

Article

Provenance Shift during the Plio-Pleistocene in the Vertex of Yangtze Delta and Its Geomorphological Implications

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Abstract: One of the key issues of the Source-to-Sink process is revealing the geomorphological evolutions of large rivers from the perspective of river sink areas. This study aims to reveal the provenance change near the vertex of the Yangtze delta during the late Cenozoic and provide insight into the Yangtze channelization into the sea due to regional tectonic subsidence. Heavy minerals and zircon geochronology in the Plio-Pleistocene sediments of the vertex of the modern Yangtze delta (core RGK15) reveal that a significant provenance shift occurred at ~2.6 Ma (the beginning of the Pleistocene). During the Pliocene, ultra-stable heavy minerals and pre-Mesozoic zircon grains predominated in the sediments, probably derived from contemporary outcrops of sedimentary rock that were widely distributed in the delta and its surrounding area. They are completely different from those in the Pliocene sediments of the south delta, indicating that decentralized, local, small watersheds dominated the Yangtze delta during the Pliocene. This resulted from the relatively elevated terrain of this region due to the adjacent ancient Zhejiang–Fujian Uplift (ZFU) at that time. However, diversified heavy minerals and zircon geochronology similar to those of the modern upper Yangtze fingerprints occur in the Pleistocene sediments of core RGK15, implying that a significant provenance shift to the Yangtze River occurred here at ~2.6 Ma. The provenance shift recorded by the cores in the south delta mainly occurred at ~1.2 Ma, indicating that the Yangtze River channel was dragged southward with the further subsidence of the ancient Zhejiang–Fujian Uplift. This study reveals the southward migration process of the Yangtze River channel with the regional tectonic subsidence from the perspective of provenance evolution, which contributes to an understanding of when the Yangtze River channelized into the sea.

Keywords: heavy mineral; zircon geochronology; Yangtze River; Cenozoic; ancient Zhejiang–Fujian Uplift

1. Introduction

The evolution of large rivers on Earth is controlled by tectonics and climate that occurred through geologic time, and those originating from the Tibetan Plateau are the most typical examples. The uplift of the Tibetan Plateau during the Cenozoic generated large rivers in South Asia that flow southward into the South China Sea, such as the Ganges River and the Mekong River, while those in East Asia

flow eastward into the East China Sea, such as the Yellow River and the Yangtze River. When these large rivers started to flow into the sea has always been a research topic of interest [1–4].

Compared with South Asian rivers, the large rivers of East Asia have a wider drainage basin and complex geological backgrounds. Among them, the basin-scale geomorphological evolutions of the Yangtze River and the Yellow River receive the most attention, because of their important contribution to material flux in the marginal seas of China [5–7]. For example, research on the formation time of the Yangtze River basin has been ongoing for a century [1,2,4,8–16]. The research locations and methods used in studying this scientific topic have changed with time. Early studies mostly focused on the upper Yangtze reached to find geomorphological evidence, especially for the capture time of the upper main tributary of Jinsha River [2,17,18]. However, as a result of technology improvement, the research concept of Source to Sink has been applied in recent years to reveal the geological evolution of the Yangtze River by tracing sediment fingerprints of the source area in the sedimentary strata of the sink area. The research locations have correspondingly shifted to the sedimentary basins of the middle and lower reaches and the estuary [4,10–16].

As the terminal sedimentary basin to the sea, the modern Yangtze delta has attracted growing attention for its potential to provide insight into the evolution of the Yangtze River, because it contains geological records of the whole drainage basin. Most studies have focused on the south delta plain to trace the provenance of the Yangtze River throughout the late Cenozoic strata (~5 Ma), using sediment provenance proxies such as heavy minerals, clay minerals, geochemistry, magnetism and zircon geochronology [4,10–16]. These studies have revealed that a provenance shift related to the Yangtze River occurred in the Early Pleistocene. However, as a result of the limitations of the research locations, they have been unable to determine the age of the Yangtze River formation in terms of this provenance shift. At the site where the Yangtze River flows out of Zhenjiang, in which the vertex of the modern Yangtze delta is located, its main channel is no longer controlled by rocks and can fluctuate wildly (Figure 1). Chen and Stanley (1995) [19] reported the thickness of Cenozoic strata over the Yangtze delta and pointed out that 200–400 m of unconsolidated sediments were deposited above bedrock in the south plain, while >1000 m of semi-consolidated sediments were deposited in the north plain. Therefore, it is necessary to clarify the provenance evolution of the north delta or of the vertex of the delta during the late Cenozoic.

Given the difficulty of drilling into the bedrock in the north delta plain owing to the thickness of the late Cenozoic strata, the vertex of the Yangtze delta is a better research location. This study aims to reveal the provenance change near the vertex of the Yangtze delta during the late Cenozoic and provide insight into the issue of Yangtze channelization into the sea using heavy mineral and zircon geochronology. The effect of regional tectonic subsidence on the geomorphological evolution of the Yangtze River is further discussed by comparing the provenance change of the south delta plain during the late Cenozoic.

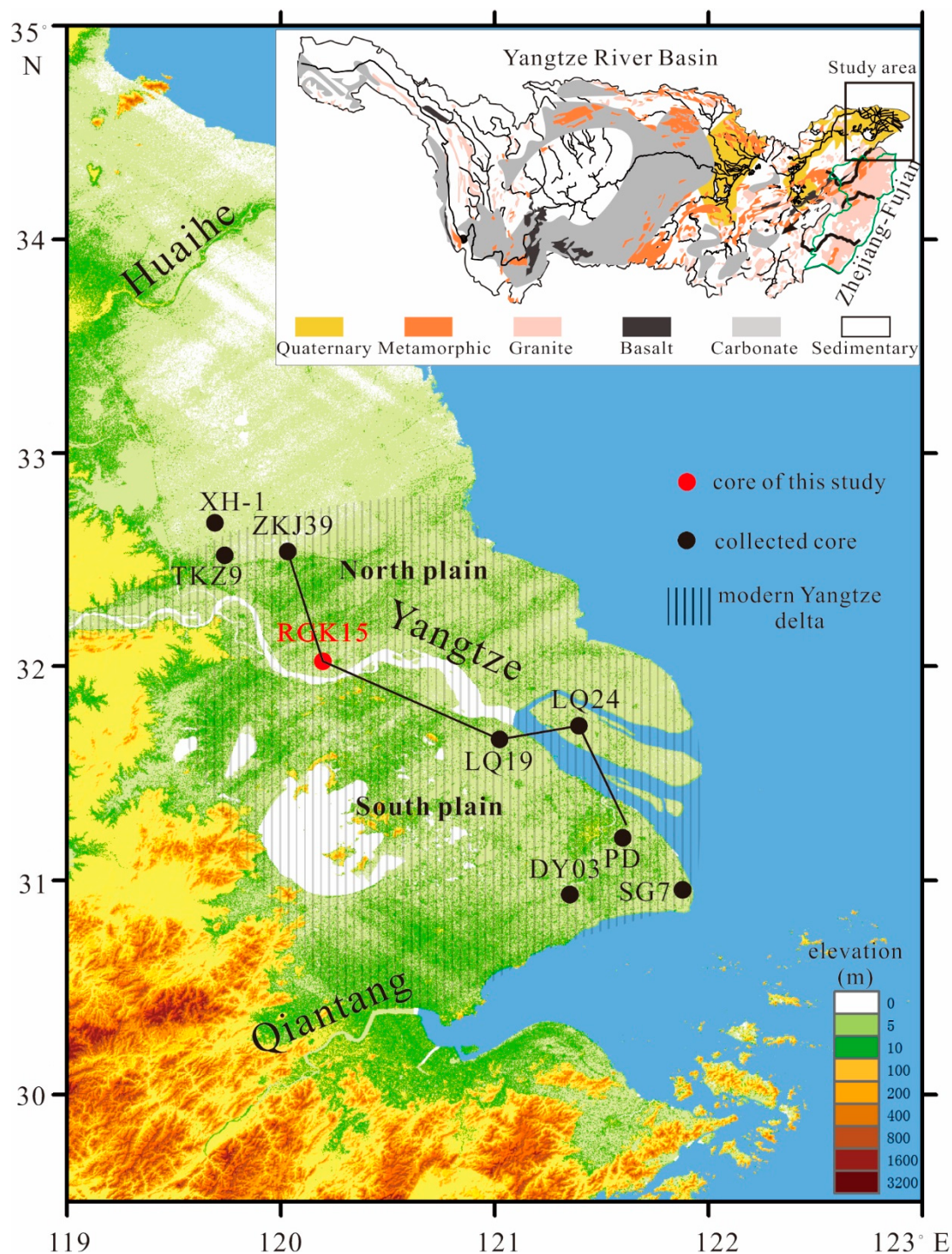


Figure 1. Topographic map and Plio-Pleistocene cores in the Yangtze delta and its surrounding area. The inset in the upper right corner is the geological map of the Yangtze River Basin and the south-eastern coast of China.

2. Regional Geological Setting

The Yangtze River originates from the Tibetan Plateau and flows eastward into the East China Sea, with a length of ~6300 km and a huge drainage basin area of $\sim 1.8 \times 10^6$ km². The river is divided into the upper, middle and lower reaches in terms of three major topographic steps of China from the west to the east. The upper reach is above Three Gorges Valley (Yichang City) within the first step of high elevation (>2000 m). Paleozoic-Mesozoic carbonate and sedimentary rocks dominate the upper basin,

along with a large-scale Mesozoic basaltic outcrop (the E'mei Basalt) and some Cenozoic felsic igneous rocks [20]. The middle reach extends to the estuary of Poyang Lake (Hukou City), and below Hukou is the lower reach. The middle and lower basins are dominated by sedimentary rocks, with some felsic igneous rocks and metamorphic rocks of the Paleozoic–Mesozoic [20].

At the point where the Yangtze River flows out of Zhenjiang, it enters the delta area where the channel is no longer controlled by bedrock (Figure 1). The Yangtze delta is the most downstream terrestrial depocenter before the Yangtze River flows into the sea, including the north and south plains bounded by the main channel. Geological surveys indicate that thick late Cenozoic sediments were deposited on Mesozoic–Cenozoic bedrocks of the Yangtze delta, with >1000 m in the north plain and 200–400 m in the south plain [19].

3. Materials and Methods

A sediment core (RGK15) with a 318-m length to the bedrock was recovered by rotary drilling from the vertex of the Yangtze delta plain (Figure 1). The core was split for photographing, lithology characterization and sampling in the laboratory.

The chronology of the core was determined by the paleomagnetic pole, combined with ages derived from Optically Stimulated Luminescence (OSL) and Accelerator Mass Spectrometry (AMS ^{14}C). A total of 606 oriented samples were taken in the fine sediment mainly composed of clay and silt for paleomagnetic analysis, and no samples were taken in gravelly sands, which often occur in the mid-lower part of the core. A paleomagnetic analysis was carried out following standard procedures at the State Key Laboratory of Marine Geology, Tongji University. Five and three samples were taken in the upper core for AMS ^{14}C and OSL dating, respectively (Tables 1 and 2; Figure 2). AMS ^{14}C ages were evaluated in the School of Archaeology and Museology, Beijing University, and OSL ages were determined by the School of Marine Science and Engineering, Nanjing Normal University. All AMS ^{14}C ages were calibrated through tree-ring correction, and those that exceeded 90% confidence at 2-sigma were adopted in this study (Table 1 and Figure 2).

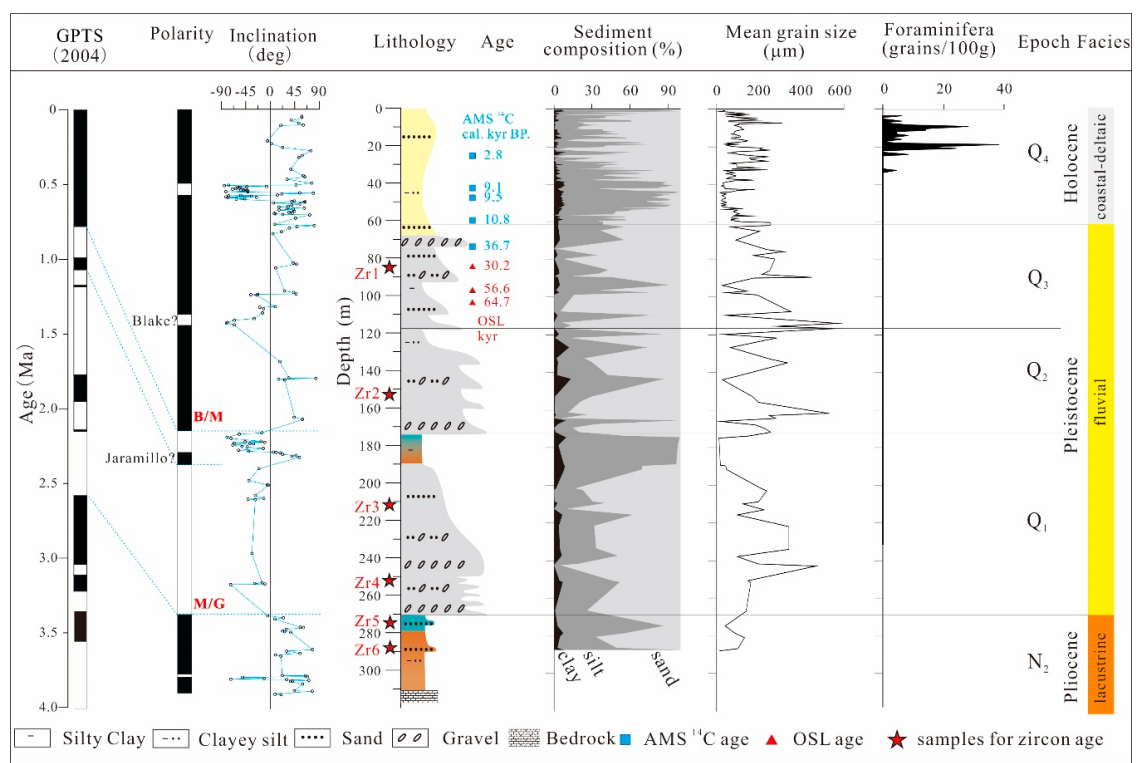


Figure 2. Chronology, lithology and facies of core RGK15. Showing the location of samples for zircon geochronology (Zr1–Zr6).

Table 1. AMS ^{14}C ages of core RGK15.

Depth (m)	Material	^{14}C Age(yr BP)	Calibrated Age (cal. yr BP)	Probability	Laboratory No.
26.4	Plant fragment	2660 $\pm$ 30	2808–2743	0.86	BA171865
45.2	Plant fragment	8205 $\pm$ 50	9305–9016	0.95	BA171869
45.9	Plant fragment	8580 $\pm$ 40	9625–9488	0.95	BA171870
63.0	Plant fragment	9410 $\pm$ 40	10,742–10,553	0.95	BA171872
71.9	Plant fragment	32,280 $\pm$ 270	36,853–35,550	0.95	BA171874

Table 2. Optically Stimulated Luminescence (OSL) ages of core RGK15

Depth (m)	Water Content (%)	K (%)	Th ($\mu\text{g/g}$)	U ($\mu\text{g/g}$)	Equivalent Dose	Age (Ka)	Age Error (Ka)	Grain Size (μm)	Laboratory No.
84	18.2	1.71	4.55	1.15	60.7	30.2	3.2	38–63	180123-15
97	27.7	1.8	6.32	1.22	114.9	56.6	5.8	38–63	180123-16
106	26.0	1.58	8.89	1.32	134.4	64.7	6.7	38–63	180123-17

The sediment facies of the core were determined by grain size and foraminifera abundance. A total of 186 samples were taken for grain size analysis with a sampling interval of ~ 0.5 m. All the samples were pre-treated with H_2O_2 and HCl to remove organic matter and carbonate, respectively, then disaggregated fully by adding sodium hexametaphosphate (NaPO_3)₆. A laser particle size analyzer (CoulterLQ-100) was used to measure sediment grain sizes (0.02–2000 μm) at the Nanjing Geological Survey Center, Nanjing, China. A total of 107 samples were taken for foraminifera statistics using a binocular microscope at the South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China.

Sediment provenance was identified in terms of heavy mineral and zircon geochronology. A total of 74 samples throughout the core were collected for heavy mineral analysis. Heavy minerals (63–125 μm) were separated by tribromomethane after removing authigenic minerals with 1 M HCl , and at least 300 grains were identified under binocular and polarizing microscopes. Zircon grains were picked out from six samples of the mid-lower core for zircon geochronology analysis (Figure 2). Zircon grains were photographed by a scanning electron microscope (XL-30 ESEM from Philips, Eindhoven, Netherlands), and their internal structures were revealed by cathodoluminescence (CL) imaging. More than 100 zircon grains were selected at random from each sample and tested for U–Pb dating by Laser Ablation–Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS, Agilent 7900, Santa Clara, CA, USA) in the State Key Laboratory of Marine Geology, Tongji University, Shanghai, China. Raw data of U–Pb ages were calibrated by zircon 91500 (1065.4 $\pm$ 0.3 Ma) as an external standard and monitored by zircon Plešovice (337.1 $\pm$ 0.37 Ma). Three kinds of ages ($^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{235}\text{U}$) were obtained following the method of [21]. Ages determined through $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ dating are representative of zircon ages of >1000 Ma and <1000 Ma, respectively [22]. Additionally, zircon ages with a discordance of $>10\%$ are considered invalid [23]. Zircon age spectra were generated by the R i386 3.4.3 program (<https://www.ucl.ac.uk/~ucfbpve/provenance>).

In addition, eight representative Plio-Quaternary sediment cores with paleomagnetic chronology and a relevant provenance proxy were collected from the Yangtze delta to help better understand sediment provenance evolution during the late Cenozoic [12,15,16,24–27].

4. Results

4.1. Chronology, Lithology and Facies of the Core RGK15

Paleomagnetic analysis of core RGK15 sediments reveals a normal polarity (Gauss epoch) on the core bottom below 270 m, and a reversed polarity (Matuyama epoch) between 272 m and 173 m, although gravelly sands are frequently present in the mid-lower core, which inevitably affects paleomagnetic sampling and data quality. Correspondingly, the Pliocene/Pleistocene boundary occurs at 272 m (~ 2.60 Ma) and the Early/Middle Pleistocene boundary is located at 173 m (~ 0.78 Ma; Figure 2).

The Jaramillo subchrons (~1.2–1.0 Ma) are recognized at depths of 190–185 m (Figure 2). The normal polarity Brunhes epoch is evidenced above 173 m. In terms of the OSL age (64 kyr) at a core depth of 103 m, the reversal polarity at 112 m is believed to be Blake subchrons (0.12 Ma), which is the beginning of the Late Pleistocene (Figure 2; Table 1). The AMS ^{14}C age of 10.8 cal. kyr BP at 59 m and 36.7 cal. kyr BP at 75 m indicates that the boundary of the Pleistocene/Holocene is defined at a core depth of 64 m, considering the lithology change (Figure 2; Table 1).

Reddish-bluish silty sediment of the Pliocene rests unconformably on bedrock at a depth of 311–272 m, implying lacustrine facies (Figure 2). The Pleistocene strata (272–64 m) contain about 12 sedimentary cycles consisting of gravels to grey sands or silts moving upwards, with four cycles in each stratum of the Early, Middle and Late Pleistocene (Figure 2). No foraminifera occur in the Pleistocene strata. All of these sedimentary characteristics reveal a typical fluvial environment. Silty and sandy sediments dominate the lower and upper strata of the Holocene (64–30 m and 30–0 m), respectively. Sand–mud couplets, formed as horizontal bedding in tidal-flat facies, are common in the lower Holocene strata and foraminifera are abundant in the upper Holocene strata, which shows a coastal-deltaic environment (Figure 2).

4.2. Heavy Mineral Characteristics in Core RGK15

The main heavy minerals throughout core RGK 15 are displayed in Figure 3. A significant change in diagnostic heavy minerals occurs at a core depth of 272 m (Figure 3).

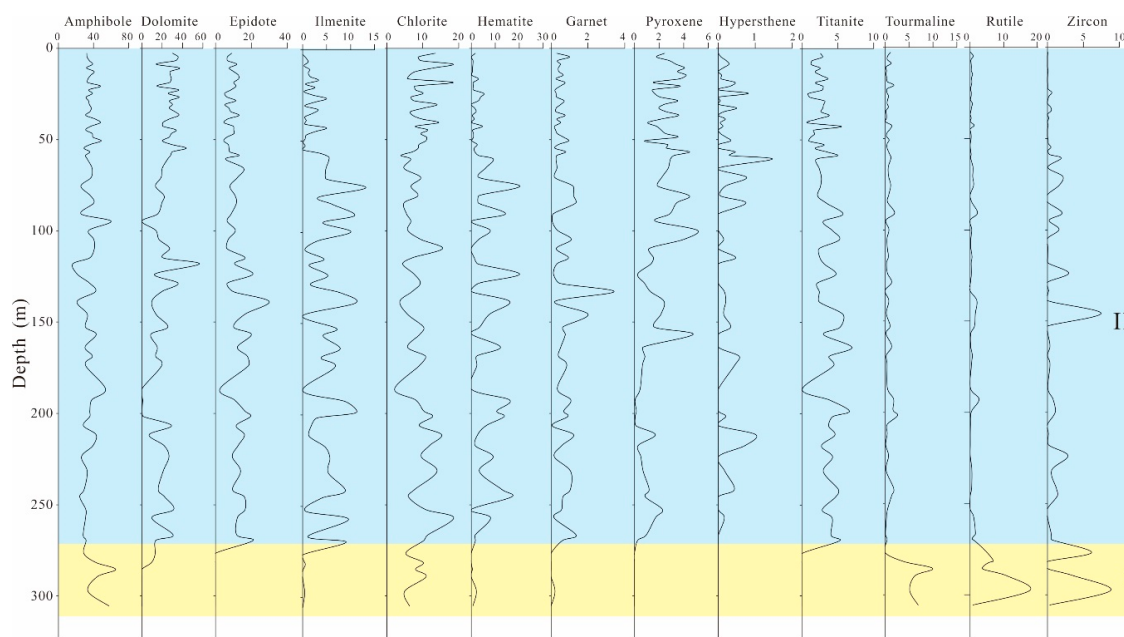


Figure 3. Heavy minerals of core RGK15. Two zones (Zone I of Pliocene and Zone II of Quaternary) can be identified.

Zone I (311–272 m, Pliocene) is represented by ultra-stable heavy minerals of zircon, rutile and tourmaline, with a total percentage of 30% (Figure 3). Amphibole accounts for 60%, and other minerals such as Ilmenite, Hematite and Garnet are rare. Notably, pyroxene, hypersthene and titanite are absent (Figure 3). Comparatively, a large variety of heavy minerals occur in Zone II (272–0 m, Quaternary), such as amphibole (~40%), dolomite (~30%), epidote (~10%), ilmenite (~5%) and hematite (~8%), among others. The minerals of zircon, rutile and tourmaline, characteristic of Zone I, decrease significantly to a total percentage of <5% (Figure 3), while the minerals that rarely occur in Zone I continuously appear at stable percentages in Zone II, such as pyroxene (<5%), hypersthene (<1%) and titanite (<5%) (Figure 3).

4.3. Detrital Zircon U–Pb Ages of Core RGK15

Most grains of detrital zircon in core RGK15 are square-pyramid-shaped and colorless or light pink. The cathodoluminescence image shows that concentric oscillatory zoning is well developed in most grains, indicative of an igneous origin (Figure 4). In total, 574 of 636 detrital zircon grains from six samples of the core RGK15 have high concordance U–Pb ages (concordance >90%), which can be used for age spectrum analysis (Figure 5). The zircon ages of the core RGK15 are distributed from the Cenozoic to the Archean, concentrated in the Paleoproterozoic (~1600–2500 Ma) and Neoproterozoic (~540–1000 Ma) with the notable absence or low abundance of Mesoproterozoic zircon grains (Figure 5; Table 3).

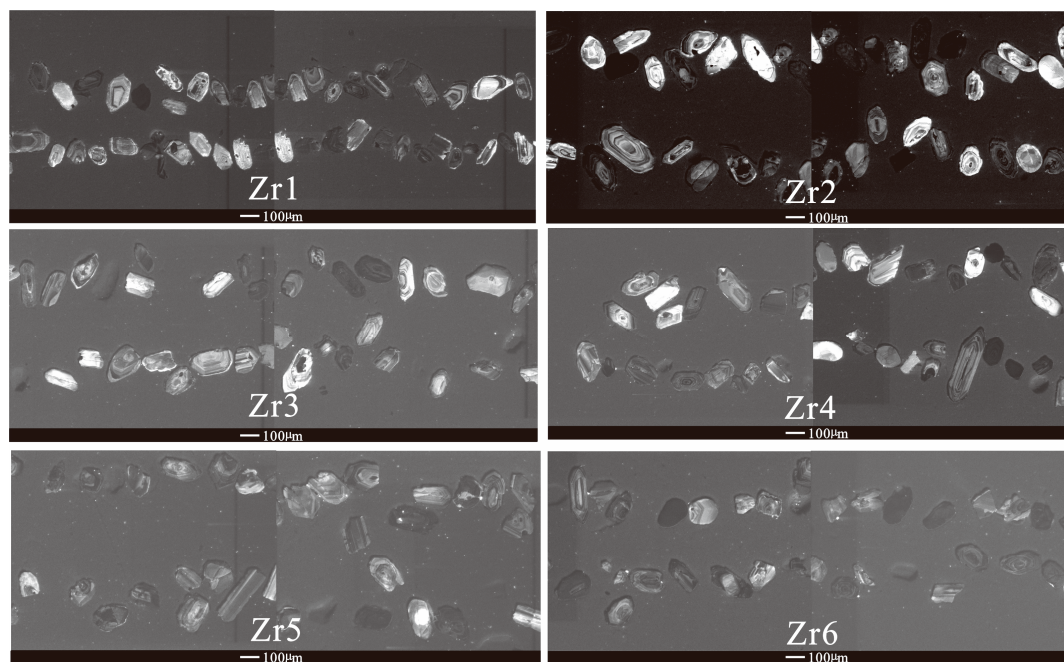


Figure 4. Morphology of detrital zircon in the sediments of the core RGK15.

Zircon age spectra of the samples of Zr5 and Zr6 (Pliocene) are completely different from those of the other samples. They are characterized by multiple peaks at ~500 Ma, ~800 Ma and ~2500 Ma (Figure 5). Proterozoic (~550–2500 Ma) and Paleozoic zircon grains (~250–540 Ma) are about 70% and 20%, respectively. (Table 3). In addition, Archean zircon grains (>2500 Ma) only contribute for ~5% (Table 3). Notably, Mesozoic zircons are rare, and no Cenozoic zircons (<65 Ma) are found (Table 3; Figure 5). Multiple age peaks at ~200 Ma, ~800 Ma, ~1800 Ma and ~2500 Ma occur in the zircon age spectra of the Quaternary samples (Zr1–Zr4) (Figure 5). Zircon ages are featured by increased Mesozoic zircon grains (>10%) and the occurrence of Cenozoic zircon grains (Table 3; Figure 5).

Table 3. Composition of zircon ages in core RGK15 (%).

Epoch	Cz	K	J	T	Pz2	Pz1	Pt3	Pt2	Pt1	Ar
Age (Ma)	<65	65–145	145–195	195–250	250–416	416–550	550–1000	1000–1600	1600–2500	>2500
Zr1	0.0	2.1	2.1	13.7	6.3	9.5	29.5	10.5	20.0	6.3
Zr2	1.0	4.0	2.0	14.0	10.0	9.0	34.0	6.0	15.0	5.0
Zr3	0.0	3.3	1.6	6.6	4.9	9.8	24.6	4.9	41.0	3.3
Zr4	0.9	8.1	2.7	4.5	12.6	8.1	33.3	6.3	22.5	0.9
Zr5	0.0	0.0	0.0	0.0	6.7	9.5	35.2	13.3	25.7	9.5
Zr6	0.0	1.0	0.0	0.0	8.8	12.7	35.3	16.7	24.5	1.0

Highlight represents the Pliocene samples.

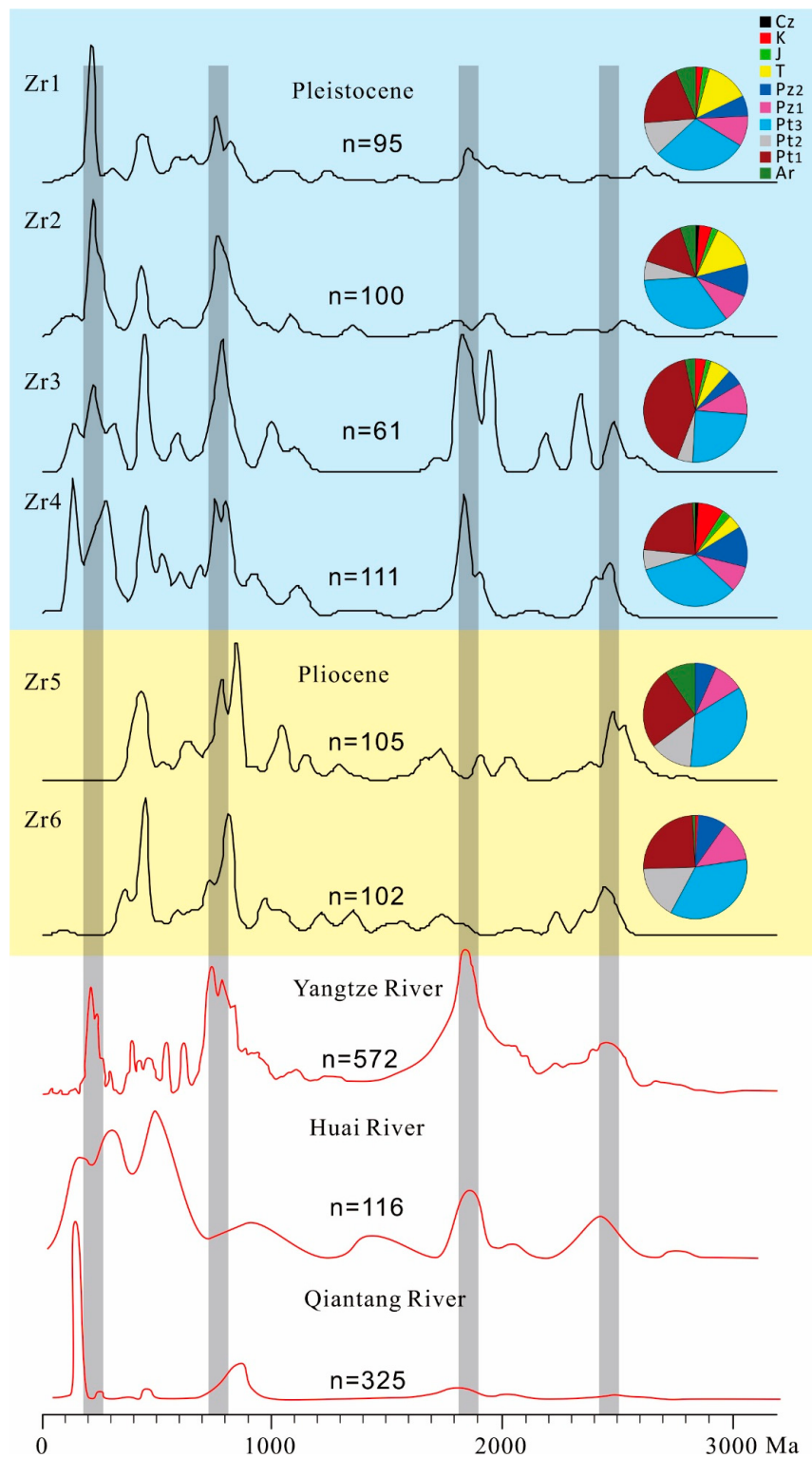


Figure 5. Kernal density estimate and pie diagrams of detrital zircon ages from samples of the core RGK15 and the potential sediment provenance. Data for the Yangtze River, Huaihe River (representative of provenance from the north region) and Qiantang River (representative of provenance from the ancient Zhejiang-Fujian Uplift) are sourced from [28–30], respectively.

5. Discussion

5.1. Provenance Identification during the Plio-Pleistocene in the Vertex of the Yangtze Delta

A significant provenance difference in core RGK15 occurs between the Pliocene and the Pleistocene, which is revealed both by heavy minerals and zircon ages (Figures 3 and 5). The heavy minerals in the Pliocene strata are relatively simple and dominated by the Zircon-Rutile-Tourmaline (ZRT) association, indicating a felsic igneous origin that is far from the heavy mineral association found in the modern Yangtze River [15,31,32] (pyroxene, titanite, dolomite, etc.). The zircon age spectrum is marked by a lack of a Mesozoic peak, which is the opposite of the zircon pattern of the modern Yangtze River [28] (Figure 5; Table 3). All of these observations suggest a sediment provenance from a pre-Mesozoic felsic region. The geological map shows that felsic igneous outcrops are distributed mainly in the middle and lower basin of the Yangtze River and south-eastern China, but their age is not limited to the pre-Mesozoic period [33] (Figure 1). Another possible provenance is the buried bedrock in the Yangtze delta and its surrounding area, which is composed of a large amount of sedimentary rock, forming in the Mesozoic period [34,35]. Studies have found that zircon ages in sedimentary rocks in the basin are usually older than the forming age of sedimentary rocks, because they are recycled from igneous rocks formed earlier in the source area [36,37]. Similarly, zircons in the Mesozoic sedimentary rock buried in the Yangtze delta are probably of pre-Mesozoic age. Meanwhile, sedimentary rock usually contains ultra-stable heavy minerals with a high Zircon-Tourmaline-Rutile (ZTR) content. All these fully match the heavy mineral association and zircon geochronology of the Pliocene sediments from the core RGK15 (Figures 3 and 5), indicating a local source from the bedrock. Here we are more inclined that the location of core RGK15 received sediments from its locality during the Pliocene.

The provenance of core RGK15 has shifted significantly since the Pleistocene, indicated by diversified heavy minerals, multiple peaks of the zircon age spectrum and the occurrence of Mesozoic zircon grains (Figures 3 and 5). In addition to felsic rocks, mafic and carbonate rocks represented by pyroxene and dolomite imply new provenances [31] (Figure 3). Diagnostic minerals of the upper Yangtze River (such as pyroxene, hypersthene, titanite and dolomite) continue to appear in the Pleistocene sediments, indicating a Yangtze origin [15,32,38] (Figure 3). This is also supported by zircon age spectra, which are similar to those of the modern Yangtze River, and the occurrence of Cenozoic zircon grains that are believed to be fingerprints of the Yangtze source [28] (Figure 5).

5.2. Provenance Shift during the Plio-Pleistocene in the Yangtze Delta Related to the Yangtze River Evolution

The cores of the late Cenozoic in the Yangtze delta generally indicate that a significant provenance shift to Yangtze-derived sediments occurred in the Pleistocene [10,12–16,25,26] (Figure 6). However, regional differences occurred during this provenance shift. This study shows that the shift in the vertex of the delta occurred at the beginning of the Pleistocene (~2.6 Ma, Figures 2 and 6), while most records in the south delta plain show that it occurred at ~1.2 Ma (Figure 6). Although there are few related studies on the north delta plain [24,26,27], the provenance shift seems to have occurred just prior to the Pleistocene (>~2.6 Ma), which is consistent with our findings. It can be seen that the Yangtze River possibly entered the sea from the north delta no later than 2.6 Ma and then shifted to the south delta until ~1.2 Ma (Figure 6).

In addition, the age of detrital zircon grains in the Pliocene sediments of the vertex delta is sharply different from that of the south delta [12] (Figure 6). The zircon age spectrum is characterized by a single Mesozoic peak in the Pliocene sediments of the south delta, while no Mesozoic peak is found in those of the vertex delta [12] (Figure 6). As mentioned above, the Pliocene provenance in the vertex delta is dominated by its locality, while the contemporary provenance in the south delta is probably related to the ancient Zhejiang–Fujian Uplift of the near east [12,15,27,38]. All of these results show that decentralized, local, small watersheds were distributed in the Yangtze delta during the Pliocene due to its relatively elevated terrain, as discussed in Section 5.3.

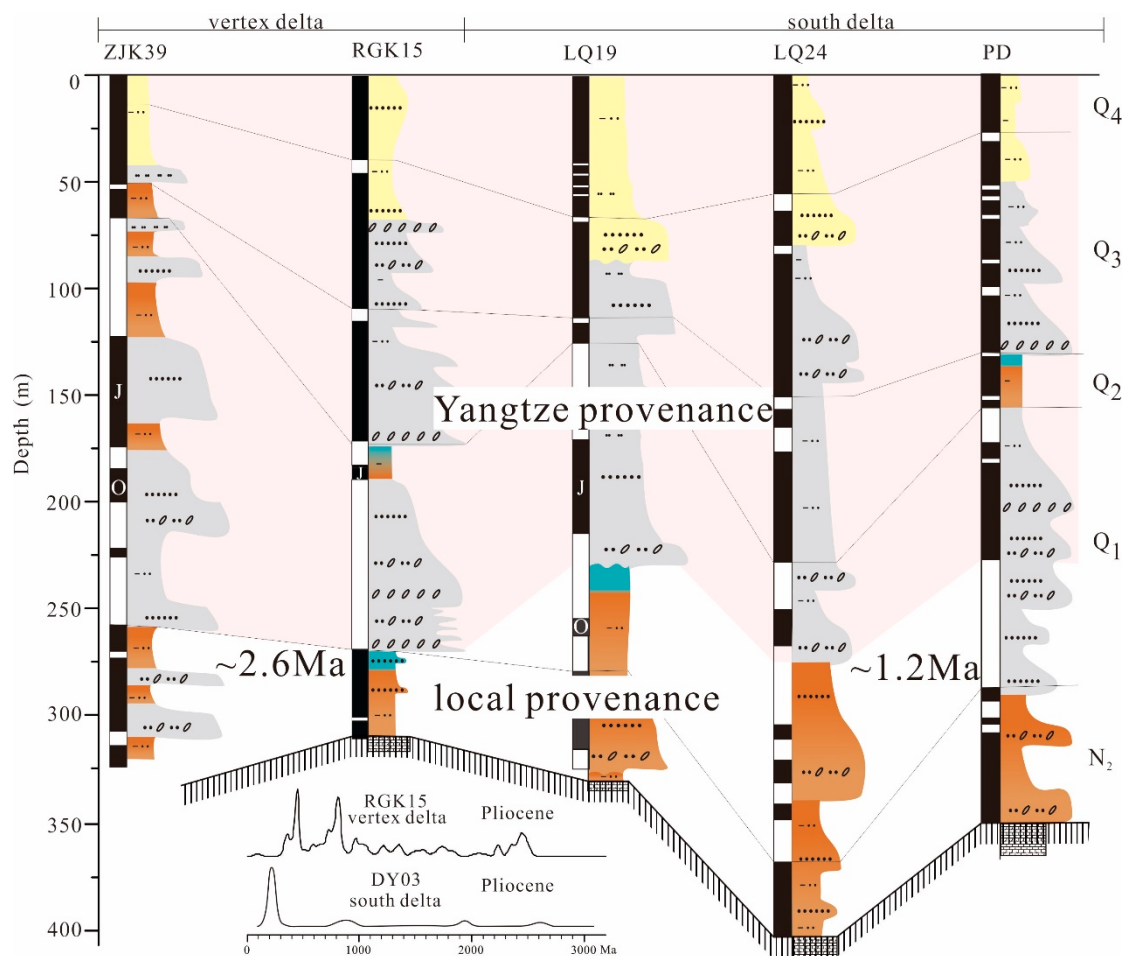


Figure 6. Regional chronostratigraphy and provenance evolution across the modern Yangtze delta section. The pink highlight denotes Yangtze-derived provenance. For lithology legends, see Figure 2. For core locations, see Figure 1. The relevant information on the chronology, lithology and provenance of the cores is cited from ZJK39 [26], LQ19 [39], LQ24 [15] and PD [13]. The inset figure in the lower-left corner shows zircon age spectra of the Pliocene sediments in core RGK15 of vertex delta (this study) and core DY03 of south delta [12].

5.3. Subsidence of the Ancient Zhejiang–Fujian Uplift during the Late Cenozoic Related to the Yangtze River Channelization

The provenance of the Yangtze delta shifted from the decentralized locality of the Pliocene to the Yangtze River basin of the Pleistocene, and the main channel migrated southward during the Pleistocene, which is closely related to the tectonic subsidence of the ancient Zhejiang–Fujian Uplift (ZFU).

There are five major tectonic units from east to west in the East China Sea, in which uplifts and basins are distributed alternately. Among them, the ancient Zhejiang–Fujian Uplift (ZFU) is the first uplift between the continent and the sea [40,41] (Figure 7). The ancient ZFU extends from the south-eastern coast of China to the south of the Korean Peninsula. It constituted a natural barrier that prevented seawater intrusion before the Quaternary [41]. It began to sink in the early Quaternary, and it completely sank below the sea level until ~0.2 Ma, when large-scale transgressions occurred in the eastern coast of China [40,42]. This is also supported by the occurrence of foraminifera starting in the late Quaternary in core RGK15 in this study (Figure 2).

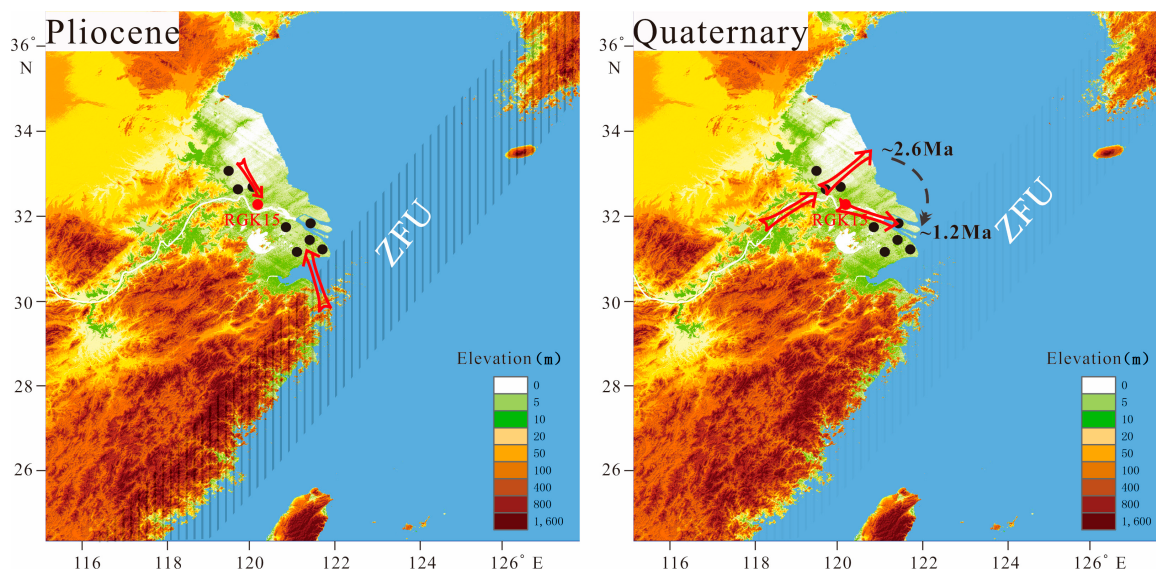


Figure 7. Sediment provenance evolution during the late Cenozoic related to subsidence of the ancient Zhejiang–Fujian Uplift (ZFU) [41,42]. Red arrows represent sediment sources. The black arrow represents the shift of the Yangtze channel with the ZFU subsidence.

Pleistocene subsidence of the ancient ZFU profoundly affected the water system of the nearby Yangtze delta. During the Pliocene, the Yangtze delta was still at a relatively high elevation. This was especially the case in the south delta within the ancient ZFU, which resulted in decentralized, local, small watersheds. With the subsidence of the ancient ZFU starting in the Pleistocene, the Yangtze River was dragged to the Yangtze delta ~2.6 Ma and then migrated to the south delta ~1.2 Ma (Figure 6). This is indicative of the rapid subsidence of the ancient ZFU starting ~1.2 Ma [42]. More research should be carried out in the north delta to reveal when the Yangtze River channelized into the sea.

6. Conclusions

Heavy minerals and zircon geochronology in the Plio-Pleistocene sediments of the vertex of the modern Yangtze delta (core RGK15) reveal that a significant provenance shift occurred at ~2.6 Ma (the beginning of the Pleistocene). During the Pliocene, ultra-stable heavy minerals of the ZTR association and pre-Mesozoic zircons predominated in the sediments, probably derived from contemporary outcrops of sedimentary rock that were widely distributed in the delta and surrounding areas. These are completely different from those in the Pliocene sediments of the south delta, indicating that decentralized, local, small watersheds dominated the Yangtze delta during the Pliocene. This resulted from the relatively elevated terrain of this region due to the adjacent ancient ZFU at that time. However, diversified heavy minerals and zircon geochronology similar to those of the modern upper Yangtze fingerprints occur in the Pleistocene sediments of core RGK15, implying that a significant provenance shift to the Yangtze River occurred here starting ~2.6 Ma. This shift, as recorded by the cores in the south delta, mainly occurred at ~1.2 Ma, indicating that the Yangtze River channel was dragged southward with the further subsidence of the ancient ZFU.

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