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Ages of Detrital Zircons from Deep-Water Gas Field L3 in the Northern South China Sea and Their Significance for Provenance Evolution

(Usia Zirkon Gersik daripada Medan Gas Air-Dalam L3 di Utara Laut China Selatan dan Kepentingan Mereka untuk Evolusi Tempasal)

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ABSTRACT

L3 is the first deepwater exploration well drilled in the Pearl River Mouth Basin, Northern South China Sea and significant hydrocarbon discoveries have been discovered in the Zhuhai and Zhujiang Formations, which have kicked off the prelude to oil and gas exploration in the deepwater areas of the northern slope of the South China Sea (SCS). However, for a long time, there has been great controversy over the cause, sedimentation on processes and control factors of high-quality reservoirs in L3 gas field. This paper analyzed the sedimentary characteristics of the high-quality sand bodies of Zhuhai Formation and Zhujiang Formation, combined with a comprehensive analysis of detrital zircon U-Pb age spectra patterns of sediments and conducted a source-to-sink comparative analysis based on the detrital zircon U-Pb age spectrum in the surrounding potential source areas. The results show that the shallow sea delta developed since the late Oligocene in L3 gas field, and the age spectrum of sedimentary zircon showed the characteristics of multi-peaking, which was the signal superposition of western paleo 'Kontum-Ying-Qiong' River and northern paleo Pearl River. Jinningian zircon spectrum peak shows an increasing trend as the sand body was gradually deposited, which indicated that the supply of paleo Pearl River in the north was gradually increasing. After the Baiyun movement at the end of the Oligocene, with the deepening of the water body, the dominant sand body of L3 in the Zhujiang Formation showed significant deep-water sedimentary characteristics of the continental slope, and the detrital zircon U-Pb age spectrum showed a significant northern paleo Pearl River source signal, indicating that the western source area had gradually weakened during the early Miocene, and the northern paleo Pearl River source mainly provided debris supply for the Baiyun sag.

Keywords: Detrital zircon U-Pb; provenance; sedimentary characteristic; source to sink; South China Sea

ABSTRAK

L3 ialah telaga penjelajahan air dalam pertama yang digerudi di Lembangan Mulut Sungai Pearl, Laut China Selatan Utara dan penemuan hidrokarbon ketara telah ditemui di Formasi Zhuhai dan Zhujiang, yang mana ia telah memulakan penjelajahan minyak dan gas di kawasan perairan dalam di cerun utara Laut China Selatan (SCS). Walau bagaimanapun, sejak sekian lama, terdapat kontroversi besar berkenaan dengan punca, proses pengendapan dan faktor kawalan takungan berkualiti tinggi dalam medan gas L3. Kertas ini menganalisis ciri endapan bagi jasad pasir berkualiti tinggi untuk Formasi Zhuhai dan Zhujiang, digabungkan dengan analisis komprehensif corak spektrum umur zirkon U-Pb gersik sedimen dan menjalankan analisis perbandingan punca-ke-tenggelam berdasarkan zirkon gersik U-Pb spektrum usia di sekitar kawasan punca yang berpotensi. Hasil menunjukkan bahawa delta laut cetek berkembang sejak akhir Oligosen di medan gas L3 dan spektrum usia zirkon sedimen menunjukkan ciri-ciri puncak-berbilang, yang merupakan isyarat superposisi paleo barat Sungai 'Kontum-Ying-Qiong' dan Sungai Pearl utara paleo. Puncak spektrum zirkon Jinningian menunjukkan corak yang semakin meningkat apabila jasad pasir dimendapkan secara beransur-ansur dan ia juga menunjukkan bahawa bekalan Sungai Pearl paleo di utara semakin meningkat. Selepas pergerakan Baiyun pada akhir Oligosen, dengan jasad air yang semakin dalam, jasad pasir dominan L3 dalam Formasi Zhujiang menunjukkan ciri-ciri sedimen air dalam yang ketara di cerun benua dan spektrum usia zirkon U-Pb gersik menunjukkan isyarat punca Sungai Pearl paleo utara yang ketara, ini menunjukkan bahawa kawasan barat punca beransur menjadi lemah semasa awal Miosen dan punca Sungai Pearl paleo utara memperuntukan bekalan serpihan untuk sag Baiyun.

Kata kunci: Ciri-ciri sedimen; Laut China Selatan; punca-ke-tenggelam; tempasal; zirkon U-Pb gersik

INTRODUCTION

Recently, large oil and gas fields in deepwater sedimentary regions have become the hot spots in the global oil and gas exploration. In the northern marginal basins of the South China Sea (SCS), hydrocarbon exploration has gradually shifted from the shelf shallow-water basins to deepwater regions, and has made significant breakthroughs (Wen et al. 2023; Zhu et al. 2021). The discovery of the deepwater fan in the L3 gas field in the Baiyun Sag of the Pearl River Mouth Basin marks a milestone in deepwater exploration in the northern South China Sea (He et al. 2007; Li et al. 2011). The important reservoirs of L3 are mainly concentrated in the Upper Oligocene Zhuhai Formation and the Lower Miocene Zhujiang Formation, which respectively developed in shallow marine delta sand bodies in the Zhuhai Formation and marginal shelf deltas and slope deepwater sedimentary systems in the Zhujiang Formation (He et al. 2012; Mi et al. 2016; Shi et al. 2010; Zhu et al. 2012). For a long time, due to the lack of geological data and the limitations of provenance analysis methods for detrital sediments in the basin, there has been significant controversy regarding the origin, sedimentary processes, and controlling factors of the high-quality reservoirs in the L3 gas field.

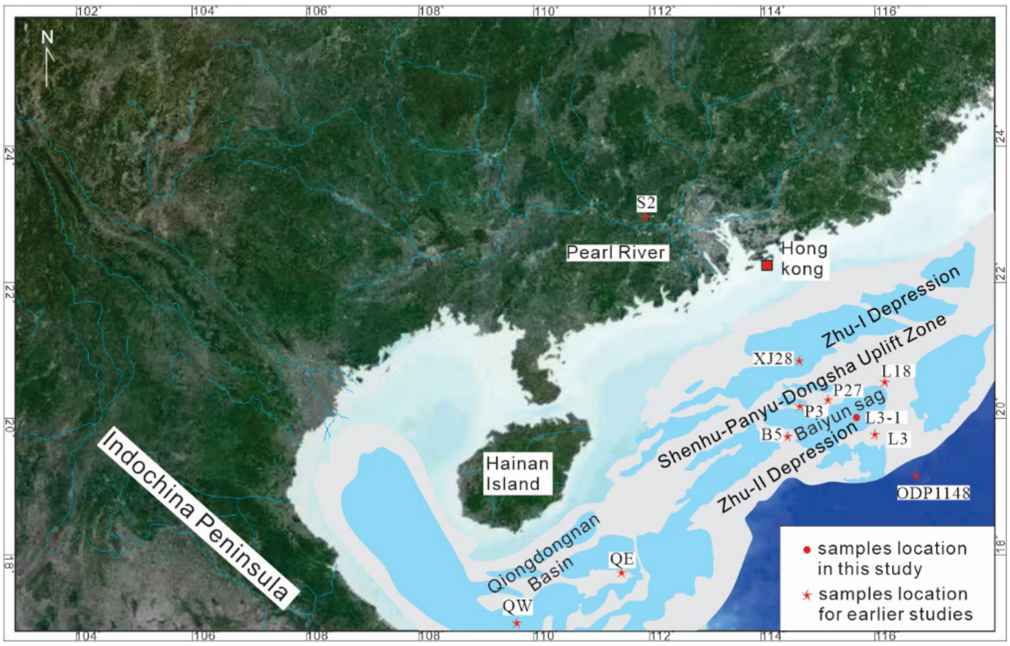
According to earlier studies, analysis of provenance evolution of clastic sediments was mainly conducted through methods such as clastic components, heavy mineral assemblages, whole-rock geochemical analysis, and seismic sequences (Xu & Jiang 2019; Xu, Du & Yang 2007; Xu et al. 2021; Yang et al. 2013; Zhao & Liu 2003). Limited by technological methods, the provenance of the Pearl River Mouth Basin was generally qualitatively determined to be the granite source rock area along the southern China coast. Early studies indicated that the paleo Pearl River began to develop from the late Oligocene, and carried large amounts of clastic materials into the Pearl River Mouth Basin. This resulted in the sedimentary filling of reservoir bodies in various sags including the Baiyun Sag where the L3 gas field is located. And sedimentary filling was primarily characterized by unidirectional transport deposition, with local supply from surrounding uplift zones (Cui et al. 2009; Liu et al. 2007; Zhang et al. 2022). Zircon U-Pb age spectrum analysis has become an effective method for improvement of sediment provenance research (Gehrels 2014; Moecher & Samson 2006; Shao et al. 2016; Zhang et al. 2020). In the past ten years or so, extensive research has been conducted in the northern part of the South China Sea on the comparison of sediment sources and sinks using detrital zircon age spectra, yielding significant discoveries. It is believed that since the Eocene and early Oligocene periods, the paleo uplift in the western South China Sea developed the ‘Kun-Ying-Qiong’ Paleo River, which continuously transported a large amount of sediment to the eastern part of the South China Sea, also providing detrital materials for the Zhu II depression in the Pearl River Mouth Basin (Cao et al. 2018; Cui et al. 2018; Shao et al. 2019, 2018, 2016). Influenced by basin tectonic evolution and sea-level changes, the Baiyun Sag received bidirectional sediment supply from the paleo Pearl River in the north and the paleo ‘Kun-Ying-Qiong’ River from the west during specific periods of time (Hou et al. 2020; Shao et al. 2019). The L3 gas field is located in the southeast of the Baiyun Sag. The core reservoirs including the sand bodies of the Zhujiang and Zhuhai formations have been discussed in detail, it helps further deepen our understanding of their sedimentary filling processes.

By conducting core sedimentary facies studies and detrital zircon U-Pb age spectra on the latest drilled core samples, we aim to investigate sedimentary characteristics, sediment provenance evolution, and sedimentary filling processes of the sand bodies in the Late Oligocene (Zhuhai Formation) to Early Miocene (Zhujiang Formation) of Well L3 in the Pearl River Mouth. This study should show the contributions of the paleo Pearl River from the north and the provenance of the west to the Oligocene-Miocene reservoirs of the L3 gas field, which largely lays a good foundation for the upcoming petroleum exploration.

GEOLOGICAL BACKGROUND

The Baiyun Sag is located in the deep-water area of the Pearl River Mouth Basin on the continental margin slope in the northern South China Sea, adjacent to the Panyu Low Uplift to the north, the South China Sea Basin to the south, the Yunkai low uplift to the west, and the Dongsha Uplift to the east (Figure 1). The sag generally trends in the north-east-east direction, with a water depth ranging from 300 to 3000 m. It is the largest Tertiary sedimentary sag discovered in the Pearl River Mouth Basin and also the largest subsidence and sedimentary center in the Paleogene of the Pearl River Mouth Basin.

The sag mainly experienced three tectonic evolution stages in the Cenozoic: rifting, thermal subsidence of depression, and neotectonic movement. The rifting stage includes three episodes of rifting in the early-middle Eocene, late Eocene to early Oligocene, and late Oligocene, which formed important unconformities such as Tg, T7, and T6, showing three-layer structural characteristics. During the rifting stage, the Wenchang Formation, Enping Formation, and Zhuhai Formation were developed, while during the thermal subsidence stage, the Zhujiang Formation and Hanjiang Formation were developed. During the neotectonic stage, the Yuehai Formation and Wanshan Formation were developed (Zhu 2010). The deep-water area of the Baiyun Sag was mainly deposited, from bottom to top, the lacustrine Wenchang Formation of the Eocene, the fluvial-lacustrine coal-bearing Enping Formation of the lower Oligocene, the shallow marine delta-deposit of Zhuhai Formation of the upper Oligocene, and deep-water fan of the sedimentary Zhujiang-Hanjiang Formation of the lower Miocene, as well as the under-compensated sedimentary deposits of the deep-water slope since the upper Miocene (Cui et al. 2009; He et al. 2016; Liu et al. 2011; Mi et al. 2016) (Figure 2).



Note: The samples of datum sources were as follows: QW and QE in the Qiongdongnan Basin were obtained from Shao et al. (2018); B5 in the Yunkai Low Uplift of the Pearl River Mouth Basin was obtained from Shao et al. (2022); L3 in the Yunli Low Uplift of the Pearl River Mouth Basin was obtained from Hou et al. (2020); L18 in the Dongsha Uplift of the Pearl River Mouth Basin was obtained from Hou et al. (2020); and XJ28 in the Pearl River Delta was obtained from Cao et al. (2018). P3 and P27 in the Panyu low uplift of the Pearl River Mouth Basin was obtained from Xiang et al. (2024) and Hou et al. (2020); S2 of Morder Pearl River was obtained from Zhong et al. (2017)

FIGURE 1. Geographical location and sample distribution map of the L3 gas field in the Baiyun Sag

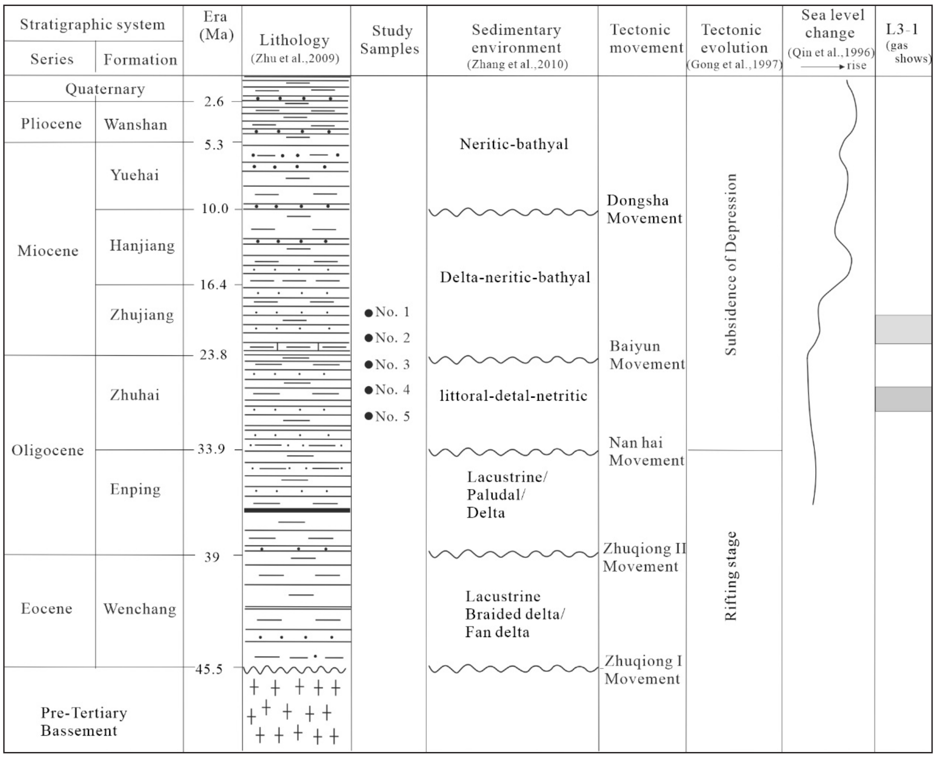


FIGURE 2. Comprehensive diagram of stratigraphic and structural evolution in the Baiyun Sag

The L3 gas field is located on a faulted anticline structure in the southeastern part of the Baiyun Sag, with a favorable combination of source rocks, reservoirs, and seals. The main gas source is the shallow lake-swamp sediments of the Enping Formation developed in the main depression of the Baiyun Sag (Mi et al. 2016; Zhu et al. 2012). The early Miocene sandy deepwater fan and the late Oligocene shelf shallow-water delta serve as the primary reservoirs, forming a composite gas accumulation with structural-lithologic traps (Zhu et al. 2010).

Drilling showed that the basement of the Cenozoic basin in the northern continental margin of the SCS is mainly composed of Yanshanian granite, with isotopic ages ranging from approximately 70.5 to 130 Ma. There are also older basement rocks, including Precambrian, Caledonian, and Hercynian metamorphic and sedimentary rocks, as well as Mesozoic sedimentary rocks. The basement was assembled from different fragments during different stages of the Caledonian, Hercynian, and Indosinian periods (Yang, Courtillot & Besse 1992), and has undergone frequent magmatic activity and modification during the Yanshanian period. Early research indicates that the potential sediment source areas for high-quality sandstone bodies in the L3 structure are mainly controlled by large rivers such as the paleo Pearl River and locally uplifted areas. Potential provenance studies indicate that the zircon age spectrum of sediments from the paleo Pearl River in northern South China shows the main peak at 148 Ma during the Yanshanian period, the secondary peak at 240 Ma during the Indosinian period, and the weak peak of 443 Ma during the Caledonian period (Cao et al. 2018). The zircon age spectrum of sediments from the paleo Kun-Ying-Qiong river channel sediments in the western South China Sea shows a wide distribution of characteristics, with a high main peak of 233 Ma in the Indosinian and 417 Ma in the Caledonian period, a secondary peak of 141 Ma in the Yanshanian period and 752 Ma in the Jinningian period, and a weak peak from 922 Ma to 2500 Ma in the Luliang period (Shao et al. 2022, 2016). The zircon U-Pb age of the paleo-uplift (Dongsha Uplift, Panyu Low Uplift, and Yunkai Low Uplift) and basin basement around Baiyun Sag is generally a single peak of the Yanshanian period, about 100-170 Ma, and there are Cenozoic magmatic rocks locally, with a peak age of less than 65 Ma (Cui et al. 2021; Zhu et al. 2021). These data have become an important basis for comparative research on sources and sinks.

MATERIALS AND METHODS

In Well L3 Quaternary, Neogene Yuehai Formation, Hanjiang Formation, Zhuhai Formation and Paleogene Zhuhai Formation are encountered. Six sets of thick sandstone reservoirs were drilled in the lower part of the Pearl River Formation and the Zhuhai Formation, and five sets of sandstone with oil and gas displays. The well is located in the deep-water area of the shelf slope zone in the Neogene, far away from the shelf slope break zone, and belongs to the southern flank of the deep-water fan of the Pearl River. The main deposition during the Neogene period were deep-sea and semi-abyssal argillaceous sediments, and thin-bedded silt and sandstone deposits have been locally developed, and the separation is poor. The lower part of the Pearl River Formation develops a submarine turbidity fan sand body with good reservoir physical properties. The Zhuhai Formation is a shallow sea delta sediment with sea-land interaction, the upper and lower members are interbedded with sand-mudstone, and the middle member is a set of huge thick black mudstone deposits.

This paper selected five samples from the Oligocene and Miocene (Zhuhai Formation and Zhujiang Formation) of Well L3 in the Baiyun Sag for detrital zircon U-Pb age spectrum analysis. The Zhuhai Formation includes three samples with sampling depths of 3515.47-3515.62 m, 3205.56-3206.31 m, and 3144.29-3145.04 m, respectively; the Zhujiang Formation includes two samples with sampling depths of 3075.11-3075.86 m and 3062.24-3063.17 m, respectively. The analysis results are to be compared with the previously published detrital zircon U-Pb age spectra from the surrounding areas (Table 1).

Zircon grain collection, mounting, Cathodoluminescence (CL) imaging and LA-ICP-MS isotopic dating were all completed at the State Key Laboratory of Marine Geology, Tongji University. The instrumentation used is a Thermo Elemental X-Series ICP-MS coupled to a New Wave 213 nm laser ablation system. In the laser ablation process, helium gas was used as carrier gas, and argon gas is used as compensation gas to adjust sensitivity. The laser beam was set to a 10 Hz ablation frequency with a 30 μm spot size. Each analysis included a background signal of 30 s and a sample signal of 70 s. The international standard zircon 91500 (1065.4 ± 0.3 Ma) was used as an external standard, with zircon standard Plešovice (337.1 ± 0.4 Ma) to monitor the accuracy of the analysis results. U-Pb isotopic ratio and age calculations were completed by software ICPMS Data Cal, and common Pb correction was performed using (Andersen 2002) method. According to Cao et al. (2017) calculated 206Pb/238U ages are adopted for zircons younger than 1000 Ma, while 207Pb/206Pb ages are adopted for ones older than 1000 Ma (Shao et al. 2018, 2016). The accepted ages were selected from a subset of both ≤10% discordance and ≤10% uncertainty (1 σ).

RESULT AND DISCUSSION

In this study, three samples including No. 5, No. 4 and No. 3 (Figure 3) are located at the Baiyun Sag, and were collected from the Zhuhai Formation of the Oligocene, with depths from bottom to top being 3515.47-3515.62 m (No. 5), 3205.56-3206.31 m (No. 4), and 3144.29-3145.04 m (No. 3) (Table 1). Sample No. 5 showed a wide range of Th (33.61-1482.80 ppm) and U (63.51-2402.73 ppm) concentrations, yielding Th/U ratios mostly falling between 0.13 and 2.27, indicating a magmatic origin. Only one was below 0.1, which might be derived from metamorphic rocks. A total of 111 data points were obtained from magmatic rocks (Figure 4). 46 analyses give $^{206}Pb/^{238}U$ age ranges between 62 Ma and 175 Ma, while 14 analyses range between 241 and 277 Ma, and 26 analyses range between 317 and 511 Ma. While only 5 analyses give $^{206}Pb/^{238}U$ ranges between 803 and 981 Ma, and 21 analyses give $^{206}Pb/^{238}U$ age ranges between 1013 Ma and 2733 Ma. Sample No. 5 showed three $^{206}Pb/^{238}U$ age peaks spectra of the Yanshanian (150 Ma), Indosinian (256 Ma), and Caledonian periods (448 Ma), respectively.

Sample No. 4 shows a variation range of Th (32.52-1484.37 ppm) and U (68.75-1602.75 ppm) concentrations, yielding Th/U ratios mostly falling between 0.16 and 2.33, indicating a magmatic origin. Two were below 0.1, which might be derived from metamorphic rocks. A total of 111 data points from magmatic rocks were obtained (Figure 4). 36 analyses give $^{206}Pb/^{238}U$ age ranges between 32 Ma and191 Ma, while 14 analyses range between 236 and 283 Ma, and 31 analyses range between 313 and 580 Ma. 17 analyses give $^{206}Pb/^{238}U$ ranges between 611 and 982 Ma, and 13 analyses give $^{206}Pb/^{238}U$ age ranges between 1008 Ma and 2508 Ma. Sample No. 4 exhibited three distinct $^{206}Pb/^{238}U$ age peaks spectra, corresponding to the Yanshanian (150 Ma), Indosinian (255 Ma), and Caledonian periods (446 Ma), respectively, along with a single peaks spectrum from the Jinningian period (960 Ma).

Sample No. 3 shows a variation range of Th (31.92-998.43 ppm) and U (44.40-2947.99 ppm) concentrations, yielding Th/U ratios mostly falling between 0.16 and 4.24,

TABLE 1. Number of detrital zircons in samples and their stratigraphic ages

Sample	No	Epoch	Numbers	Note	Provenance division
L3	NO.1	Early Miocene	110	this study	Baiyun Sag
	NO.2	Early Miocene	109	this study	Baiyun Sag
	NO.3	Late Oligocene	105	this study	Baiyun Sag
	NO.4	Late Oligocene	111	this study	Baiyun Sag
	NO.5	Late Oligocene	112	this study	Baiyun Sag
L3	L3	Early Miocene	107	Hou et al. (2020)	Yunli low uplift
QW	QW-LM	Early Miocene	244	Shao et al. (2018)	'Kontum-Ying-Qiong' River
QE	QE-UO	Early Miocene	184	Shao et al. (2018)	'Kontum-Ying-Qiong' River
QE	QE-LM	Late Oligocene	51	Shao et al. (2018)	'Kontum-Ying-Qiong' River
B5	B5-1	Early Oligocene	83	Shao et al. (2022)	Yunkai low uplift
B5	B5-2	Late Oligocene	102	Shao et al. (2022)	Yunkai low uplift
P27	P27	Early Oligocene	108	Xiang et al. (2024)	Panyu low uplift
P3	P3	Early Miocene	42	Hou et al. (2020)	Panyu low uplift
XJ28	XJ28-4, XJ28-5, XJ28-6, XJ28-7	Early Miocene	342	Cao et al. (2018)	Pearl River delta
	XJ28-8, XJ28-9, XJ28-1	Late Oligocene	220	Cao et al. (2018)	Pearl River delta
	XJ28-2	Early Oligocene	95	Cao et al. (2018)	Pearl River delta
L18	L18-1	Late Oligocene	126	Hou et al. (2020)	Dongsha uplift
	L18-2	Late Eocene-Early Oligocene	103	Hou et al. (2020)	Dongsha uplift
S2	S2-5	Mordern	87	Zhong et al. (2017)	Mordern Pearl River

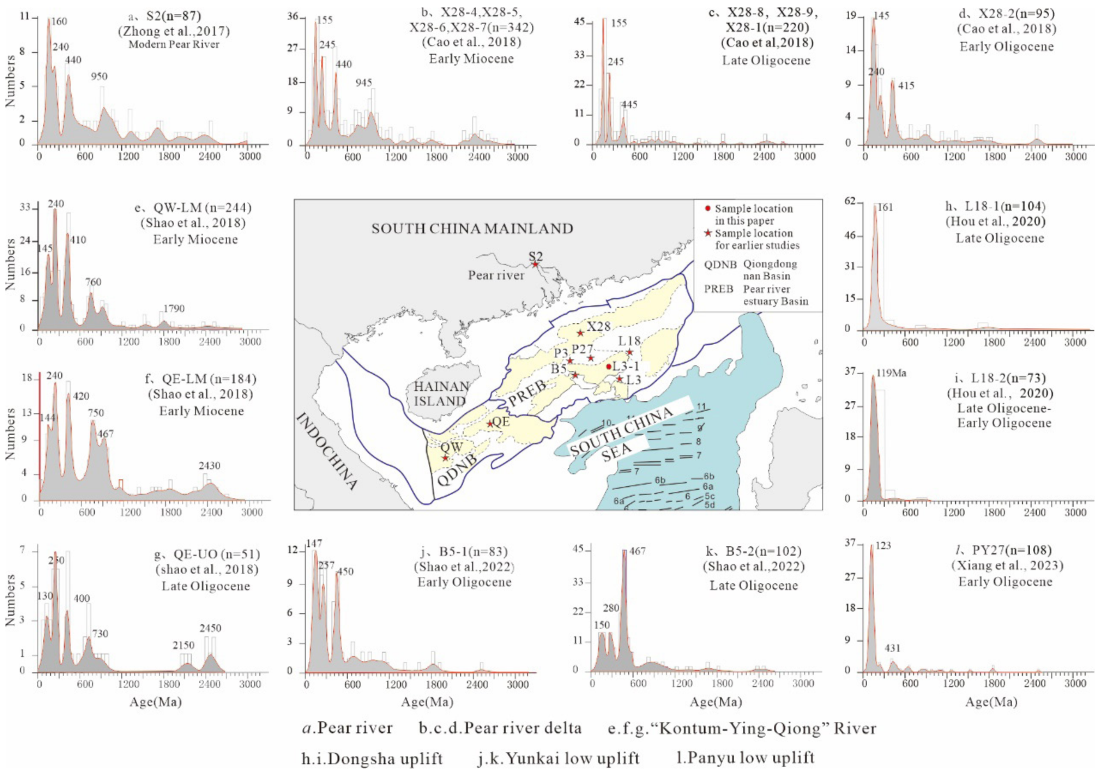


FIGURE 3. Detrital zircon age spectrum of potential provenance sediments in the Baiyun Sag

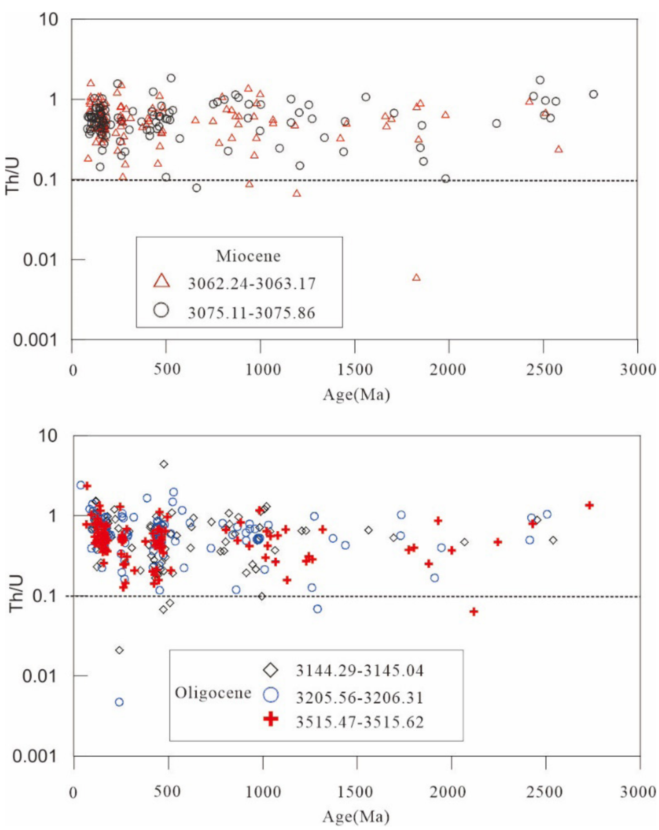


FIGURE 4. Th/U ratio and U-Pb age distribution of detrital zircons from the Late Oligocene-Early Miocene in L3

indicating a magmatic origin. Only four were below 0.1, which might be derived from metamorphic rocks. A total of 105 data points were obtained from magmatic rocks (Figure 4). 35 analyses give $^{206}Pb/^{238}U$ age ranges between 91 Ma and 191 Ma, while 39 analyses range between 210 and 541 Ma. Only 19 analyses give $^{206}Pb/^{238}U$ ranges between 615 and 993 Ma, and 12 analyses give $^{206}Pb/^{238}U$ age ranges between 1007 Ma and 2540 Ma. Sample No. 3 exhibited two distinct $^{206}Pb/^{238}U$ age peaks spectra, corresponding to the Yanshanian (143 Ma) and Caledonian periods (447 Ma), respectively, along with a single peak spectrum from the Jinningian period (988 Ma).

Two samples including No. 2, and No. 1 located at the Baiyun Sag, and were collected from the Zhujiang Formation of the Middle Miocene, with depths from bottom to top being 3075.11-3075.86 m (No. 2) and 3062.24-3063.17 m (No. 1), respectively (Table 1). Sample No. 2 shows a variation range of Th (6.68-1227.51 ppm) and U (26.50-2196.47 ppm) concentrations, yielding Th/U ratios mostly falling between 0.10 and 1.83, indicating a magmatic origin. Only one was below 0.1, which might be derived from metamorphic rocks. A total of 108 data points were obtained from magmatic rocks (Figure 4). 51 analyses give $^{206}Pb/^{238}U$ age ranges between 91 Ma and 283 Ma, while 22 analyses range between 306 and 573 Ma, and 11 analyses range between 662 and 998 Ma. 25 analyses give $^{206}Pb/^{238}U$ ranges between 1002 and 2766 Ma. Sample No. 2 exhibited two distinct $^{206}Pb/^{238}U$ age peaks spectra, corresponding to the Yanshanian (149 Ma) and Caledonian periods (465 Ma), respectively.

Sample No. 1 shows a variation range of Th (39.86-1149.22 ppm) and U (73.73-1820.23 ppm) concentrations, yielding Th/U ratios mostly falling between 0.11 and 1.62, indicating a magmatic origin. Only three were below 0.1, which might be derived from metamorphic rocks. A total of 107 data points were obtained from magmatic rocks (Figure 4). 44 analyses give $^{206}Pb/^{238}U$ age ranges between 87 Ma and 184 Ma, while 17 analyses range between 234 and 289 Ma, and 15 analyses range between 312 and 468 Ma. Only 17 analyses give $^{206}Pb/^{238}U$ ranges between 1067 and 2581 Ma. Sample No.1 exhibited three distinct $^{206}Pb/^{238}U$ age peaks spectra, corresponding to the Yanshanian (163 Ma), Indosinian (266 Ma), and Caledonian periods (473 Ma), respectively.

SEDIMENTARY CHARACTERISTICS

The Oligocene-Miocene sedimentary characteristics of the deepwater area of Baiyun Sag are of great significance for deepwater oil and gas exploration. The Oligocene-Miocene (23.8 Ma) is an important sedimentary-tectonic transition plane in the Pearl River Mouth Basin, corresponding to major events of Baiyun movement such as the jump and deflection of the expansion ridge in the SCS and the abrupt change of the provenance of the paleo Pearl River, all of which are recorded in the deep-sea sediments of the ODP1148 station (Li et al. 2006; Shao et al. 2004).

The tectonic events result in the abrupt changes in the provenance of the sedimentary environment of the Baiyun Sag, and the corresponding migration of the shelf slope break from the southern uplift zone to the northern slope in the Baiyun Sag, causing the sedimentary slope break zone of the southern uplift belt to develop the Zhuhai Formation as a retrogradational depositional sequence. On the northern slope, the Zhujiang Formation-Hanjiang Formation developed a transgression and accretion depositional sequence (Liu et al. 2011). As a result, the sediments in the Baiyun Sag have changed from being mainly characterized by sand-rich before the Oligocene to being mainly mud-rich sedimentary accumulation since the Miocene (Shao et al. 2007).

The core samples of the L3 Zhuhai Formation show the sedimentary characteristics of the coastal shallow sea-shallow water delta. The lithology is mainly gray fine sandstone, silty fine sandstone, and occasionally medium coarse sandstone. The lower part of the layer develops a typical rhythmic and symmetrical tidal bedding with strong bioturbation structure, indicating a typical product of intertidal-subtidal sedimentation. In the central part, a large section of massive sandstone is developed, and floating gravel is found in the sandstone, exhibiting characteristics of granular flow sedimentation. The middle and upper sandstone is interbedded with mudstone and is rich in bedding and wormhole biodisturbance structure, and sandstone and siltstone constitute a normal grain sequence. The black massive mudstone that developed in the upper part has no bedding and wormholes, and contains scattered biological fossils, indicating the formation is in deeper water bodies (Figure 5).

The core samples result from the Zhujiang Formation of the Miocene in Well L3 exhibit slope deep-water sedimentary characteristics. Large sections of massive mudstone have undeveloped bedding, undeveloped wormholes, and weak biological disturbance. A large number of layered siderites have developed in the mudstone, the sandstone layer is in abrupt contact with the overlying and underlying mudstone layers, and the overall bedding of the sandstone is not developed. Some intervals showed inverse grading, indicative of gravity flow characteristics. The mudstone is interbedded with a thin layer of sandstone, which has the characteristics of contour flow (Figure 5).

Studies have shown that shelf-margin deltas and slope deep-water depositional systems developed during the Miocene, and there is a ‘source-sink’ response relationship. Controlled by the changes in relative sea level and the shelf break slope zone, the development of shelf deltas is re-transported at the shelf break slope zone, forming a deep-water depositional system in the deep-water area (Liu et al. 2011).

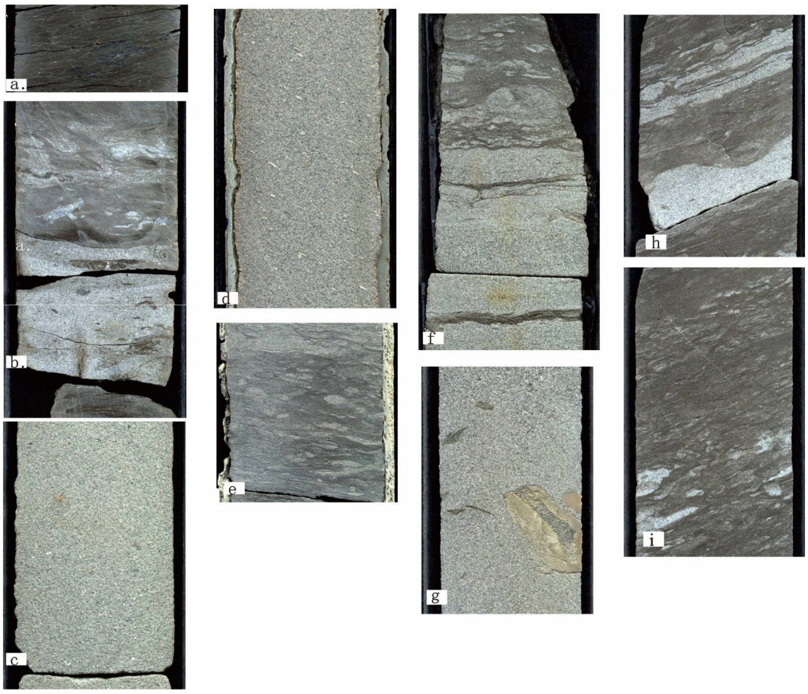


FIGURE 5. Typical sedimentary structures in the Late Oligocene-Early Miocene core of L3 (a) Stratified siderite, with depths of 3060.55-3060.60 m in the Early Miocene, (b) Abrupt contact between sandstone and mudstone layers, with depths of 3061.89-3062.00 m in the Early Miocene, (c) Massive sandstone, with depths of 3067.62-3067.77 m in the Early Miocene, (d) Oriented arrangement of shells within the sand body, with depths of 3074.11-3074.28 m in the Early Miocene, (e) Abundant bedding and wormhole biodisturbance structure, with depths of 3153.18-3153.28 m in the Late Oligocene, (f) Normal grading of sandstone and siltstone, with depths of 3516.32-3516.50 m in the Late Oligocene, (g) Mudstone clasts floating within the sandstone, with depths of 3522.91-3523.06 m, in the Late Oligocene, (h) Rhythmic bedding, with depths of 3529.03-3529.38 m in the Late Oligocene, and (i) Symmetrical ripple marks indicating tidal bedding, with depths of 3529.34-3529.47 m in the Late Oligocene

SEDIMENT PROVENANCE ANALYSIS AND SEDIMENTARY ENVIRONMENT EVOLUTION

During the Early Oligocene, the paleo Pearl River began to develop along the coast of South China, mainly carrying clastic rocks into the coast of the SCS. Due to the barrier effect of the Shenhu-Panyu-Dongsha uplift belt, the sedimentation of the paleo Pearl River mainly entered the local basin of the Zhu-I depression. Meanwhile, the 'Kontum-Ying-Qiong' River developed in the northwestern part of the South China Sea (Cui et al. 2018; Shao et al. 2019, 2018). It carried mafic or ultramafic materials originating from the uplift in north-central Vietnam into the central canyon belt of the Qiongdongnan Basin in the western part of the South China Sea. It also transported a large amount of material to the eastern part of the South China Sea, the deposition being recorded in the Baiyun Sag of the Zhu II Depression in the Pearl River Mouth Basin, as well as in areas such as the southwestern Taiwan Basin and the Liyue-Palawan.

During the Late Oligocene, the 'Kontum-Ying-Qiong' River in the western South China Sea reached its peak development, continuing to transport terrigenous materials from the western side of the SCS towards the Pearl River Mouth Basin. At the same time, the Pearl River Mouth Basin has increased and expanded to the inland of South China, providing a significant increase in sediments, causing the Pearl River Delta to cross the Panyu low uplift and enter the Baiyun Sag (Hou et al. 2020; Shao et al. 2019). Under the control of regional tectonic sedimentation and sea-level changes, paleo Pearl River sediments formed a large-scale northwest-southeast trending shelf delta-shelf margin delta-deepwater fan depositional system within the Baiyun Sag (Tian, Zhang & Zhao 2022). At this time, the Baiyun Sag received mixed sediments from both the 'Kontum-Ying-Qiong' River in the western South China Sea and the Pearl River in the northern part of the South China Sea (Hou et al. 2020; Shao et al. 2020).

Three samples were obtained from the Late Oligocene sediments of the L3 well in the Baiyun Sag, with their detrital zircon $^{206}Pb/^{238}U$ ages concentrated between 150 and 960 Ma. The zircon age spectra exhibit a multi-modal pattern, dominated by Yanshanian and Caledonian zircons, with subordinate peaks of Indosinian and Jinningian zircon ages (Figure 6). Significant differences are observed among the samples from bottom to top. The bottommost sample No. 5 (3515.47-3515.62 m) does not display a Jinningian peak, whereas the subsequent samples No. 4 (3205.56-3206.31 m) and No.3 (3144.29-3145.04 m) show an increasing trend of Jinningian peaks, with the Jinningian peak in sample No.3 being significantly higher than that in sample No. 4. Additionally, the bottommost sample No.5 (3515.47-3515.62 m) and the middle sample No. 4 (3205.56-3206.31 m) exhibit obvious Indosinian zircon peaks, while sample No. 3 (3144.29-3145.04 m) has fewer Indosinian zircon peaks (six samples), which blend into the Yanshanian zircon peaks. The enhanced Jinningian and weakened Indosinian zircon age spectra mentioned above indicate the superimposition of sediment sources from the paleo Pearl River in the north and the 'Kontum-Ying-Qiong' River in the west. Throughout this period, a consistently high Yanshanian zircon peak suggests contributions from sediments in local uplift zones, such as the Dongsha Uplift and Yunkai Low Uplift (Han et al. 2017).

From the Late Oligocene to the Early Miocene, the Baiyun movement (23.8 Ma) occurred, and the SCS expanded further, accompanied by the expansion ridge jumping from south to north, and the shelf slope break zone in the Pearl River Mouth Basin suddenly jumped from the south side of the Baiyun Sag to the north side of the Sag. As a result, the Pearl River Mouth Basin has entered a coastal environment, and the Baiyun Sag has transformed into a bathyal-to-abyssal environment. At this time, the paleo Pearl River rapidly expanded to the areas of the Zuo River, You River, Red River and Nanpan River, while the 'Kontum-Ying-Qiong' River was gradually submerged by the SCS with the further expansion of the SCS.

The sedimentary detrital zircon age spectra of sediments on both the southern and northern sides of the Baiyun Sag (such as P3 and L3) exhibit signals of provenance from the paleo Pearl River, indicating that the main deposition in the Baiyun Sag which was predominantly controlled by the paleo Pearl River provenance (Hou et al. 2020). The two samples (3075.11-3075.86 m and 3062.24-3063.17 m) obtained from the Zhujiang Formation in L3 well show that the ages of detrital zircons in the sediments are mainly concentrated between 150 to 473 (Ma), including zircons from the Yanshanian, Indosinian, and Caledonian periods. As the samples are distributed from bottom to top, the zircon age spectra show an increasingly strong signal of the paleo Pearl River provenance. However, the peaks of zircon age spectra representing provenance from the western 'Kontum-Ying-Qiong' River, such as the Indosinian, Caledonian, and Jinningian periods, show a weakening trend. At this time, the Pearl River Delta further expanded, completely controlling a vast area of the Pearl River Mouth Basin, and forming a source-sink system consisting of a continental shelf delta, a land-slope channel, and a deep-water fan in the Baiyun Sag (Figure 7).

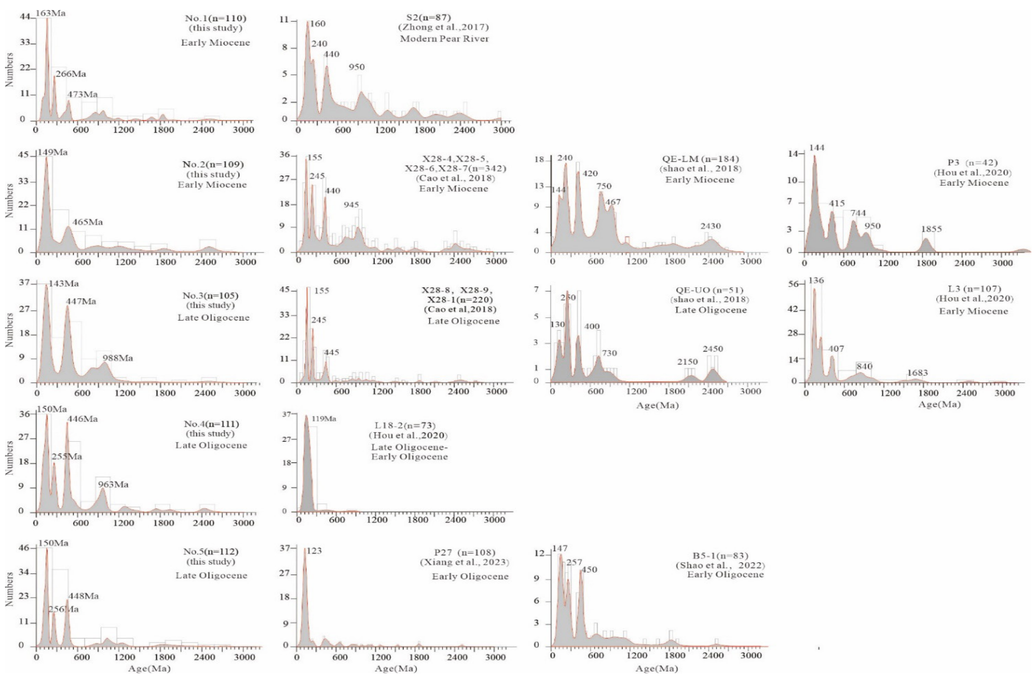


FIGURE 6. Comparison of detrital zircon ages between the Late Oligocene to Early Miocene sediments of the L3 well and source region detrital zircons

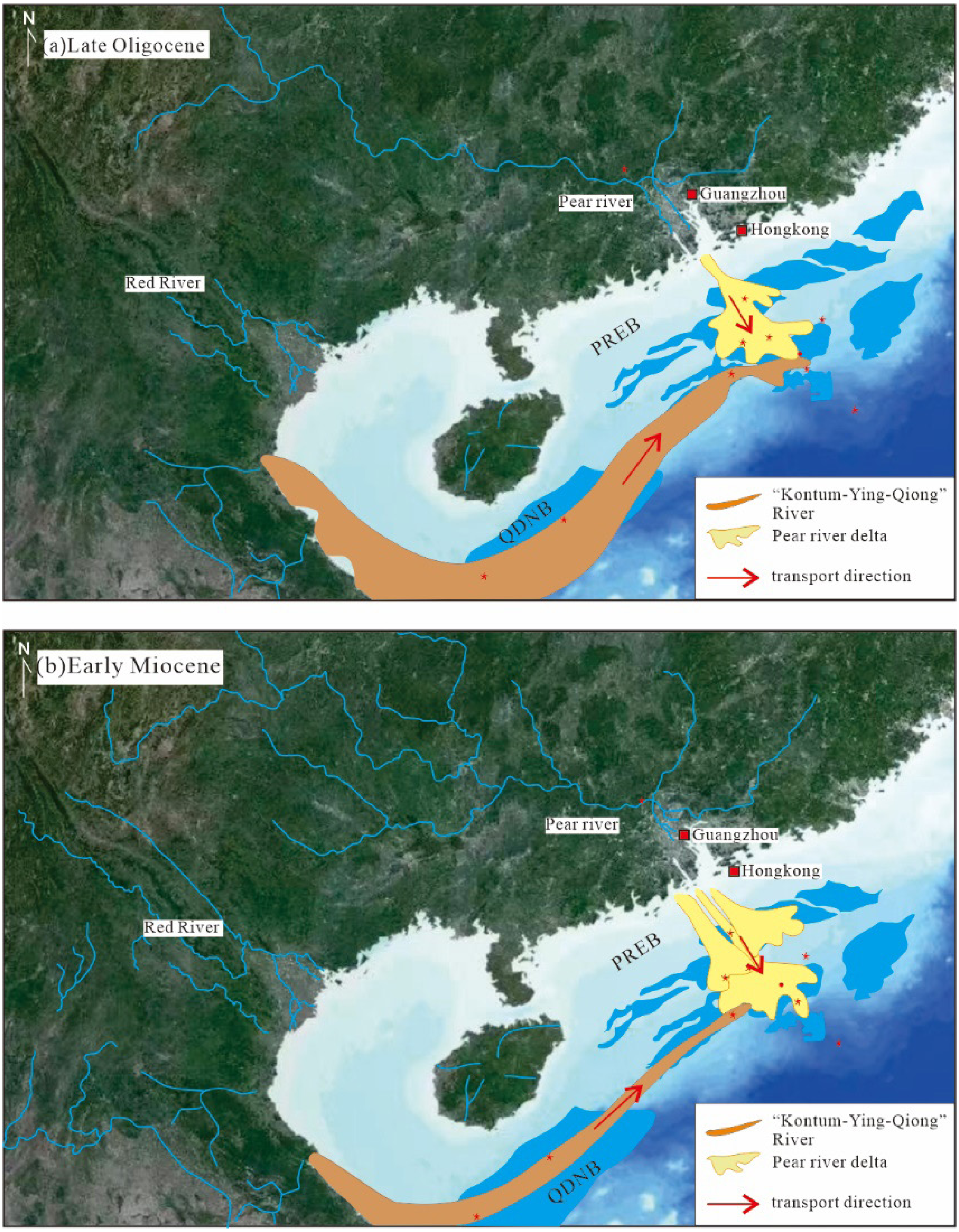


FIGURE 7. Sedimentary filling process in the L3 gas field in the Baiyun Sag from the Late Oligocene to the Early Miocene

CONCLUSION

Based on the results of zircon $^{206}Pb/^{238}U$ ages analysis of potential sources around the Pearl River Mouth Basin, the sediments of the Zhuhai Formation-Zhujiang Formation in the L3 gas field were selected for sedimentological characteristics and zircon $^{206}Pb/^{238}U$ ages analysis. The results show that: Cores indicate that the Zhujiang Formation sand bodies in the L3 gas field exhibit typical deepwater slope sedimentary structures, such as massive mudstone with undeveloped wormholes and undeveloped bedding, and layered siderite distribution. Locally, there are abrupt contacts between sand and mud layers, with features of reverse grain order. In contrast, the Zhuhai Formation sand bodies develop typical tidal bedding, abundant bedding, burrow bioturbation structures, and normally graded sandstones and siltstones, indicating shallow water delta deposits.

During the Late Oligocene, the shallow-water delta sedimentary sand bodies in the Zhuhai Formation of the L3 gas field were mainly supplied by bidirectional sources from the western and northern South China Sea, with additional contributions from local uplift zones. The zircon $^{206}Pb/^{238}U$ ages is characterized by multi-peak, and the zircon peak of the Jinningian period increases with the deposition time of sand bodies from old to new, indicating that the provenance signals from the paleo Pearl River in the north and the 'Kontum-Ying-Qiong' River in the west overlapped in the basin.

After the Baiyun movement, with the transfer of the shelf slope break from the south to the north of the Baiyun Sag and the gradual rise of sea level, the 'Kontum-Ying-Qiong' River in western China was gradually submerged by the SCS during the Early Miocene, and the supply of material resources weakened. Correspondingly, the zircon $^{206}Pb/^{238}U$ ages of sediments in the Zhujiang Formation of the L3 gas field exhibit increasingly prominent provenance signals from the paleo Pearl River, which primarily provided material for the shelf delta and deepwater fan depositional systems in the Zhujiang Formation of the L3 gas field.

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