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Geochemical characteristics of Oligocene-Miocene sediments from the deepwater area of the northern South China Sea and their provenance implications

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Abstract

Geochemical and detrital zircon U-Pb dating data for drilled sediments from the Baiyun deepwater area of the northern South China Sea demonstrate a change of sedimentary sources from the Oligocene to the Miocene. Zircon ages of the pre-rift Eocene sequences are dominated by Yanshanian ages with various peak values (110–115 Ma for U1435 and L21; 150 Ma for H1), indicating local sediment supply from the pre-existing Mesozoic magmatic belt. For the Oligocene sediments in the northern part of the basin, the rare earth elements show different distribution characteristics, indicating sediment supply from the paleo-Zhujiang River (Pearl River), as also confirmed by the multimodal zircon age spectra of the Lower Oligocene strata in Well X28. By contrast, a positive Eu anomaly characterizes sediments from the western and southern parts of the basin, indicating potential provenances from intermediate to basic volcanic rock materials. The Baiyun Movement at the end of the Oligocene contributed to a large-scale subsidence in the deepwater area and also a northward retreat of continental shelf break, leading to deepening depositional environment in the basin. As a result, all the detrital zircon ages of the Upper Oligocene strata from Wells X28, L13, and L21 share a similar distribution, implying the possible control of a common source like the Zhujiang River. During the Miocene, whereas sediments in the northern area were mainly sourced from the Zhujiang River Delta, and those in the southern deepwater area continued to be affected by basic volcanic activities, the Dongsha Uplift could have contributed as the main source to the eastern area.

Key words: geochemistry, zircon U-Pb age, provenance, South China Sea, Baiyun deepwater area

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1 Introduction

The South China Sea (SCS) is one of the most tectonically active regions in the marginal sea of the West Pacific. The northern SCS is situated in a transitional zone between the Tethys and paleo-Pacific tectonic domains, and also in an interactive zone of the Indo-Australian, Eurasian, and Philippines plates (Li et al., 2008). During the Yanshanian period (~200–65 Ma), the active continental margin turned to a passive margin. Subsequently in the Cenozoic period, many marginal seas developed (Pubellier and Morley, 2014) with the northern SCS deepwater areas undergoing complicate evolution processes. Since the Eocene, sedimentary basins in the northern SCS have evolved into diverse depositional environments from continental riverine, lacustrine, transitional, to neritic and abyssal facies (Li et al., 2009). The Zhujiang River flowing into the northern SCS is the oldest river in eastern China which possibly first initiated no later than Oligocene, and the Zhujiang River Delta is the only oil-enriching region among the large river deltas in eastern China. The slope area of the SCS lies in the lower reaches of the Zhujiang River and shows good petroleum potential as it contains organic-rich lacustrine shales formed in rifting stage as the source rock. Deepwater fan systems and abundant oil and gas resources have been discovered, placing the region into a global hot spot for deepwater petroleum exploration (Pang et al., 2006; Zhu et al., 2009; Zhang et al., 2015; Mi et al., 2016). The Cenozoic stratigraphy and relevant tectonic events in the northern SCS are summarized in Fig. 1 (Pang et al., 2007).

As an extended part of the South China block, the northern SCS basement consists of rock types similar to those outcropped in South China (Xu et al., 2013; Sun et al., 2014). The northern SCS basement mainly includes Paleozoic metamorphic rocks, Mesozoic metamorphic rocks, Mesozoic sedimentary rocks, intermediate acid intrusive rocks, intermediate basic magmatic rocks, extrusive rocks and transition crust basalt, with magma changed from acid in land to basic toward the sea (Wang et al., 2002; Shao et al., 2015). These basement rocks could have affected the sediment composition and accumulation during the early formation of the basin.

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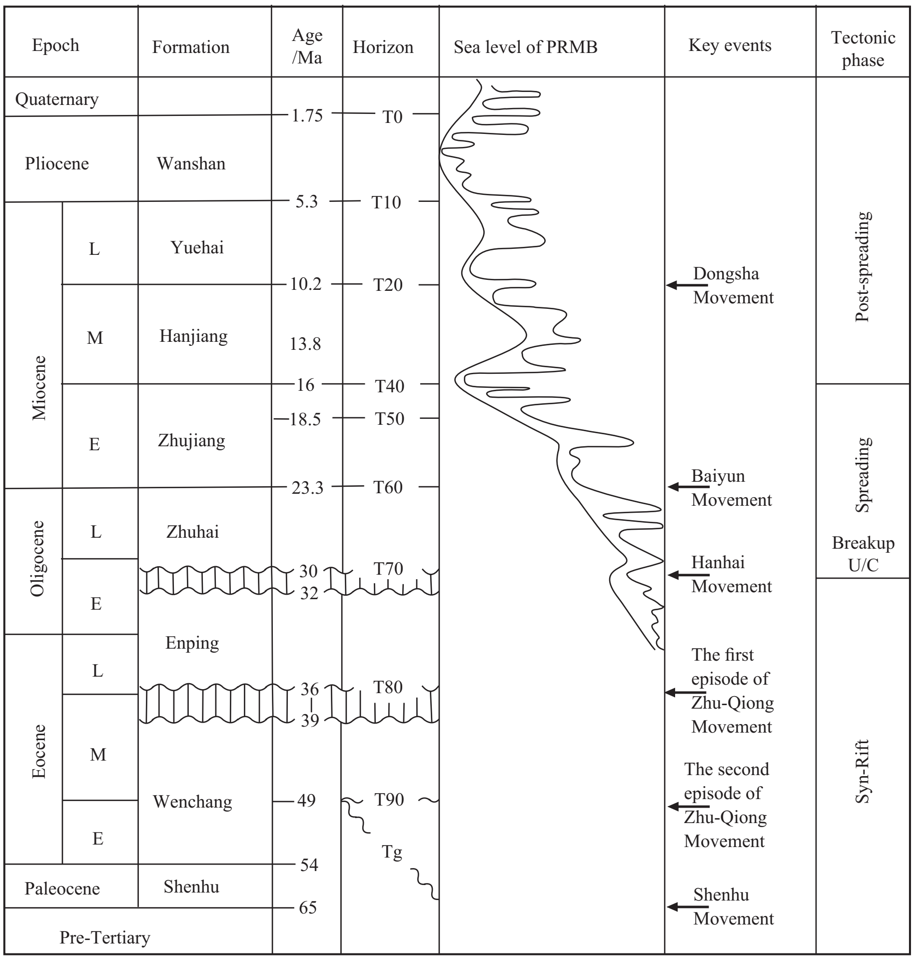

Fig. 1. Stratigraphic column and major tectonic events of the Zhujiang River Mouth Basin.

Previous studies indicates consistent feature of multi-sediment source filling for sediments from deepwater area of the northern SCS during the late Oligocene (Xie et al., 2014; Shao et al., 2016). A significant change in the composition of sediments took place at the end of the Oligocene (23.3 Ma), or the Baiyun Movement; as a result, the sedimentary environment in the Baiyun Sag was transformed from the neritic continental shelf in the late Oligocene to the continental slope in the early Miocene (Li et al., 2005), leading to a provenance change mainly from the proximal areas in the Oligocene to the distal areas in the Miocene (Shao et al., 2008). Deepwater fan systems formed mostly by turbidity current process in the Baiyun Sag since the early Miocene (Pang et al., 2007, 2008).

However, the provenance change from Oligocene to Miocene sediments in the deepwater area of the northern SCS remains a subject of dispute. Ocean Drilling Program (ODP) Site 1148 firstly revealed the abrupt changes across the Oligocene/Miocene boundary in both the acoustic and resistivity logging curves (Shipboard Scientific Party, 2000). The sediment recovered from this section shows deformed slump structures, which are quite different from the normal deep-sea Oligocene and Miocene sequences (Clift et al., 2002; Li et al., 2003). Li et al. (2003) proposed that the Oligocene sediments in the northern SCS were dominantly derived from a southwestern provenance (Indochina-Sunda Shelf and possibly northwestern Borneo) before changing to a northern provenance from South China in the Miocene. Based on single quartz grain oxygen isotope ratios, grain-size of isolated terrigenous materials, terrigenous mineral accumulation rate and scanning electron microscopy analysis of isolated quartz from ODP Site 1148, Li et al. (2011) proposed five stages for the evolution of the SCS basin, which were characterized by sediment source changes mainly from Palawan in the early stage to older sediment rocks in inland South China after 25 Ma. A later study by Wei et al. (2012) favored a sediment source from the southward drifting Palawan Continental Terrane, but their predicted geochemical signatures of potential source areas largely derived from modern sediments, which may not fully represent those of the Paleogene source-to-sink systems. In contrast to these interpretations of a southern source for the northern SCS sediments, however, most provenance studies emphasize a northern provenance from South China based on sedimentary and conventional geochemical evidence (e.g., Clift et al., 2002; Lan et al., 2014; Shao et al., 2015).

Sedimentary rocks preserve a relative complete record of the provenance composition and tectonic settings as well as crustal evolution. Mineral types and depositional environment information can be unveiled by routine sedimentary-petrological and geochemical analyses, including core observation, rock slice identification and elemental analysis. While mineral types can signal source rocks and source areas, rare earth elements (REE) are always in extremely low concentration in biogenic sediments from the deep ocean, so their presence may provide further evidence of sediment sources. REE elements are almost entirely derived from terrigenous supply with relative short residence time, and they are stable and rarely affected by fluvial transportation and sedimentation processes. As a result, they are considered as important indicators for provenance discrimination and tectonic analyses (McLennan, 1989; McLennan et al., 1993). Similarly, the diagnostic zircon is mainly originated from magmatic and metamorphic rocks and its U-Pb age is generally not affected by metamorphism, weathering, and sedimentary recycling (Cherniak and Watson, 2001; Fedo et al., 2003). Therefore, detrital zircon U-Pb dating analysis allows for an optimal solution to the problems of provenance discrimination and stratigraphic constraint when studying strata lack volcanogenic intercalations or fossils (Nelson, 2001; Dickinson and Gehrels, 2009).

Based on REE geochemistry and detrital zircon U-Pb dating analysis, this paper discusses sediment provenance and its evolution process during Oligocene-Miocene in the deepwater area of the northern SCS and evaluates the implications of regional-scale tectonic and sedimentary evolution in this area.

2 Materials and methods

A total of 1 021 core and cutting samples were collected from 13 wells in the Baiyun Sag deepwater area of the northern SCS (Fig. 2). Sediment provenances evolution was investigated through comparative analysis on REE characteristics and detrital zircon U-Pb dating (P33, L21 and U1435) from the Oligocene to early Miocene. Briefly, both P33 and L21 were carried by Shenzhen Branch of China National Offshore Oil Corporation in 1984 and 2012, separately, while U1435 was conducted by IODP349 in 2014.

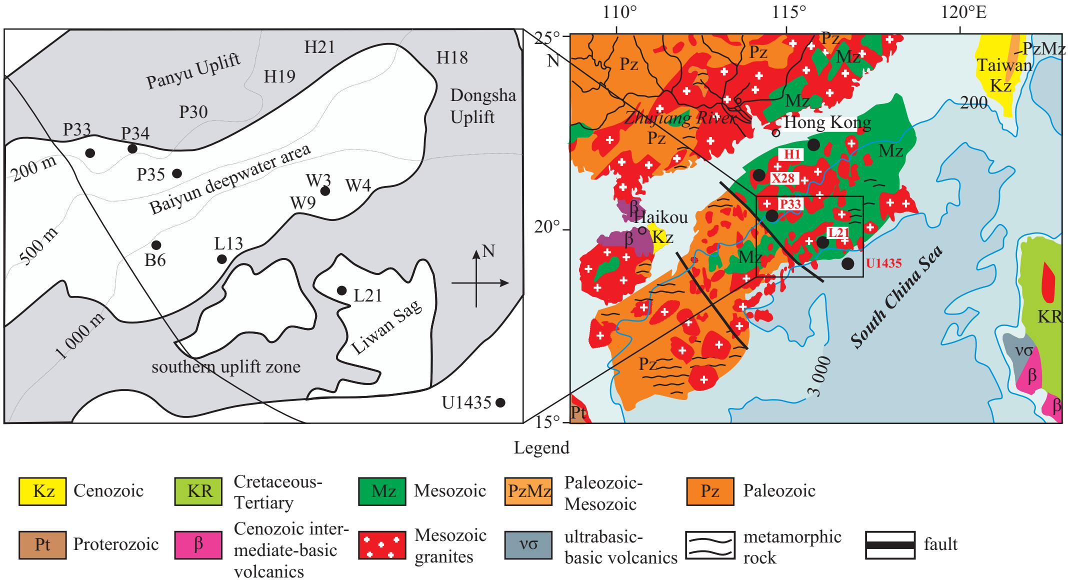

Fig. 2. The study area in the northern South China Sea and the location of sampled boreholes. Detrital zircon dating was done for samples from Wells U1435, L21, L13, X28 and H1. The basement lithologies were modified from Sun et al. (2014).

For geochemical analysis, samples were washed with deionized distilled water and dried at <60°C, before being crushed and ignited at 620°C for 60 min to remove organic matter and interlayer water from clay minerals. After weighing and calculation of the ignition loss, 0.1 mol HCl was used to remove marine $CaCO_3$. Samples were then dissolved in mixed HF and HNO_3, and one repeated sample and one blank sample were analyzed for every 30 samples in order to check for consistency. After dissolution, trace elements and REE were measured by inductively couple plasma-mass spectrometry (ICP-MS, Thermo Elemental X-Series), with 1×10^{-9} Rh added to keep measuring consistency. Each sample was measured for six times, calibrated with international rock standards (e.g., GSR-1, JSD-1), and checked with drift control samples, duplicate samples and blank samples. External precision (1σ) is usually better than 2% and the obtained concentrations are in agreement with the recommended data of these reference materials. Relevant analytical details were described by Li et al. (2002) and Wei et al. (2006). The geochemical analysis was conducted at the State Key Laboratory of Marine Geology, Tongji University.

Detrital zircons were extracted from bulk samples in the laboratory of the Institute of Regional Geology and Mineral Resources, Hebei Province, China, using conventional heavy liquid and magnetic separation techniques. More than 1 000 grains from each sample were picked, from which about 250 random grains were mounted in epoxy resin under the binocular microscope. Prior to geochronological analysis, the polished epoxy disks were imaged using cathodoluminescence (CL) in order to locate proper analytical spots in zircon oscillatory zoning (Fig. 3). U-Pb dating was performed by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the State Key Laboratory of Marine Geology, Tongji University, China. The instrumentation comprises a Thermo Elemental X-Series ICP-MS coupled to a New Wave 213 nm laser ablation system. The laser beam was set to a 10 Hz repetition rate with a spot size of 30 μm. The ablated material was then carried to the ICP-MS with a He-Ar gas mixture. Each analysis incorporated 20 s of gas blank followed by 50 s of data acquisition. Zircon 91500 ((1 065.4±0.3) Ma; Wiedenbeck et al., 1995) was used as an external standard, and was analyzed twice every seven analyses. Accuracy was monitored by zircon Plešovice with an age of (337.1±0.4) Ma (Sláma et al., 2008). U-Th-Pb isotopic ratios were calculated using ICPMS-DataCal (Liu et al., 2010) followed by the common Pb correction method of Andersen (2002). The age data were reported at 1σ level of uncertainty. The best ages were extracted from a 90% concordant subset, wherein the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages

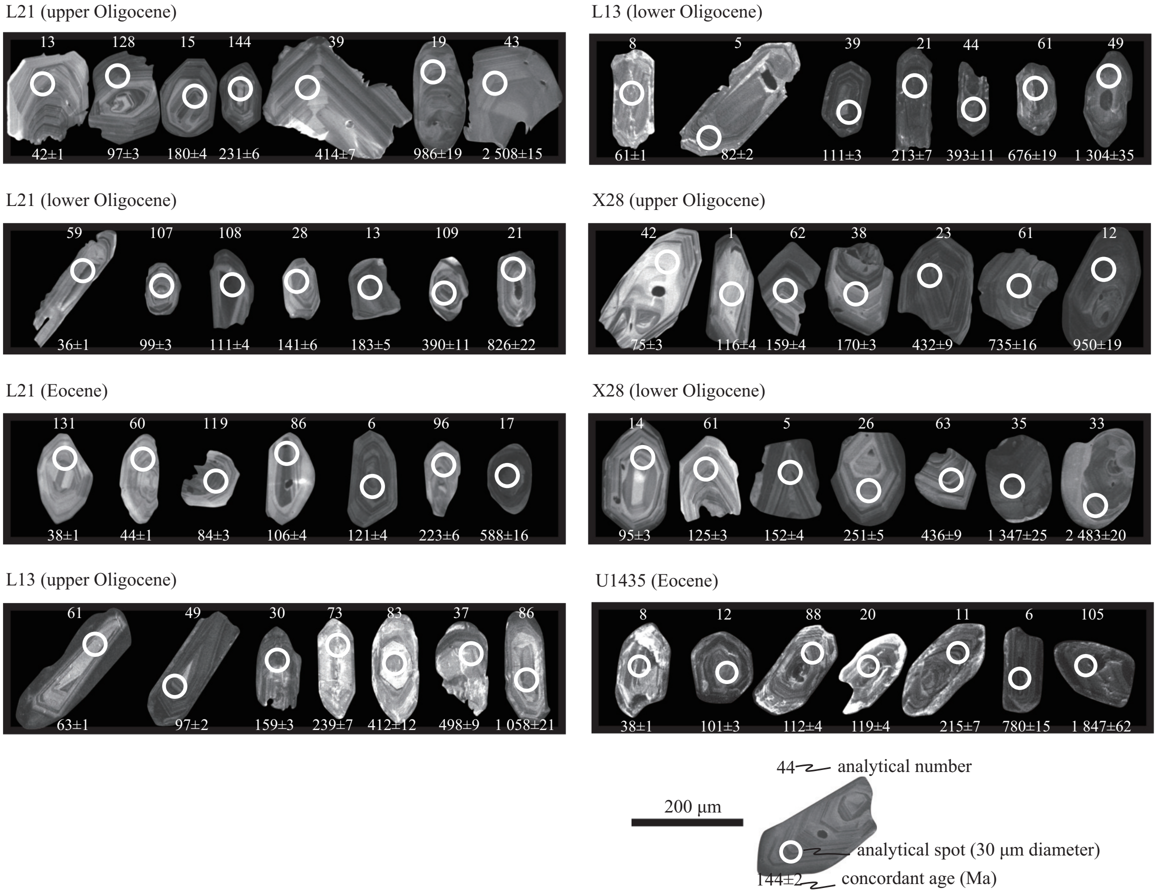

Fig. 3. CL images of zircon particles for certain analytical samples.

were adopted for zircons younger and older than 1 000 Ma, respectively (Compston et al., 1992). In this study, age results were visualized as kernel density estimation and histograms using Density Plotter (Vermeesch, 2012).

3 Results and discussion

3.1 *Geochemical characteristics of REE*

REE include light rare earth elements (LREE) La, Ce, Pr, Nd, Sm, and heavy rare earth elements (HREE) Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu. The average REE content of sediments in the Baiyun deepwater area of the northern SCS is 152.5×10^{-6}. The LREE/HREE ratio is between 2.44 and 4.46, indicating LREE enrichment.

The REE from the upper crust features relative LREE enrichment and Eu depletion, whereas Eu enriches in the lower crust and mantle and displays positive anomaly, with small variations between LREE and HREE contents (McLennan, 1989; McLennan et al., 1993). Accordingly, Eu anomaly has been widely employed for extrapolating the felsic or mafic nature of parent rocks (McLennan et al., 1993; Shao et al., 2010). As large rivers often drainage a very large area, their sediments are largely well mixed, with the REE close to the average value of the upper crust.

The geochemical results indicate that, in the early Oligocene (before 32 Ma, Fig. 4a), provenance for the northern Baiyun deepwater area was different from its counterpart in the south. The Chondrite-normalized REE distribution pattern of Well P33 features relative LREE enrichment and negative Eu-anomalies, almost parallel to that of the post-Archean Australian Shale (PAAS). The REE distribution pattern is similar between Well W3 and Well P33, illustrating a provenance from sedimentary rock or acid magmatic rock. In Wells W9 and W4 from the southern Baiyun Sag, however, both LREE and HREE show little difference in their distribution pattern with positive Eu-anomalies, reflecting some addition of basic rock materials in provenances different from that of Well W3 and localities in the northern part. It is noteworthy that the REE distribution patterns of the sediments from U1435 and L21 are very similar to that from the northern Baiyun deepwater area, indicating similar parent rock types.

Sediments of the late Oligocene (23.8–32 Ma, Fig. 4b) in Wells P33, P34 and P35 from the northern Baiyun deepwater area are characterized by LREE enrichment, comparable HREE contents, and negative Eu-anomalies, showing a strong similarity with the PAAS REE pattern likely controlled by provenances from the paleo-Zhujiang River Delta. Sediments in wells from the southern Baiyun deepwater area maintain their REE characteristics as in the early Oligocene, suggesting additional materials from basic rocks. Locating on a volcanic island in the central Baiyun deepwater area, Well B6 can be expected to have a large amount of intermediate-basic volcaniclastic materials, thus more positive Eu-anomalies. Sediments in Well H21 from the eastern depression show REE characteristics of neutral volcanic materials influenced by Dongsha volcanic activities.

The REE distribution of early Miocene sediments (18.5–23.8 Ma, Fig. 4c) from Wells P33, P34, P35, and H19 in the northern Baiyun deepwater area displays characteristics similar to that of the late Oligocene, implying a continuous control by the paleo-Zhujiang River Delta. The REE patterns for Wells W3, W4 and W9

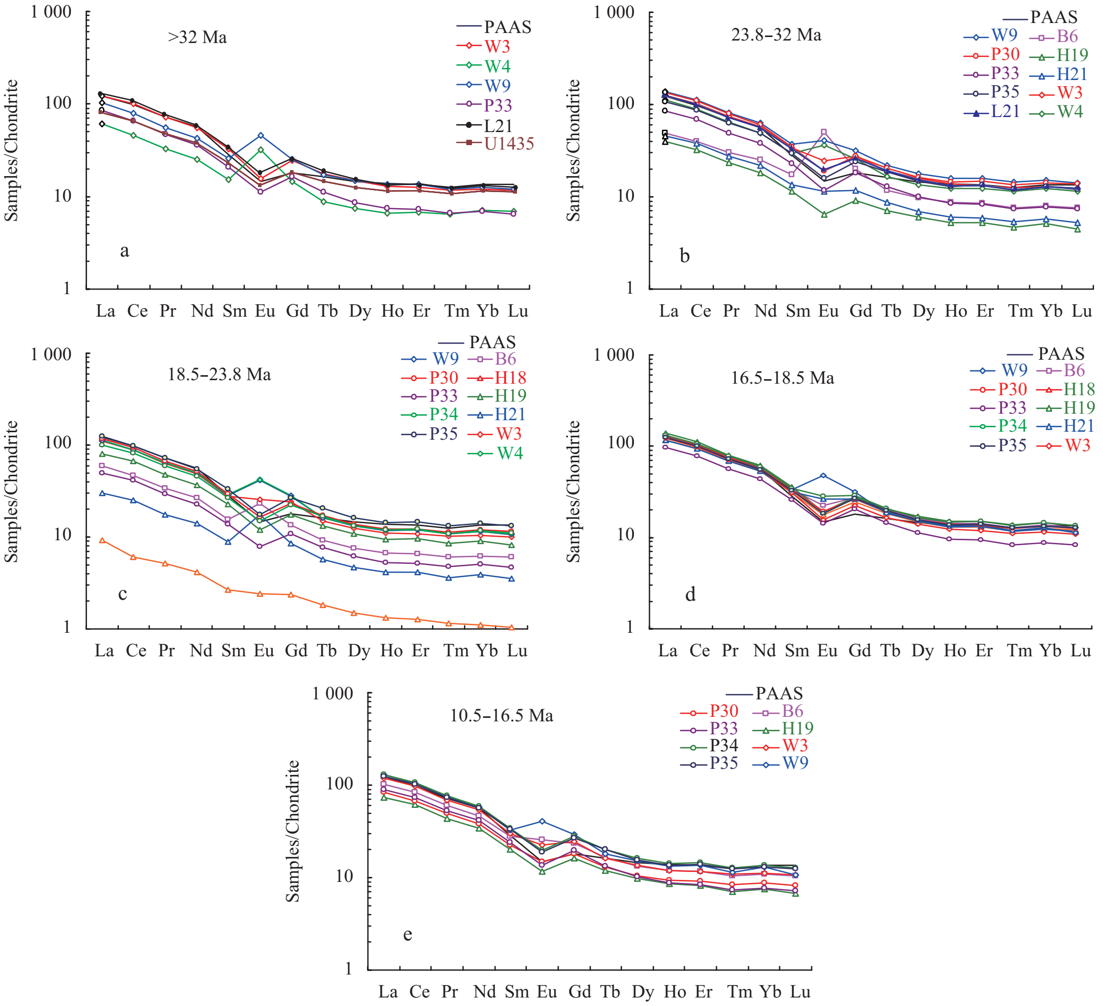

Fig. 4. Chondrite-normalized REE distribution patterns of Oligocene and Miocene sediments in the northern South China Sea (chondrite data cited from Sun and McDonough (1989)).

from the south, Wells H18 and H21 from the east and Well B6 from the west all show no Eu-anomaly or weak positive Eu-anomaly, which indicate the influence of intermediate-basic volcanic sources.

From the late Oligocene to the early Miocene, sediments in the northern Baiyun deepwater area were controlled by the paleo-Zhujiang River, while the southern part was influenced by basic volcanic rocks. In the early Miocene, deepwater environments developed in the studied area with the deposition of abundant basic volcanic materials, as indicated by the positive Eu-anomaly. The REE changes were considered to reflect increasing volcanism due to intense tectonic activities in the deepwater region of the northern SCS except the shallower northern part.

More specifically, the distribution characteristics of LREE and HREE in Wells P30, P33, P35, and W3 show a sudden change at 23.8 Ma (Fig. 5), driven by abrupt changes in sediment composition, as indicated by Nd isotope changes in sediments from near the Oligocene boundary at ODP1148 and Well P33 (Shao et al., 2008). All of these illustrate a major provenance change in the northern SCS which is also probably related to large scale headwater erosion of the paleo-Zhujiang River and increasing sediment transport distance about 23 Ma ago by the Baiyun Movement (Pang et al., 2009). The Baiyun Movement has had a substantial impact on sediment supply from the paleo-Zhujiang River and deposition offshore at the time.

In the early Miocene (16.5–18.5 Ma, Fig. 4d), sediments of the northern Baiyun deepwater area were mainly controlled by paleo-Zhujiang River Delta, while basic volcanic clastics materials increased in the northern part due to enhanced volcanic activities. The negative Eu-anomaly shown in eastern wells indicates the absence of intermediate-basic volcanic materials. Instead, reef carbonates began to develop in the Dongsha Uplift area since 18.5 Ma, thereby diluting the input of terrigenous clastic sediments (Liu et al., 2007).

In the middle Miocene (10.5–16.5 Ma, Fig. 4e), the REE characteristics in the Baiyun deepwater area except wells from the south show rich LREE, less HREE and negative Eu-anomaly, all similar to that of PAAS. This similarity indicates a strong mixture of all sorts of sediments, as the REE pattern of larger river sediments often closely resemble those of the upper crust exemplified by the PAAS due to a large drainage area, long transportation distance and well mixed sediments. The REE pattern therefore implies the continuous control by the paleo-Zhujiang River Delta on deep water deposition when seafloor spread further south and tectonic activities became relatively weak in the middle Miocene in the northern SCS.

Although close to each other in the southern deep water area,

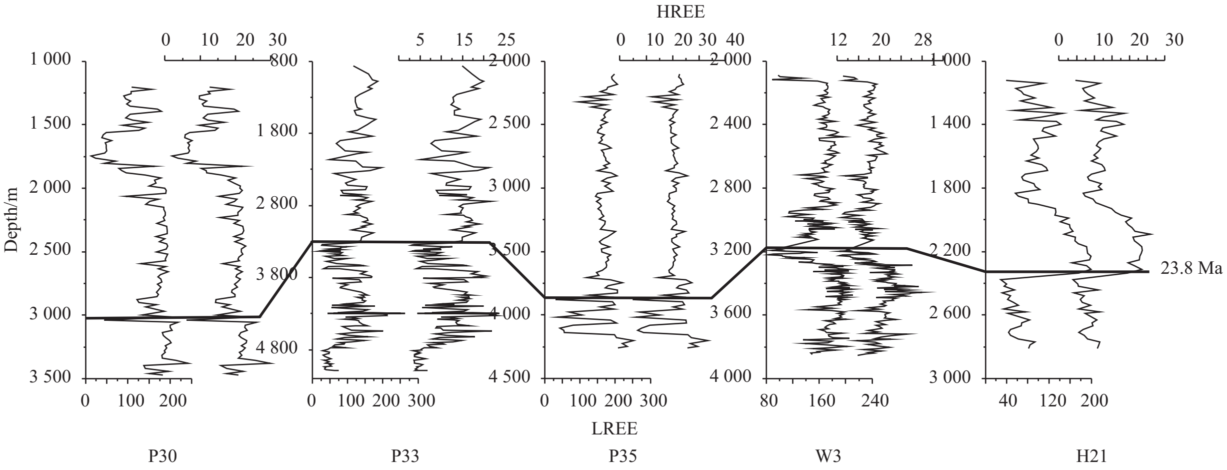

Fig. 5. LREE and HREE variations in wells from the northern South China Sea, showing a sudden change at 23.8 Ma caused by the Baiyun Movement.

Well W9 is different from Wells W3 and W4 in a negative Eu-anomaly for most of the time except the early Miocene (Fig. 4), thus similar to the pattern of Well P33. In both Wells W4 and W9, the positive Eu-anomalies are present until the middle Miocene, indicating continuous volcanic influence. The cluster of most data points on the La/Lu-Zr/Hf-Th/U plot also testify a similar provenance for W4 and W9 but a different source for W3 with relatively high Th/U values (Fig. 6). Thus, these REE patterns demonstrate that sediments of Well W3 were controlled not only by the paleo-Zhujiang River Delta during Oligocene and Miocene, but also by basic volcanic activities driven by the Baiyun Movement at around 23.8 Ma.

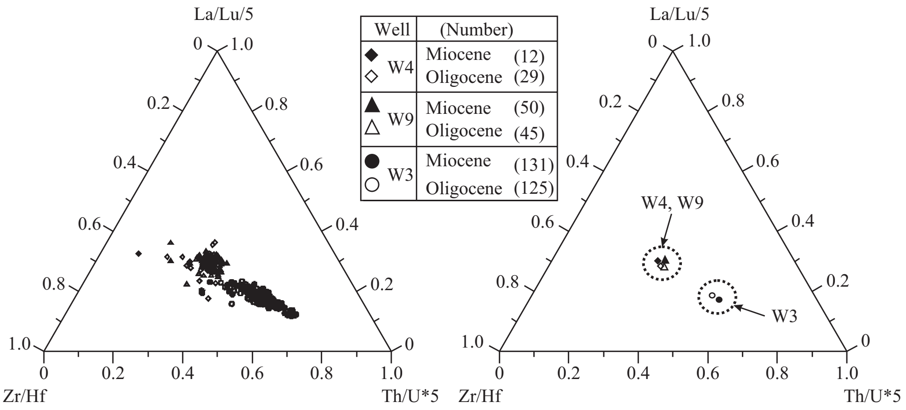

Fig. 6. The La/Lu-Zr/Hf-Th/U ternary plots for trace elements of the Oligocene-Miocene sediments from the southern Baiyun deepwater area. Left—based on individual samples; right—based on the average values number of samples (not amount of samples).

3.2 *Provenance implied by zircon dating*

A change in the subduction angle of the western Pacific Plate towards Eurasia during the late Mesozoic has been considered as the main cause of seaward migration of igneous activities in South China. For example, Zhou and Li (2000) divided the Mesozoic igneous rocks into three Yanshanian groups with ages of 180–160 Ma, 160–140 Ma and 140–90 Ma, respectively, presumably in responding to different stages of activities involving a recession of the subduction plate and a steepening subduction angle, as well as the trending of younger ages of igneous rocks from land to sea (Li and Li, 2007). The Cenozoic Zhujiang River Mouth Basin developed on a pre-Paleogene basement which also formed as an extension of South China landmass (Wang et al., 2002; Xu et al., 2013). Based on gravity and magnetic and drilling data, Wang et al. (2002) and Sun et al. (2014) reported basement lithologies dominated by the Mesozoic granitoid igneous rocks, and secondarily by granodiorite, diorite, quartz diorite and adamellite in the eastern part, and by Paleozoic metamorphic rocks in the western part (Fig. 2). Both K-Ar and Rb-Sr dating of 21 granitoid samples by Li et al. (1998) placed the majority (19 samples) in an age range between 118.9 Ma and 70.5 Ma, while the other two samples registered (153.0±6.0) Ma and (130.0±5.0) Ma, respectively. Similar age ranges have also been obtained by zircon dating (Xu et al., 2016). Zircon U-Pb dating of 15 granite samples in wells from basin basement by Shi et al. (2011) also yielded ages ranging from 163.8 Ma to 100.4 Ma. It is noteworthy that the age data reported here were obtained from relatively shallow part of the basin. Similarly, most detrital zircon ages of the Eocene sediments from the continent-ocean transition (U1435) and the Zhujiang River Mouth Basin (L21 and H1) are clustered between 200 Ma and 80 Ma, with a common peak of ~110–115 Ma for U1435 and L21 and a 150 Ma peak for H1 (Fig. 7), reflecting that the source rock of H1 in the northern part of the Zhujiang River Mouth Basin was relatively older than that in

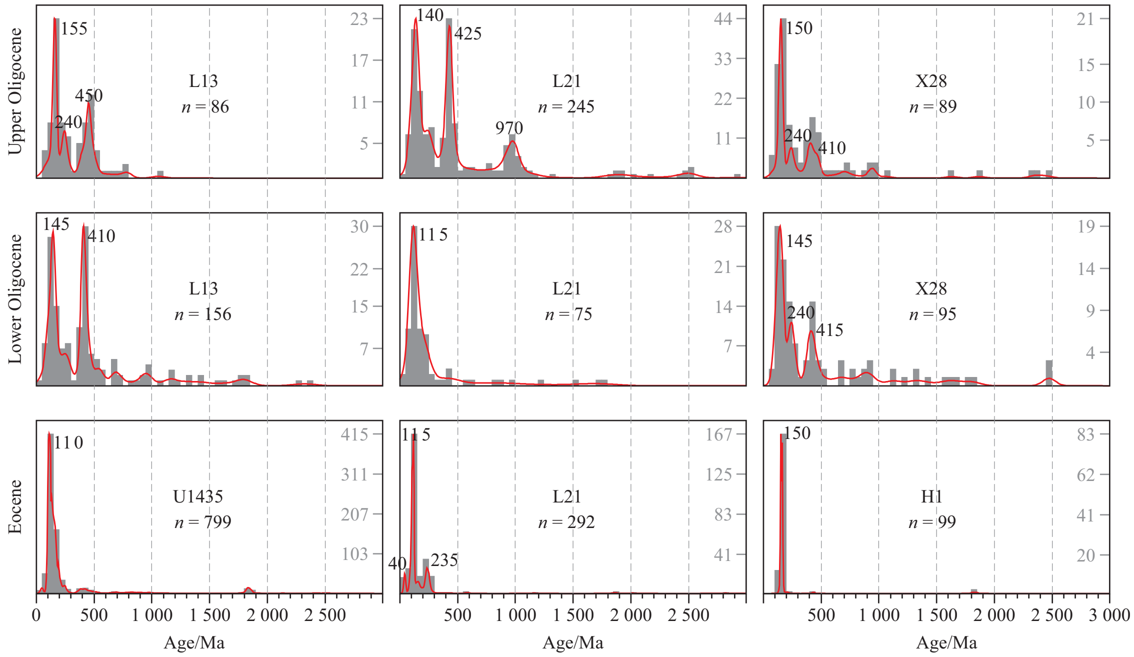

Fig. 7. Detrital zircon U-Pb age spectra and histograms for samples from Wells H1, X28, L13, L21, and U1435, revealing the Eocene to Oligocene provenance evolution in the northern South China Sea. The letter *n* represents number of concordant zircons.

southern part of the basin, which matches well with the age of the magmatic basement rocks described above. All these thus indicate that the Eocene sediments from the Zhujiang River Mouth Basin and from U1435 could have been transported from separated source rocks along the South China margin or even the basement highs in the shallow part of the basin dominated by Mesozoic granites that formed the main part of the regional continental crust (Fig. 1).

The detrital zircon ages for the Lower Oligocene strata in Well X28 from the northern Zhujiang River Mouth Basin with several Mesozoic peaks are different from those of the Eocene in H1 from the northeast with a single 150 Ma peak, indicating that the drainage area of the paleo-Zhujiang River enlarged and older basements had contributed to sediment supply in Well X28. However, the detrital zircons from L13 contain much more relatively older aged grains than those from X28 and L21, suggesting the Paleozoic rocks in the western part of the basin was the dominant source. Meanwhile, the detrital zircon age distribution for L21 did not change much from the Eocene to the early Oligocene, reflecting little effects by the paleo-Zhujiang River on this area (Fig. 7).

For the late Oligocene, the detrital zircon ages from X28, L13, and L21 all show common peaks at ~150, 240, and 410–450 Ma, albeit with an additional peak of 970 Ma in L21, which indicate a common provenance dominated by Mesozoic and Paleozoic magmatic rocks.

3.3 *Birth of the Zhujiang River*

Previous studies have shown that a paleo-Zhujiang River Delta already existed as early as the Eocene, although it was probably much smaller and located farther offshore than its modern counterpart (Clift et al., 2002; Shao et al., 2015). Geochemical evidence suggested that this small-scale paleo-Zhujiang River Delta was formed near sedimentary sources from basement uplifts during the Eocene and early Oligocene (Shao et al., 2015). The REE elements and detrital zircon ages analyzed in this study show different Eu-anomaly and zircon U-Pb data of the Eocene from those of the (late) Oligocene-Miocene (Figs 4 and 7), indicating near-source accumulation in the Eocene, most likely from uplifted and eroded Mesozoic igneous and metamorphic rocks surrounding these wells at that time. Therefore, the similar characteristics of depositional ages and sediment composition between localities demonstrate that the Paleocene-Eocene faulted basins in the northern SCS received sediments mainly from the nearby Mesozoic magmatic highlands. Seismic profiles (Shao et al., 2013; Xie et al., 2014) and distinct detrital zircon age spectra between U1435 (Mesozoic and older due to metamorphism) and L21 and H1 (almost exclusively Mesozoic) (Fig. 7) together imply a relatively diverse topography for the region with basins filled by voluminous clastics from a large Mesozoic granite provenance (Li and Li, 2007; Xu et al., 2016). However, the zircon age spectrum of Well H1 is relatively unimodal and old, reflecting the drainage of the paleo-Zhujiang River was very small, probably limited to the coastal area at the time.

Variations in the early Oligocene detrital zircon age spectra among X28, L13, and L21 indicate their different sources. With abundant Paleozoic zircons and frequent Mesozoic ones, Well L13 probably received sediment mainly from the uplifted basements highs in the west of the basin (Fig. 2). All the detrital zircon ages of late Oligocene sediments from X28, L13, and L21 show similar distribution likely from a common source area. All these results combined indicate a limited influence of the paleo-Zhujiang River on the location of Well X28 only in the early Oligocene, but its influence further expanded to the southern part of the Zhujiang River Mouth Basin (Well L21) in the late Oligocene.

4 Conclusions

Our geochemical study of sediments in the Baiyun deepwater area of the northern SCS reveals three Chondrite-normalized REE distribution characteristics corresponding to provenance changes in different parts of the Baiyun deepwater area in the northern SCS from the Oligocene to Miocene. The Oligocene–

Miocene sediments from the northern part of the studied area show similar Chondrite-normalized REE features as for the PAAS, with relative LREE enrichment, comparable HREE contents and negative Eu-anomalies, indicating a main source from the paleo-Zhujiang River with parent rock types dominated by sedimentary rocks and or acid magmatic rocks. In the southern part of the Baiyun deepwater area, the Oligocene sediments are characterized by reduced divergence between LREE and HREE with obvious positive Eu-anomalies marking a basic magmatic supply. In particular, Well B6 on a volcanic island in the central area features a strong positive Eu-anomaly due to the deposition of abundant intermediate to basic volcanic materials. However, the early Miocene REE patterns of Well B6 and those in wells from the north became similar, while the contemporary sediments from the eastern area featured no Eu-anomalies or positive Eu-anomalies, indicating volcanic influence from the Dongsha Uplift. Negative Eu-anomalies affected by acid magmatic rocks did not occur around this area until 18.5 Ma.

Our data indicate that the Baiyun movement at ~23.8 Ma had greatly influenced the sediment composition in the deepwater region, mainly through changes of parent rock types driven by headwater erosion and drainage expansion of the paleo-Zhujiang River. Significant REE changes from the late Oligocene to the early Miocene suggest increased volcanic activities and deposition of intermediate and basic volcanic materials in the eastern, western, and southern parts of the deepwater area in the northern SCS. Although all are located in the southern deepwater area and close to each other, Wells W3, W4 and W9 show strong differences in their sediment composition due to a higher variety of parent rock types. Well W3 received sediments from a stable source from the paleo-Zhujiang River Delta during the late Oligocene-Miocene, although interrupted by volcanic activities driven by the Baiyun movement at ~23.8 Ma. For Wells W4 and W9 from the southern uplift, basic magmatic source was dominant until the middle Miocene.

Detrital zircon ages indicate that the paleo-Zhujiang River was a young rivulet in the Eocene and transported Mesozoic igneous (with age peak of 150 Ma) from the South China margin to the northern part of the Zhujiang River Mouth Basin. Its influence reached Well X28 area in the early Oligocene, and the southern part of the basin in the late Oligocene, implying continuing increase of the river drainage with time.

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