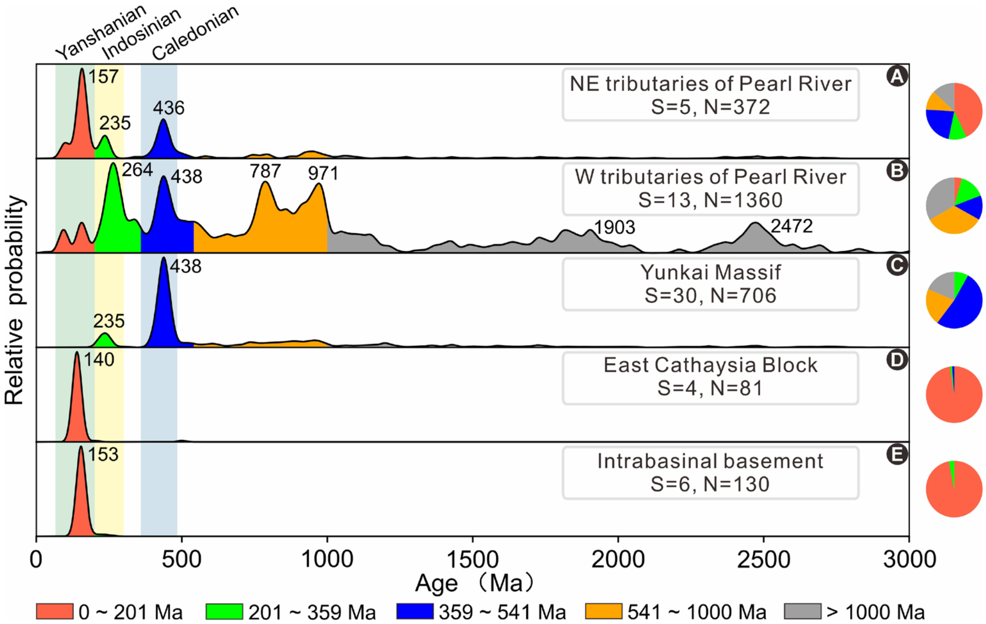


**FIGURE 2** | Kernel density estimation (KDE) plots of zircon U–Pb age spectra from potential source areas. Pie charts are used to indicate the percentage proportions of identified ages. N, number of analytical zircon grains; S, number of analytical samples. See the data sources in Table S1.

by widespread Yanshanian volcanic and granitic rocks (Xu et al. 2007; Lin et al. 2018).

The South China Block served as the main source for the PRMB, feeding the basin via the Pearl River as well as the mountain rivers (Jiao et al. 2018; Liu, Chen, et al. 2022). The sediment contribution from the Pearl River can be traced using the zircon U–Pb age spectra of modern river sands. The northeastern tributaries of the Pearl River (Dong and Bei Rivers) are dominated by a major Yanshanian peak (at ca. 157 Ma) with minor Indosinian (peak at ca. 235 Ma) and Caledonian (peak at ca. 436 Ma) clusters (Figure 2A; Xu et al. 2007; Zhao et al. 2015; He et al. 2020). The present-day zircon signature of the western tributaries of the Pearl River (He, Gui and Liu Rivers, etc.) is dominated by a major Indosinian peak (at ca. 264 Ma) with significant Caledonian, Neoproterozoic, and Paleoproterozoic clusters (Figure 2B; Zhao et al. 2015; Liu et al. 2017; He et al. 2020). In addition to the Pearl River system, small rivers along the coast of South China also provide detritus to the continental margin basins. The Yunkai Massif, located in the western West Cathaysia Block, made a significant contribution to the northern SCS, including the Beibuwan Basin and the western PRMB (Gong et al. 2021; Liu, Chen, et al. 2022). The zircon U–Pb age spectrum of 30 published samples from the Yunkai Massif is characterised by a strong Caledonian peak at ca. 438 Ma (Figure 2C; Wang et al. 2007, 2011, 2012; Wan et al. 2010; Chen et al. 2012). It has been suggested that the East Cathaysia Block played an important role in the eastern PRMB fill (Jiao et al. 2018; Wang et al. 2018; Li et al. 2024). The zircon U–Pb age spectrum of four previously published samples from the East Cathaysia Block exhibits a major Yanshanian peak at ca. 140 Ma (Figure 2D; Shi et al. 2011; Chen et al. 2024).

## 3 | Data and Methods

In this study, two recently collected sandstone samples from the late Oligocene Enping Sag in the northern PRMB (samples E1 and E2), along with 32 published late Oligocene samples from the whole PRMB (Shao et al. 2016, 2019; Wang et al. 2017, 2019; Cao et al. 2018; Yan et al. 2018; He et al. 2020; Hu et al. 2023) and 58 published samples from potential source areas, were employed for a systematic provenance analysis. The Pearl River tributaries were used as a proxy for the paleo-drainage system and to represent potential source areas. Zircon sample sets for potential source areas and late Oligocene depositional sinks are reported in Tables S1 and S2, respectively. Two conducted but unpublished zircon samples (E1 and E2) from the Enping Sag in the northern PRMB were provided by the China National Offshore Oil Corporation. U–Pb dating was performed by laser ablation-inductively coupled plasma-mass spectrometry, using a spot size of 30 μm and a laser frequency of 10 Hz. The analysis included a background acquisition of ca. 25 s, followed by 50 s of data acquisition for each spot. Zircon 91,500 was used as an external standard and zircon Plešovice was used to monitor the accuracy of the acquired U–Pb data. The best ages of zircon U–Pb dating with a 1σ level of uncertainty were selected from $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages for zircon younger and older than 1000 Ma, respectively, and the grains with > 10% age discordance were discarded. Zircon U–Pb ages were visually shown as kernel density estimate (KDE) plots with a bandwidth of 15 Ma (Vermeesch 2012). A Kuiper test was used to statistically evaluate the similarity between the zircon U–Pb ages of the different samples. The smaller the Kuiper test-based V value, the more similar the multi-sample age signatures. Kuiper test-based multidimensional scaling (MDS) was employed for further comparison of the zircon U–Pb ages. The MDS plot separates the samples with different U–Pb age spectra and groups those with similar U–Pb age spectra (Vermeesch 2013). The KDE visualisation, Kuiper test and MDS analysis were conducted using the Python-based detritalPy program (Sharman et al. 2018). In addition, a Monte Carlo approach was used to estimate the relative contributions of potential source areas to the late Oligocene PRMB. The cross-correlation coefficient, Kuiper, and K-S tests were implemented in the Monte Carlo modelling, and the preferred contributions based on the K-S test were presented in this study. The Monte Carlo modelling was conducted using the Matlab-based DZmix program (Sundell and Saylor 2017).

## 4 | Results

157 concordant zircon U–Pb ages ranging from 3238 Ma to 92 Ma have been obtained from the two late Oligocene samples, E1 and E2, and these ages are reported in Table S3. The age spectrum of sample E1 is characterised by major Yanshanian and Caledonian peaks (at ca. 159 and 432 Ma, respectively) with minor Indosinian and Neoproterozoic clusters (Figure 3A). Sample E2 exhibits a multi-modal age distribution, with well-developed Caledonian, Yanshanian and Indosinian peaks at ca. 434, 155 and 247 Ma, respectively (Figure 3B).

## 5 | Discussion

### 5.1 | Source-to-Sink Correlation

In Figure 4, the KDE plots of these late Oligocene samples are presented to illustrate the difference in zircon age signatures between the multiple units of the PRMB. For the northern PRMB (Figure 4C), the late Oligocene deposits show a similar age signature to the northeastern tributaries of the Pearl River. They are dominated by a major Yanshanian age peak with some Indosinian and Caledonian clusters. Quite different from the age distribution in the western tributaries of the Pearl River (Figure 2B), the Neoproterozoic and Paleoproterozoic clusters are rare in the northern PRMB. Thus, we infer that the northern PRMB was mainly fed by the northeastern tributaries of the Pearl River and that the western tributaries made little contribution during this time. A Caledonian age peak is also observed in the Enping Sag in the northern PRMB, indicating some likely effects from the Yunkai Massif. For the western PRMB (Figure 4A), a major Caledonian age peak, similar to that of the Yunkai Massif, is found in both Wenchang and Yangjiang Sags, showing the significant contribution of the Yunkai Massif to the western PRMB. In addition, the Yanshanian age peak and Indosinian cluster are also found in the Yangjiang Sag, probably caused by the sediment contribution of the northeastern tributaries of the Pearl River. For the southern PRMB (Figure 4B), the Baiyun Sag exhibits a more complex age distribution towards the west. The eastern Baiyun Sag is dominated by a single Yanshanian age peak. A similar unimodal Yanshanian age distribution can be observed in both the East Cathaysia Block and the igneous basement of the PRMB, but younger (late Yanshanian at ca. 140 Ma) in the former and older (early Yanshanian at ca. 153 Ma) in the latter (Figure 2). Therefore, the early Yanshanian age peak in the eastern Baiyun Sag probably indicates an intrabasinal basement source during the late Oligocene. The western and central Baiyun Sag are characterised by major Yanshanian and Caledonian age peaks with a minor Indosinian cluster, probably fed by the northeastern tributaries of the Pearl River and the Yunkai Massif. Furthermore, the significant Yanshanian, Indosinian, and Caledonian age populations are found in the Kaiping and Liwan Sags in the southern PRMB, where they may be caused by multiple contributions from the northeastern tributaries of the Pearl River and the Yunkai Massif. In contrast to the complex age distributions in the northern, western and southern PRMB, the eastern PRMB is dominated by a simple late Yanshanian age peak (Figure 4D), indicating an East Cathaysia Block main source. For the Central Uplift Zone (Figure 4E), the western and central parts of the Central Uplift Zone are dominated by a strong Yanshanian age peak with minor Indosinian and Caledonian clusters, indicating the contribution of the northeastern tributaries of the Pearl River, while the eastern part of the Central Uplift Zone is dominated by a unimodal early Yanshanian age peak, indicating an intrabasinal basement source.

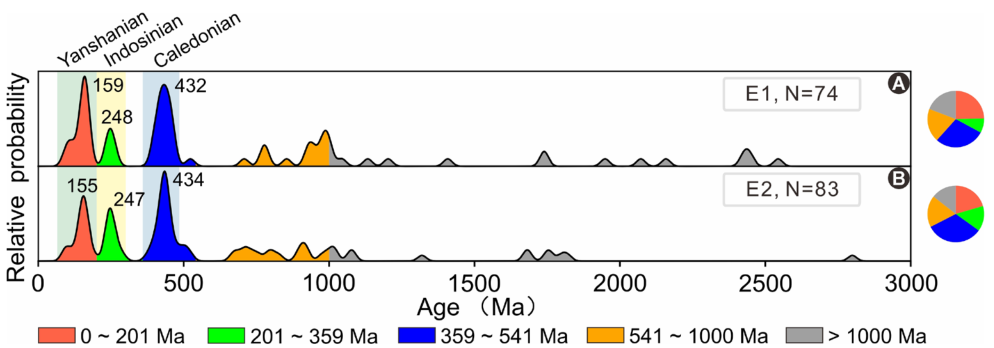


**FIGURE 3** | KDE plots of zircon U–Pb age spectra of two late Oligocene samples from the Enping Sag in the northern PRMB, northern South China Sea. Pie charts are used to indicate the percentage proportions of identified ages. N, number of analytical zircon grains.

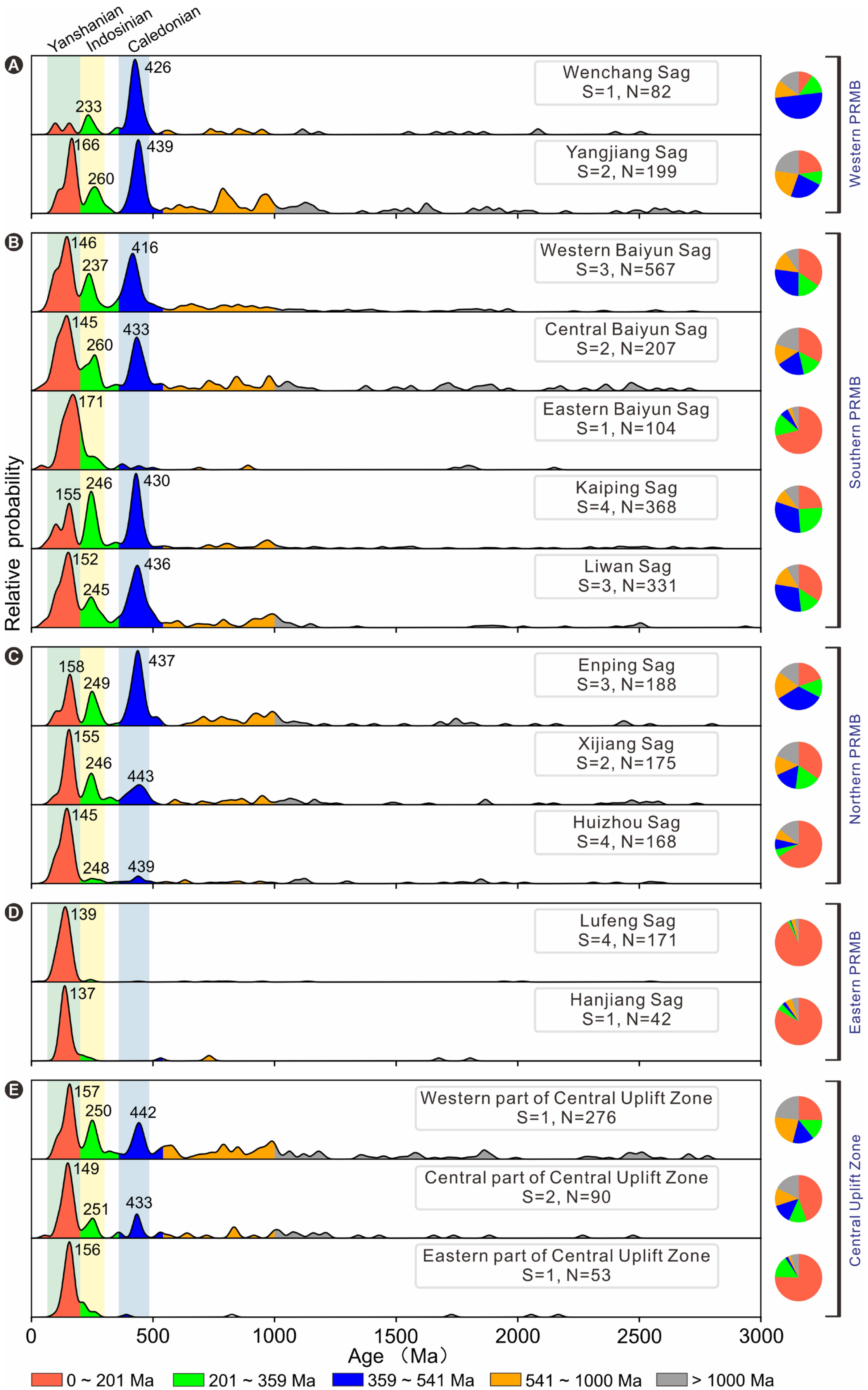


**FIGURE 4** | KDE plots of zircon U–Pb age spectra from different units of the late Oligocene PRMB. Pie charts are used to indicate the percentage proportions of identified ages. N, number of analytical zircon grains; S, number of analytical samples. See the data sources in Table S2.

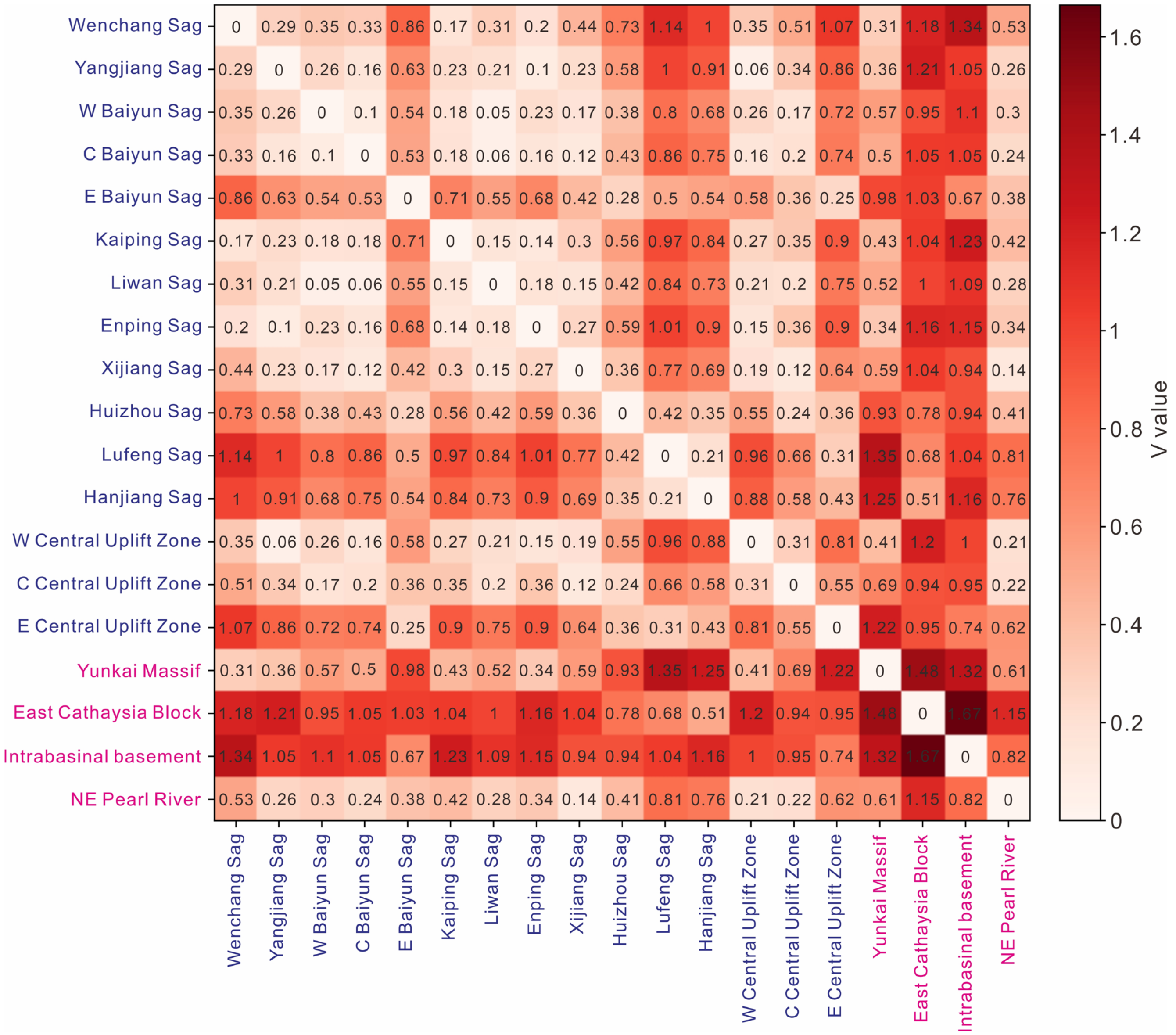


**FIGURE 5** | Heat map showing the similarity of zircon U–Pb age spectra between the late Oligocene PRMB samples and their source areas based on a Kuiper test.

Visual comparison of KDE plots identifies the source areas of the late Oligocene PRMB as the northeastern tributaries of the Pearl River, the Yunaki Massif, the East Cathaysia Block and the intrabasinal basement. A Kuiper test and MDS analysis provide further details of the correlation between source areas and depositional sinks. As graphically represented in Figure 5, the Yunkai Massif displays lower V values for the western and southern parts of the PRMB; the East Cathaysia Block shows lower V values for the eastern PRMB; the intrabasinal basement shows lower V values for the eastern Baiyun Sag in the southern PRMB and for the eastern part of the Central Uplift Zone; and the northeastern tributaries of the Pearl River show lower V values for the northern and southern parts of the PRMB as well as for the western and central parts of the Central Uplift Zone.

A MDS plot based on the Kuiper test is shown in Figure 6. Zircon samples from different units of the PRMB and from source areas are divided into four groups. The Wenchang, Yangjiang, Kaiping, Enping, Liwan, western and central Baiyun Sags, western Central Uplift Zone and their likely source, the Yunkai Massif, are labelled as Group A; the Lufeng, Hanjiang, Huizhou, and the likely source of the East Cathaysia Block are labelled as Group B; Group C, affected by the northeastern tributaries of the Pearl River, includes all the sags of the northern and southern PRMB, the Yangjiang Sag in the western PRMB, and the Central Uplift Zone; the eastern Baiyun Sag, eastern part of the Central Uplift Zone, Huizhou Sag, and their likely source of the intrabasinal basement are labelled as Group D.

Based on a comprehensive analysis of the KDE visualisation, Kuiper test and associated MDS comparison, a source-to-sink correlation from the multiple sediment sources to the late Oligocene PRMB is proposed. Detritus eroded from the Yunkai Massif was mainly transported to the western and southern PRMB, detritus from the East Cathaysia Block mainly dominated the eastern PRMB, and detritus delivered by the

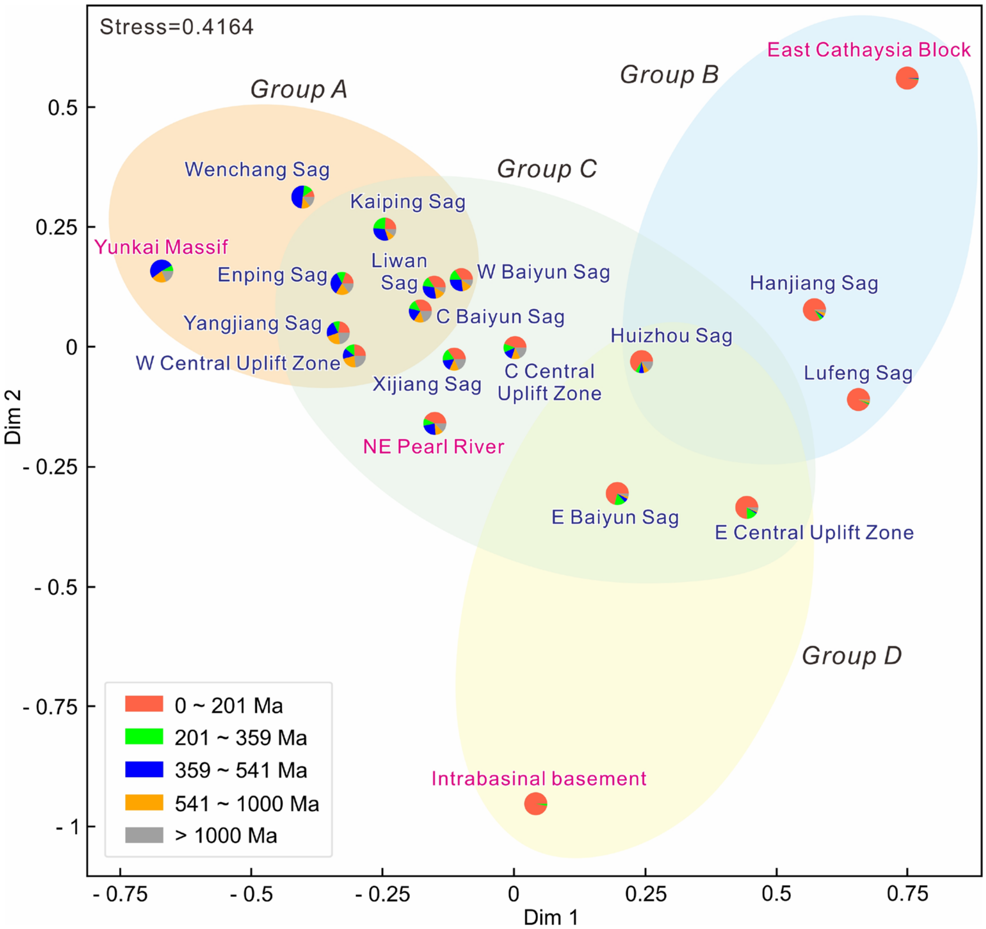


**FIGURE 6** | Multidimensional scaling plots of zircon U–Pb age spectra for the late Oligocene PRMB samples and their source areas.

northeastern tributaries of the Pearl River mainly dominated the northern and southern PRMB. In addition, the intrabasinal basement had some effects on the eastern Baiyun Sag in the southern PRMB and on the eastern part of the Central Uplift Zone.

## 5.2 | Relative Sediment Contribution

The varying contributions of different source areas to the late Oligocene PRMB is estimated using a Monte Carlo model. In this approach, the results of the KDE, Kuiper test, and MDS analyses are used to constrain the different source areas for the various units of the PRMB. Here, the Yunkai Massif, the northeastern tributaries of the Pearl River, and the intrabasinal basement are defined as source areas for the southwestern PRMB, including the western PRMB, the southern PRMB, the Enping Sag in the northern PRMB and the western part of the Central Uplift Zone; while the East Cathaysia Block, the northeastern tributaries of the Pearl River and the intrabasinal basement are defined as source areas for the northeastern PRMB, including the eastern PRMB, the Xijiang and Huizhou Sags in the northern PRMB, and the eastern and central parts of the Central Uplift Zone.

As revealed by the age populations of 29 boreholes presented in Figure 7A, the late Oligocene PRMB had a more complex age distribution towards the southwest. The northeast is characterised by a major Yanshanian age cluster, while the southwest is characterised by a significant Caledonian age cluster with a wide age distribution. The estimated relative contributions of age-diagnostic source areas to the late Oligocene PRMB are reported in Table S4 and the K-S test-based contributions are shown in Figure 7B. Sediments in the western PRMB were mainly contributed by the Yunkai Massif, while in the eastern PRMB, materials were mainly contributed by the East Cathaysia Block. The southern PRMB sediments were contributed by the Yunkai Massif and the northeastern tributaries of the Pearl River simultaneously. For the northern PRMB, apart from the contribution from the northeastern tributaries of the Pearl River, the Huizhou Sag was also affected by the East Cathaysia Block, and the Enping Sag was mainly dominated by the Yunkai Massif source.

Regarding the significant Caledonian age clusters in the southern PRMB, previous studies suggested that they were contributed by the catchment of the Xiangjiang River, one of the tributaries of the Yangtze River (Yan et al. 2018), or by the rivers of Central Vietnam (Shao et al. 2019). Actually, these Caledonian age clusters can also be traced in the western PRMB and in the Enping Sag in the northern PRMB (Figure 4). We suggest that the significant Caledonian age cluster was likely contributed by the Yunkai Massif in the northwest of the PRMB. This is further supported by the decreasing percentage of the Caledonian age population and the decreasing relative contribution of the Yunkai Massif from the western to the southern PRMB during the late Oligocene (Figure 7).

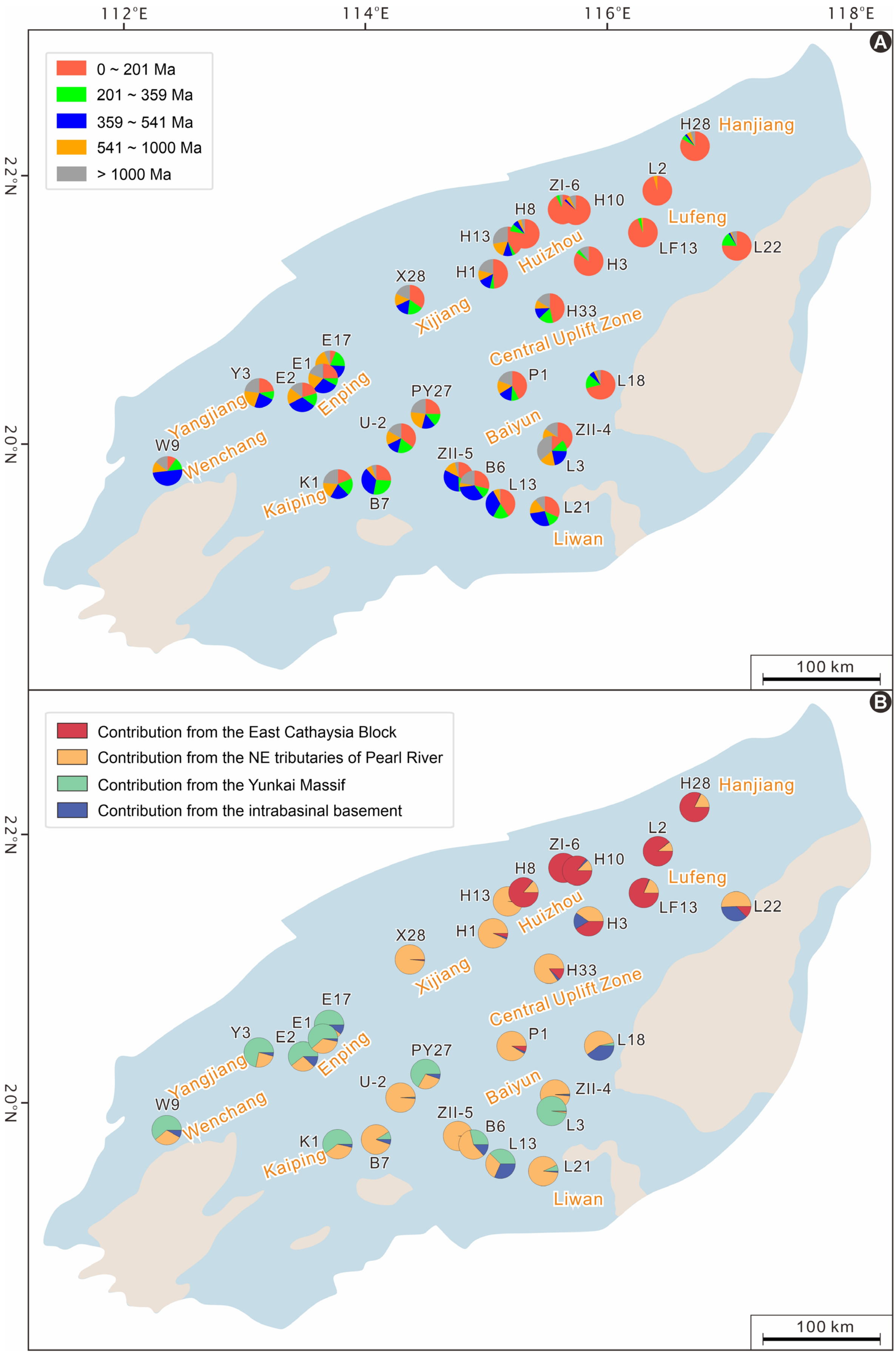


**FIGURE 7** | Geological map of the PRMB with pie charts showing (A) percentage proportions of identified ages in these late Oligocene samples and (B) relative sediment contributions of source areas to these samples.

### 5.3 | Implications for the Drainage Network

#### 5.3.1 | Late Oligocene Drainage Pattern

The Yangtze Block has an Archean to Proterozoic basement with a complex zircon U–Pb age distribution (Xu et al. 2007). Compared to the other potential sources, the sediments of the western tributaries of the Pearl River draining the Yangtze Block are characterised by abundant Neoproterozoic and Paleoproterozoic age clusters (Figure 2). However, the late Oligocene Huizhou and Xijiang Sags in front of the Pearl River estuary exhibit a similar age distribution, with rare Neoproterozoic and Paleoproterozoic clusters, to the north-eastern tributaries of the Pearl River (Figure 4). As sediments from the northern PRMB show greater sensitivity to the Pearl River evolution than those from the western and southern PRMB, the zircon signature of the northern PRMB probably excludes the Yangtze Block as a catchment for the paleo-Pearl River during the late Oligocene. In addition, as stated above (Sections 5.1 and 5.2), the late Oligocene paleo-Pearl River had a significant impact on the northern and southern PRMB, which is different from the dominant role of the Pearl River in the PRMB since the Miocene (Cao et al. 2018; Shao et al. 2019; Liu, Chen, et al. 2022). We thus infer that the paleo-Pearl River underwent only limited development within the Cathaysia Block in the late Oligocene.

The Nanduhe River, with a limited catchment area, flows from the south margin of the Yunkai Massif into the northern SCS in the present day (Figure 1A), and the sediments in the Nanduhe River estuary exhibit a similar Caledonian age peak to the Yunkai Massif (Zhong et al. 2017). Based on the zircon U–Pb geochronology, a significant Yunkai Massif source is identified for the PRMB, and it had a previously overlooked effect on the western and southern PRMB during the Oligocene (Figure 8). We thus infer that the paleo-Nanduhe River, with a larger catchment area, flowed through the Yunkai Massif into the PRMB during the Oligocene. While the paleo-Pearl River contributed to the northern and southern PRMB and the paleo-Nanduhe River contributed to the western and southern PRMB, the small mountainous rivers in the East Cathaysia Block made an obvious contribution to the eastern PRMB during the late Oligocene (Jiao et al. 2018).

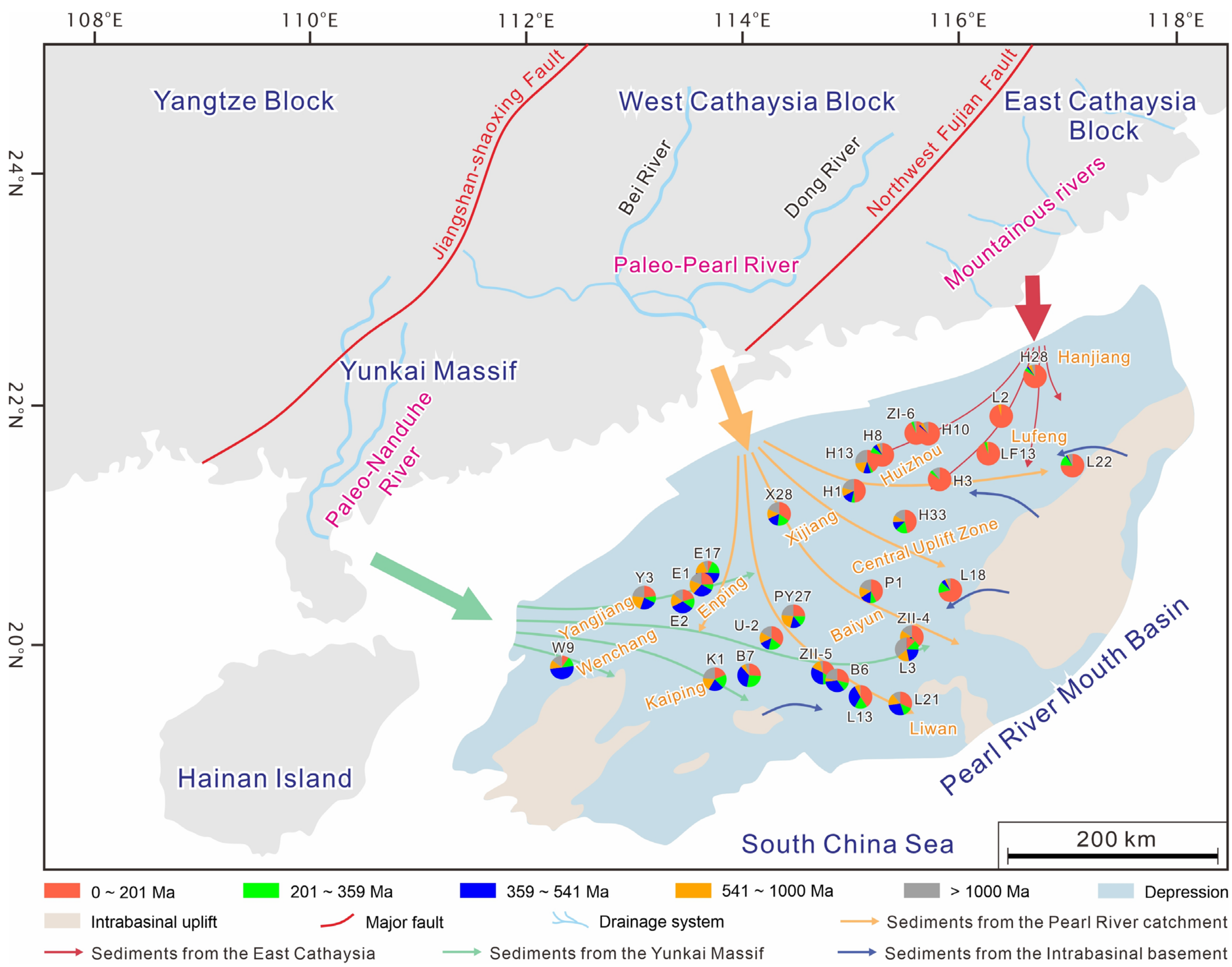


**FIGURE 8** | Schematic diagram with reconstructed drainage networks illustrating the source-to-sink system from the South China Block to the PRMB during the late Oligocene. Zircon U–Pb age signatures of the late Oligocene PRMB are also shown.

### 5.3.2 | Early Miocene Drainage Reorganisation

Taking evidence from a growing number of zircon U–Pb geochronological studies on the PRMB, a rapid increase in the proportion of Neoproterozoic zircon age clusters (1000 ~ 541 Ma) between the late Oligocene and the early Miocene sediments in borehole X28 in the northern PRMB probably indicates the westward expansion of the paleo-Pearl River (Figures 8 and 9; Cao et al. 2018; Shao et al. 2019). In addition, the high abundance of the Caledonian zircon ages, which was recorded in the Paleogene sediments, gradually decreased in the western and southern PRMB after the late Oligocene (Figure 9; Yan et al. 2018; Shao et al. 2019; Liu, Chen, et al. 2022; Hu et al. 2023), and the paleo-Nanduhe River appears to have lost its upstream catchment area and to have contributed little to the PRMB in the early Miocene.

The geometry and evolution of drainage systems are closely linked to the tectonic deformation of the landscape and the resulting climatic variability (Clark et al. 2004; Nie et al. 2018). Researchers widely accept that the Tibetan Plateau uplift dominated the East Asia landscape in the Cenozoic (Wang et al. 2014; Ding et al. 2022; Lu et al. 2023). It has been summarised that the Tibetan Plateau has evolved through three stages: the formation of a regional proto-plateau (40~30 Ma), the outward growth of the plateau (30~25 Ma), and the formation of the present-day configuration of the plateau (25~15 Ma). During the 25~15 Ma interval, following the delamination and break-off of Indian and Asian lithosphere, widespread magmatism developed within the southern and northern Tibetan Plateau, and the surface uplifted rapidly from the late Oligocene onwards (Ding et al. 2022). In addition, evidence from apatite and zircon fission-track thermochronology suggests that significant exhumation of the Yunkai Massif has occurred since 25 Ma, triggered by the India-Asia collision and associated lateral extrusion of the Indochina Block (Li et al. 2005). As the Tibetan Plateau continued to uplift and approach its present elevation, the East Asian monsoon circulations strengthened during the early Miocene (Clift, Hodges, et al. 2008; Wu et al. 2022; Lu et al. 2023; Lin et al. 2024), thereby enhancing precipitation and accelerating erosion of the

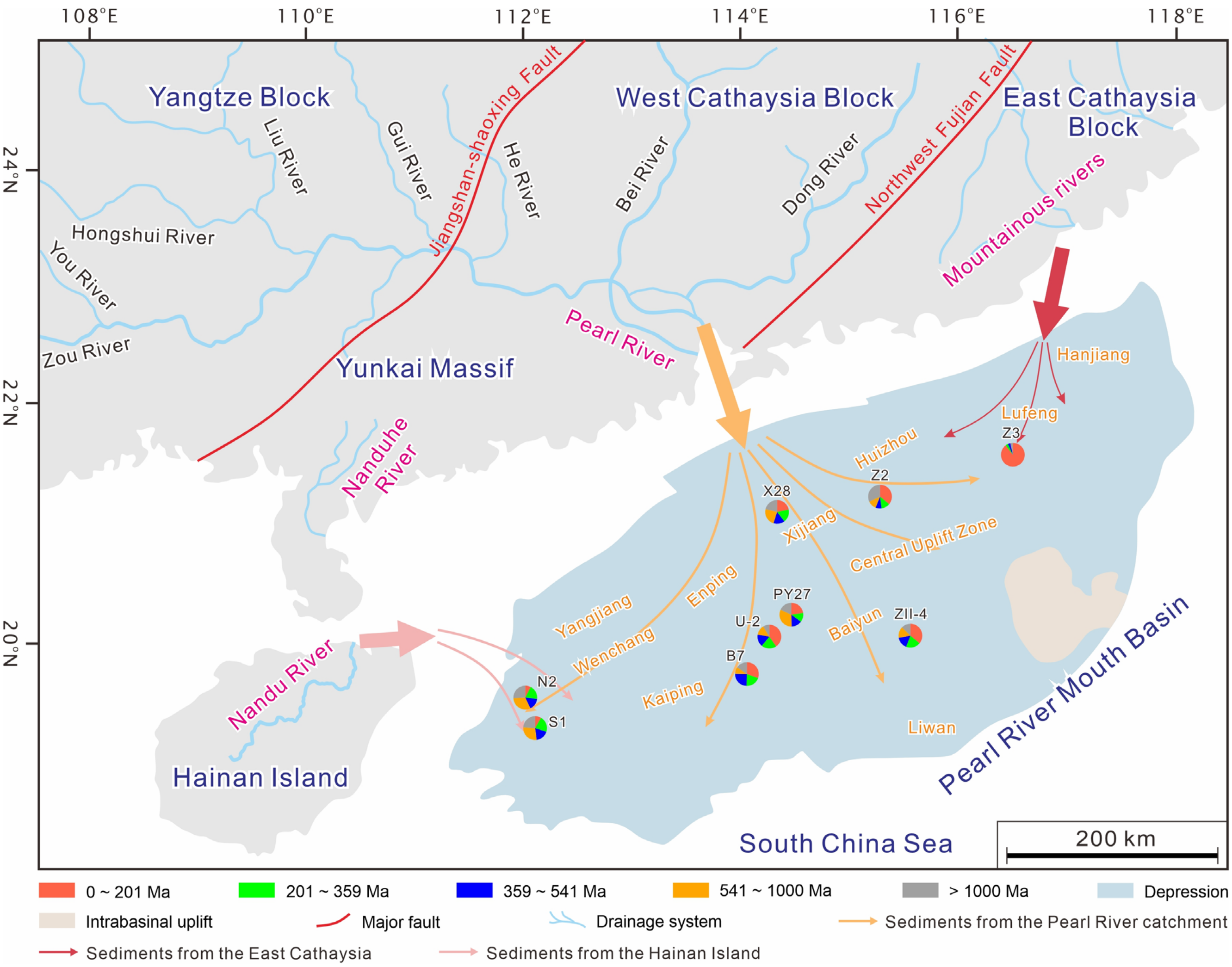


**FIGURE 9** | Schematic diagram with drainage networks illustrating the source-to-sink system from the South China Block to the PRMB during the early Miocene. Zircon U–Pb age signatures of the early Miocene PRMB are also shown. Early Miocene samples from boreholes N2 and S1 are from Liu, Chen, et al. (2022); B7 is from Yan et al. (2018); U-2 and ZII-4 are from Shao et al. (2019); PY27 is from Hu et al. (2023); X28 is from Cao et al. (2018), Shao et al. (2019); Z2 and Z3 are from Liu, Suo, et al. (2022). Sediment routing from Hainan Island to the western PRMB is modified from Liu, Chen, et al. (2022).

drainage system. Taking together the significant surface uplift and strengthening of the monsoon in East Asia and the sediment provenance archives in the PRMB, we favour a westward expansion of the paleo-Pearl River, approaching its current pattern by the early Miocene. Triggered by the Yunkai Massif exhumation, the upstream part of the paleo-Nanduhe River was captured by the Pearl River during the early Miocene, and, like today, the Nanduhe River only drained the south margin of the Yunkai Massif (Figure 9).

In accordance with global eustatic fluctuations, a substantial rise in sea level occurred in the PRMB during the early Miocene (Haq et al. 1987; Qin 2002). Marine fossils have only been documented in the northern PRMB since the early Miocene (ca. 22 Ma), suggesting that these areas were dominated by terrestrial or littoral environments prior to this time (Pang et al. 2007). The late Oligocene of ODP Site 1148 in the southern PRMB was a mid- to upper-slope environment with water depths of about 1000 m, whereas it became a lower-slope environment with water depths of more than 1500 m in the early Miocene (Shao et al. 2004; Zhao 2005). It is inferred that the drainage expansion, in conjunction with sea level rise, resulted in an increased delivery of detrital material to the expansive PRMB through the Pearl River. Compared to the late Oligocene, the Nanduhe River lost its effect on the PRMB, and the PRMB was almost completely dominated by the Pearl River in the early Miocene (Figure 9).

## 6 | Conclusions

The PRMB exhibited marked provenance variability during the late Oligocene. The late Oligocene PRMB was fed by a hitherto overlooked paleo-Nanduhe River draining the Yunkai Massif, accompanied by the paleo-Pearl River draining the Cathaysia Block, the mountainous rivers draining the East Cathaysia Block, and the intrabasinal basement. Unlike the early Miocene or present day, the paleo-Nanduhe River had a larger catchment area and made a significant sediment contribution to the western and southern PRMB during the late Oligocene. Simultaneously, the paleo-Pearl River developed only to a limited extent with an obvious contribution to the northern and southern PRMB. Following the growth of the Tibetan Plateau and the exhumation of the Yunkai Massif, the paleo-Pearl River expanded westwards and apparently captured the upstream part of the paleo-Nanduhe River in the early Miocene, resulting in the present-day Pearl River with a dominant effect on the PRMB.


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#### Conflicts of Interest

The authors declare no conflicts of interest.

#### Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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**Supporting Information**

Additional supporting information can be found online in the Supporting Information section.