

Paleogene transgression process and environmental evolution in the deepwater area of the Baiyun Depression in the northern South China Sea

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Abstract

Multiple borehole samples are collected from the Baiyun Depression in deep-water area of the northern South China Sea (SCS) in an effort to reconstruct transgression processes during the Paleogene based on palynalgal analysis. This study indicates that the Baiyun Depression generated a large group of palynopore assemblages and fluvial/lacustrine-related algae during the early and middle Eocene when the Wenchang Formation was deposited. The entire depression was dominated by fluvial and lacustrine facies before transgression. Its eastern and southeastern sags transitioned to shallow marine environment by generating a large abundance of marine dinoflagellates during the Enping deposition of the late Eocene. Meanwhile, the southern uplift zone simply yielded fluvial/lacustrine-related palynopores and algae, and was dominated by the fluvial and lacustrine environment during the early stage of the Enping Formation, prior to shifting into transitional setting in the later period. Northwestern sags remained extensive fluvial and delta facies without existence of marine dinoflagellates. It was until the depositional stage of the Zhuhai Formation (Oligocene) that the overall depression was strongly impacted from transgression process. Both eastern and southeastern sags were mainly under deep marine setting on a continental slope while northwestern and southern areas developed transitional facies. Although distribution and accumulation patterns varied greatly among sub-sags, the overall Baiyun Depression was characterized by widespread development of marine dinoflagellates. It should be noted that the northwestern sag also partly generated large-scale river delta deposits. Due to the eustatic rise and change of SCS spreading axis, the overall Baiyun Depression was mostly influenced by the deep marine environment on a continental slope during the early Miocene. Both northwestern sag and southern uplift zone were found plentiful marine dinoflagellates. In summary, transgression initiated from the eastern and southeastern Baiyun Depression before subsequently progressing into the farther west. Evolution of transgression process is also greatly consistent with the gradual westward expansion of the SCS.

Key words: South China Sea, Paleogene, transgression, sedimentary environment, plant ecology

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1 Introduction

Located at the intersection of the Eurasia, Pacific and India-Australia, the South China Sea (SCS) is the largest marginal sea in the Western Pacific area and has kept a complete sedimentary record of regional tectonic processes since the Cenozoic, which remain hotly debated and attracts widespread attention. The Pearl River Mouth Basin is the largest Cenozoic basin in the northern SCS. As the largest and deepest sub-unit within the Pearl (Zhujiang) River Mouth Basin, the Baiyun Depression has undergone a series of complex tectonic events (Zhu, 2010; Zhao et al., 2021). With formation and development of the SCS, the Baiyun Depression has gradually changed from continental to marine facies (Gao et al., 2021; Zhang et al., 2021b). Since it is located near the oceanic-continental transition zone, the Baiyun Depression was influenced by different provenances and thereby is of great significance in studying the sedimentary evolution of the SCS (Fig. 1).

Many indices and tools aim for paleo-sedimentary environment reconstruction, which is essential in basin research. Palaeontology is widely used by numerous researchers due to its higher precision on time constraints. In particular, plant ecology is largely affected by preservation condition of fossil records. Based on different ecological characteristics, plants are generally categorized into terrestrial and coastal species, freshwater algae and brackish-water algae. Paleo-depth and paleo-environmental restoration are usually achieved by assessing different types and their proportions of pollen and algae assemblages (Hao and Mao, 1993; Wu et al., 2003; Mai et al., 2016).

In order to generate a better understanding of northern SCS sedimentary evolution, it is important to systematically investigate regional geological background by relying on multidisciplinary and integrated analytical approaches. In this study, we combine pollen and algae analyses from Baiyun Depression drilling

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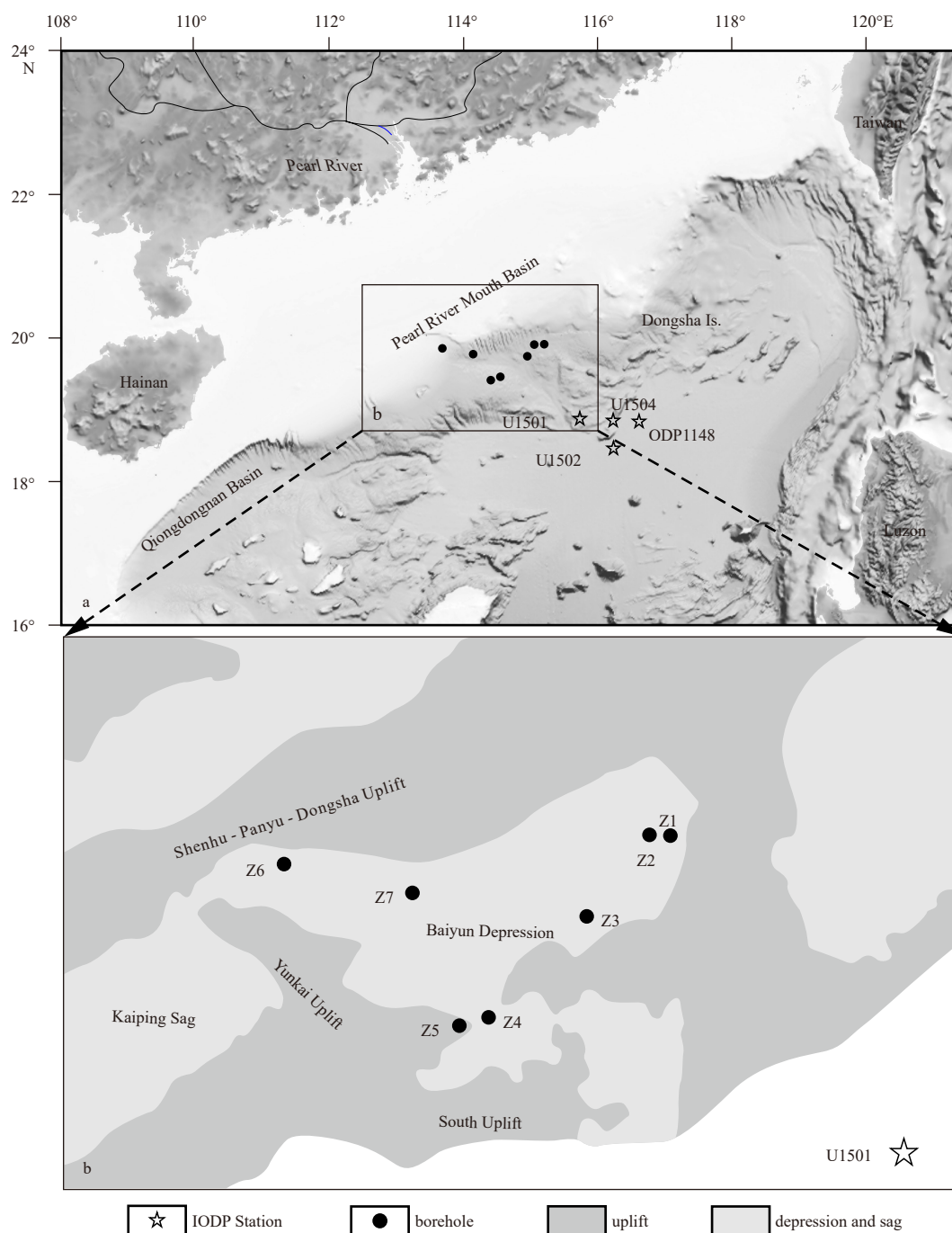


Fig. 1. Regional geological background and geographic locations of drilling samples in this study.

samples with other micropaleontology studies to reveal transgression processes of a basin scale and reconstruct basinal sedimentary environment during Paleogene. This study is also promising to provide a deeper understanding of both SCS evolution as well as paleogeographic patterns from a wider perspective.

2 Geological background

The Baiyun Depression is located at the deep-water area of the southern slope of Pearl River Mouth Basin in the northern SCS. It is formed above the oceanic and continental transitional crust, with water depths ranging from 200 m to 2 000 m. The Baiyun Depression is the largest and deepest depression in the Pearl River Mouth Basin and has a total area larger than 2×10^4 km², about 70% of which is deeper than 500 m. Geographically, it is

surrounded by Panyu Low Uplift to the north, Dongsha and Dongsha Uplift to the east, South Uplift to the south, and Yunkai Uplift to the west (Fig. 1). In particular, the Baiyun Depression generates Cenozoic sedimentary succession of 11 km in thickness (Pang et al., 2007; Zhang et al., 2014; Zhao et al., 2017; Feng et al., 2021), and keeps valuable records of environmental evolution of the SCS since its origination. The Baiyun Depression was stepwise deposited with the Wenchang Formation (fault stage) in the early and middle Eocene, the Enping Formation (fault-sag stage) in the late Eocene, the Zhuhai Formation in the Oligocene and the Zhujiang Formation in the early Miocene (subsidence stage), which were in general under control by different tectonic settings.

Previous studies indicate that the Baiyun Depression was

dominated by continental-lacustrine-delta sedimentary environment during the deposition of the Wenchang Formation (the early-middle Eocene) (Zhang et al., 2019; Gao et al., 2021; Xiong et al., 2021; Guo et al., 2022; Wu et al., 2022). It was until the late Eocene when the Enping Formation was deposited that the entire Baiyun Depression was affected by transgression to varying degrees and formed marine sediments within its sub-sags. The Baiyun Depression was generally influenced by a continental-

marine transitional and shallow marine environment. In particular, the western Baiyun Depression generated large-scale braided river delta facies which were mainly sourced from eastward-flowing river systems (Wang et al., 2011; Zhang et al., 2015; Li et al., 2017; Shao et al., 2019). When the lower Zhuhai Formation was deposited in the early Oligocene, the regional sea level increased rapidly, and extensive transgression occurred in the Baiyun Depression (Fig. 2). With the gradually increasing influence from

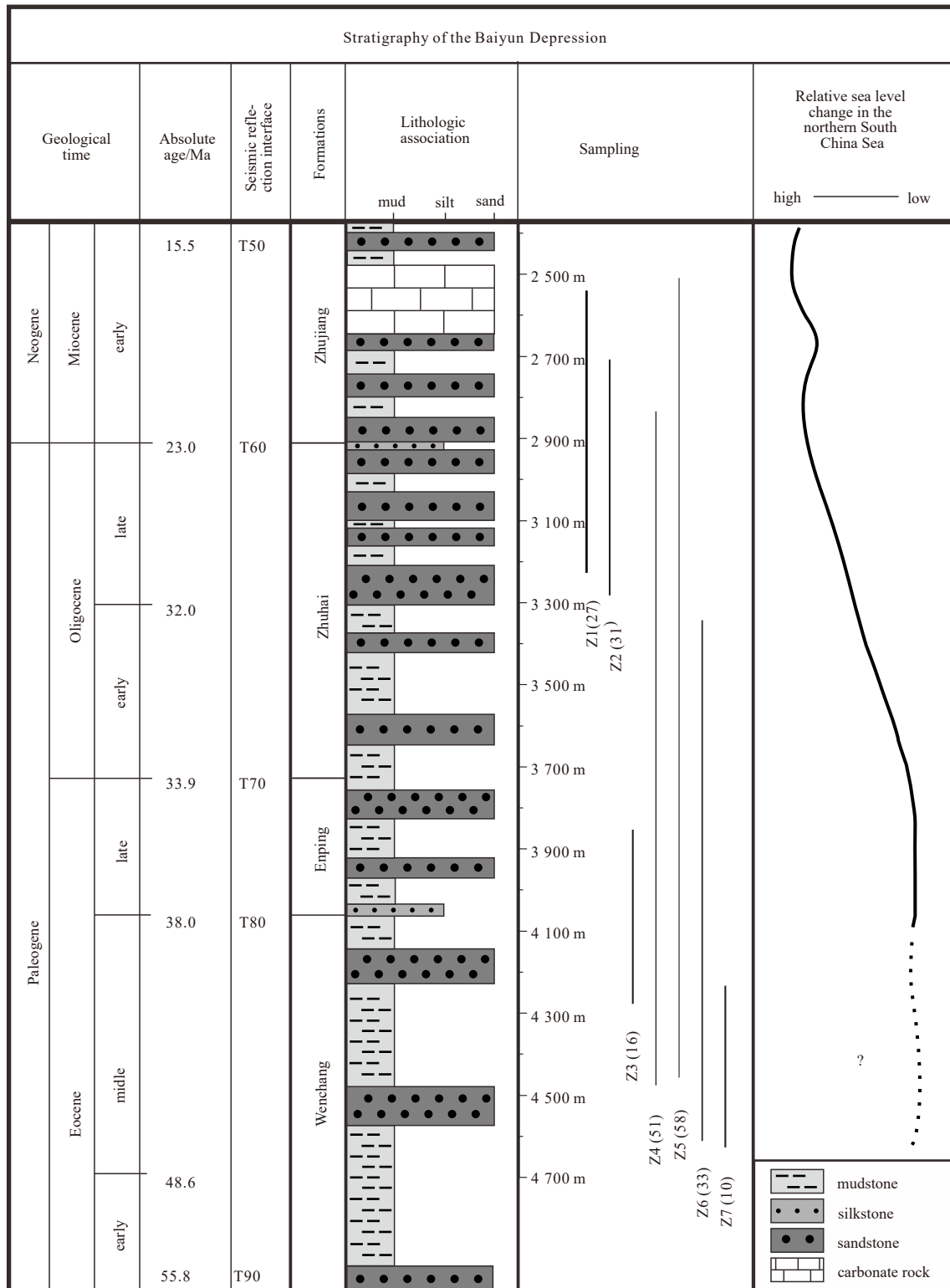


Fig. 2. Stratigraphy of the Baiyun Depression.

the Paleo-Pearl River input, a large delta was initiated and developed in the northern depression (Zhang et al., 2021a). During the late Oligocene when the upper Zhuhai Formation was formed, the Paleo-Pearl River delta extended greatly into the southern depression under a general regression environment. This was subsequently shifted into a new stage of transgression when the Zhujiang Formation was developed in the early Miocene (Liu et al., 2007; Wu et al., 2010; Zhang et al., 2014; Shao et al., 2017; Fan et al., 2021). However, transgression-regression patterns and evolution of individual scenarios within the Baiyun Depression remain lack of detailed and systematic investigation (Gao et al., 2021).

3 Materials and methods

In this study, seven wells were selected from different deep-water areas of the Baiyun Depression, including Z1, Z2, Z3, Z5, Z4, Z6 and Z7. A total of 226 cutting rock drilling samples were analyzed for palynologic palaeoecological studies. Geographic location map of our study area and drilling location distribution are shown in Fig. 1. The study strata and sample depth are shown in Fig. 2.

Our samples were first rinsed by hydrochloric acid and hydrofluoric acid in order to remove interlayered calcium carbonate and siliceous matter, separately. A collection of paly pollen, planktonic algae, organic-walled microfossils and other organic matter were then obtained via a sieve mesh of 7 mm in diameter. Biomarkers from Palyology Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences, including 27 637 fern spores were added into our washed samples, followed by observation and counting of species and number of palynalgal fossils under a LEI-CA(DMR) biological microscope. Samples were all processed and analyzed at the State Key Laboratory of Marine Geology, Tongji University. Only samples containing more than 65 spores and pollen fossils with statistical significance were selected in this study.

Basically, our palynalgal results were divided into three groups, which are palynophytes (including fern spores, gymnosperms pollen, angiosperms pollen), fluvial and lacustrine algae and marine dinoflagellates. Due to their sensitivity and tendency to both humidity and temperature, palynophytes are considered as useful indicators for vegetation distributed in coastal and source regions, and generally imply dominance of terrigenous environment. Algae, on the other hand, mainly exist in aquatic environment, such as dinoflagellates, stomatophora and other autobiota, which are of small sizes and widely distributed of high abundance in marine environment. Discostellaria and plicifera indicate freshwater environment dominated by river and lacustrine facies, while globococcus and granulococcus imply freshwater-brackish water environment (Fig. 3). Since algae are sensitive to paleosalinity, they are usually regarded as an important palaeoecological signal in basal paleoenvironmental studies.

The relative abundance of algae and dinoflagellates is closely related to the proximity of sediments to shoreline as well as the water depths of deposits. For example, the relative abundance of palypollen decreases in a simple trend from the margin of continental shelf, main body of continental shelf, continental slope to continental uplift. However, abundance of marine dinoflagellates develops in a more complicated pattern. These organisms rarely appear at the margin of continental shelf, and their relative abundance rises with the increase of water depths from the continental shelf margin to outer shelf. Farther away from outer shelf to continental slope and continental uplift (namely progressive increase of water depths), concentration of marine dino-

flagellates alternatively goes down. Therefore, changes in contents of various algae species are effective for the interpretation of aquatic environmental changes (Mamet and Copeland, 1982). In this study, sedimentary environment as well as marine-terrestrial facies shift of the Baiyun Depression in different stages were assessed by relative abundances of fluvial and lacustrine algae, marine dinoflagellates in combination with complementary micropaleontological data from the other drilling samples in this area. Transgression-regression processes and sedimentary transition from terrestrial to marine facies in Paleogene were studied and summarized in an integrated perspective. Environmental evolution of the northern SCS was further investigated with complementary supporting evidence from the research updates of SCS ocean drillings.

4 Results

The Baiyun Depression is divided into four major regions including the east, southeast, Southern Uplift and northwestern units based on geographic locations of our studied boreholes.

4.1 Eastern sag: Well Z1 and Well Z2

There are two boreholes located in the eastern part of the Baiyun Depression including Z1 and Z2. Twenty-seven and thirty-one cutting samples were extracted from the 2 540–3 227 m interval of Well Z1 and 2 705–3 280 m interval of Well Z2, respectively. Changes in assemblage patterns and contents of palypollen, fluvial and lacustrine plankton and marine dinoflagellates are shown in Fig. 4.

There are 17 Enping Formation samples from the 2 960–3 227 m interval of Well Z1, which contain high abundance of pollen and marine dinoflagellates. Therein, proportion of pollen ranges from 45.0% to 89.9% with an average of 54.9% and marine dinoflagellates vary between 3.7% and 53.3% (averaging at 41.4%), including *Cleistosphaeridium* spp. and *Spiniferites* spp. However, algae species indicating fluvial and lacustrine facies are in extremely low concentration and account for only 0.5%–8.5% in proportion (average 3.8%). There are 10 Zhuhai Formation samples from the 2 540–2 900 m section of Well Z1, which are dominated by pollen assemblage varying from 64.1% to 98.0% (averaging at 88.8%). Marine dinoflagellates are mainly *Spiniferites* spp. and are in low but continuous content with a range of 1.0%–31.4% (average 9.7%).

Content of fluvial and lacustrine algae (mainly *Leiosphaeridia*) is fairly low and ranges from 0 to 4.6% (average 1.4%).

Well Z2 shows a similar spore-algal assemblage pattern to Well Z1. There are 8 Enping Formation samples from the 3 095–3 280 m interval and palypollen content ranges between 37.9% and 66.3% (average 55.2%). Marine dinoflagellates are mainly *Operculodinium centrocarpum*, *Cordosphaeridium* spp., *Spiniferites* spp., and their contents vary from 26.5% to 65.9% (average 43.3%). However, algae indicating fluvial and lacustrine facies are in extremely low proportion, accounting for only 0 to 7.2% (average 1.5%). There are 23 Zhuhai Formation samples from the 2 705–3 085 m section, dominated by sporopolypyrrium assemblage with 86.9%–99.2% in proportion (average 94.6%). Algae assemblage, on the other hand is in a limited proportion, with marine dinoflagellates (mainly *Operculodinium centrocarpum*) continuously appearing in 0–8.5% (average 3.1%) and algae indicating fluvial and lacustrine facies (mainly *Granodiscus*) in 0–8.3% (average 2.4%).

4.2 Southeastern Sag: Well Z3

In this study, Well Z3 is the only borehole studied for palyn-

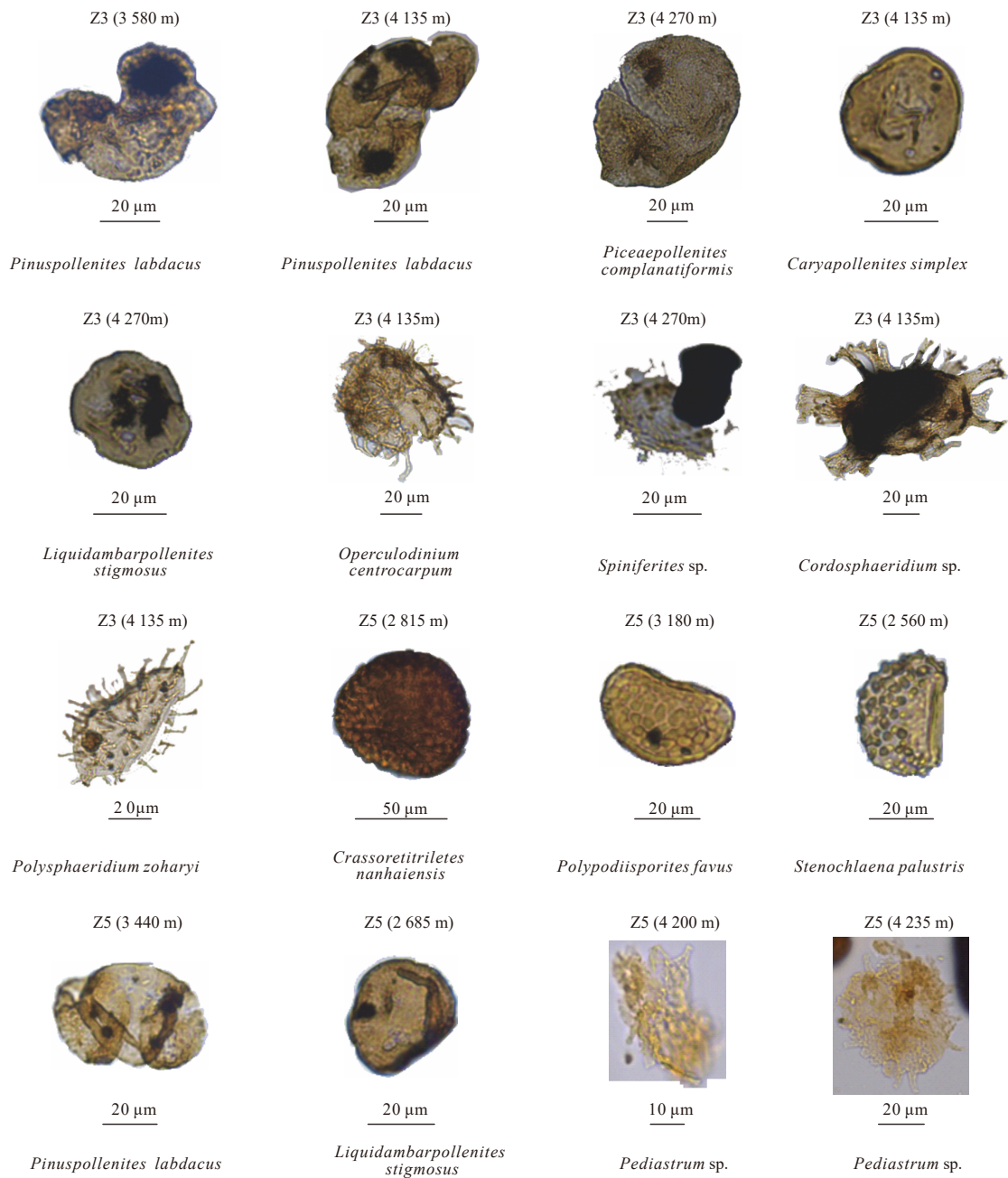


Fig. 3. Representative palynalgal fossils of Lower Cenozoic samples, the Baiyun Depression.

algal paleoecological analysis in the southeastern Baiyun Depression, and a total of 16 cutting rock samples were collected from its 3 850–4 275 m interval. Changes in assemblage patterns and contents of palypollen, fluvial and lacustrine plankton and marine dinoflagellates are shown in Fig. 4.

There is one Wenchang Formation sample from the 4 270–4 275 m interval of Well Z3, which is dominated by palynophyllous assemblages with a proportion of 82.3%. Algae indicating fluvial and lacustrine environments mainly consist of *Pediastrum* and make up 15.2% in proportion. Content of marine dinoflagellates is extremely low and account for only 2.5%. There are 8 Enping Formation samples from the 4 040–4 210 m section, which remain dominated by sporopollenium assemblage varying between 43.4% and 71.0% (average 58.7%). Marine dinoflagellates are mainly composed of *Spiniferites* spp. and *Operculodinium centrocarpum* and are in a modest proportion ranging from

27.1% to 56.6% (average 39.7%). Algae indicating fluvial and lacustrine facies (mainly *Polysphaeridium zoharyi*) are in rather limited contents with a range of 0–4.6% (average 1.5%). There are 7 Zhuhai Formation samples from the section of 3 850–4 005 m, which is predominated by sporophylline assemblage with a range of 76.8%–88.3% (average 81.7%). Compared with the underlying Enping Formation samples, content of marine dinoflagellates (mainly *Spiniferites* spp and *Operculodinium centrocarpum*) decreases significantly and accounts for 7.5%–22.5% (mean 14.7%) in proportion. Similarly, algae for fluvial and lacustrine facies (mainly *Pediastrum* and *Granodiscus*) remain in rather low concentration ranging from 0.7% to 7.7% (average 3.6%).

4.3 Southern uplift in the Baiyun Depression: Well Z5 and Well ZA

Fifty-eight and 51 cuttings samples were collected from the

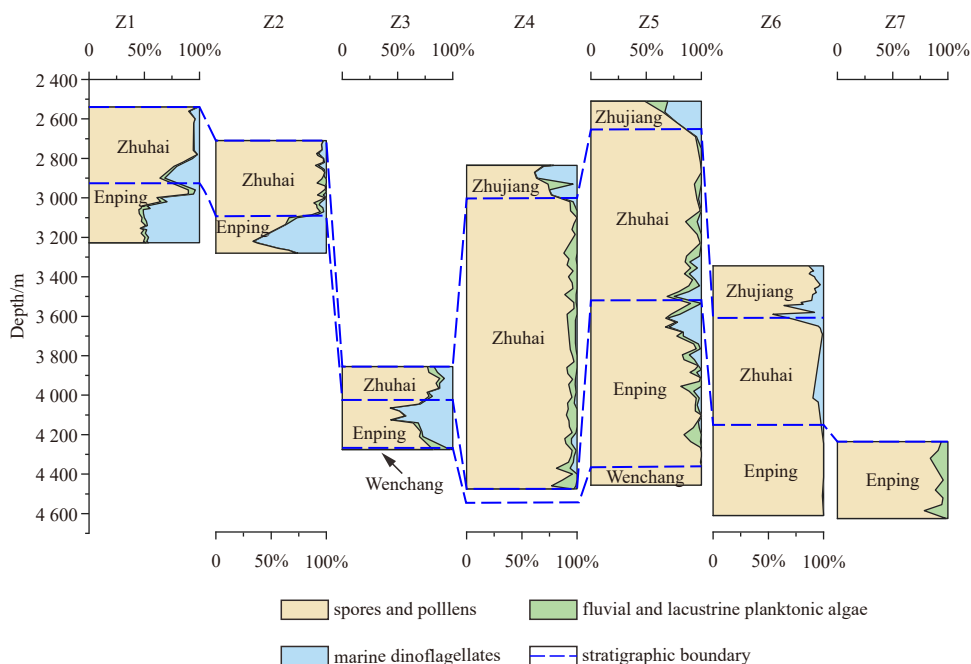


Fig. 4. Assemblages and contents of palynalgal fossils of Eocene-Lower Miocene drilling samples in the Baiyun Depression.

section of 2 510–4 456 m in Well Z5 and section of 2 805–4 475 m in Well Z4, separately. Changes in assemblage patterns and contents of palypollen, fluvial and lacustrine plankton and marine dinoflagellates are shown in Fig. 4.

There are 5 Wenchang Formation samples selected from the section of 4 37–4 456 m in Well Z5, which are exclusively palynological fossils without any algae records. Thirty-two Enping Formation samples were extracted from the interval of 3 535–4 355 m, showing a predominance of sporopolypyrrium assemblage with 67.8%–100% in proportion (average 90.2%). Algae for fluvial and lacustrine facies (mainly *Pediastrum* sp.) are in low but continuous content ranging from 0 to 18.8% (average 4.1%). In particular, content of *Granodiscus* increased during the later depositional stage of the Enping Formation. Marine dinoflagellates are in low content within the lower Enping Formation, but increase sharply (mainly *Operculodinium centrocarpum* and *Spiniferites* sp.) in the section of 3 500–3 700 m by reaching 0–29.1% in proportion (average 5.7%). There are 18 Zhuhai Formation samples collected from the interval of 2 690–3 500 m which are dominated by sporopolysm assemblage ranging from 68.9% to 100% (average 90.9%). Algae indicating fluvial and lacustrine facies (mainly *Granodiscus* and *Pediastrum* sp.) are in fairly low proportion but continuous existence with a range of 0–11.7% (average 4.6%). Marine dinoflagellates continuously exist within the lower Zhuhai Formation and are notably dominated by *Operculodinium* spp. in the interval of 3 495–3 500 m. However, marine dinoflagellates are observed sporadically within the upper succession of the Zhuhai Formation and account for 0–24.5% in proportion (average 4.4%). There are three Zhujiang Formation samples collected from the section of 2 50–2 620 m, which are mainly comprised of sporopolypyrrium assemblage varying from 48.8% to 77.9% (average 64.0%). Content of marine dinoflagellates (mainly *Operculodinium centrocarpum* and *Spiniferites* spp.) is significantly high in proportion with a range of 22.1%–33.2% (average 28.5%). Algae for fluvial and lacustrine facies (mostly *Pediastrum* sp.) are in the lowest proportion ranging from 0 to 20.8% (average 7.5%).

Well Z4 generates similar spore-algal assemblage pattern to Well Z5. There are 44 Zhuhai Formation samples extracted from the section of 3 015–4 475 m, which are dominated by sporopolypyrrium assemblage with a range of 77% to 100% in proportion (average 92.9%). Algae indicating fluvial and lacustrine facies (mainly *Pediastrum*) are in relatively low content but of continuous existence, with a variation from 0 to 12.4% (average 6.0%). Marine dinoflagellates appear sporadically within the lower Zhuhai Formation while are extremely difficult to detect in the upper Zhuhai Formation samples, which altogether range from 0 to 6.2% (average 1.1%). There are 7 Zhujiang Formation samples obtained from the section of 2 805–2 985 m, which are dominated by sporopolypalynous assemblage with a content of 61.4%–76.7% (average 70.7%). Compared to the underlying Zhuhai Formation samples, marine dinoflagellates increase sharply reaching 3.6%–38.1% (average 25.3%) and are mainly composed of *Operculodinium centrocarpum* and *Spiniferites* spp. Algae indicating fluvial and lacustrine facies are in the lowermost proportion with a range of 0 to 22.6% (average 4.0%), and are only recognized in a large number (mostly *Pediastrum*) in the section of 2 925–2 930 m

4.4 The northwestern part of the depression: Z6 Well, Z7 Well

Thirty-three and 10 cuttings samples were collected from the section of 3 345–4 610 m in Well Z6 and section of 4 230–4 625 m in Well Z7, separately. Changes in assemblage patterns and contents of palypollen, fluvial and lacustrine plankton and marine dinoflagellates are shown in Fig. 4.

There are 5 Enping Formation samples obtained from the section of 4 245–4 610 m within Well Z6, which are predominated by the sporophyllum assemblage with a content of 99% to 100% (average 99.8%). Algae indicating fluvial and lacustrine facies were not counted for this interval in this study. No marine dinoflagellates have been observed. There are 8 Zhuhai Formation samples extracted from the interval of 3 615–4 035 m, which are mostly composed of sporopolypyrrium assemblage ranging from 92.5% to 99.0% (average 93.2%). Algae indicating fluvial and la-

custrine facies were not counted for this interval in this study. A large number of marine dinoflagellates (27.5%) were found only at the uppermost 3 615 m while the rest of the Zhuhai Formation are rarely identified with marine dinoflagellates. There are 20 Zhujiang Formation samples obtained from the section of 3 345–3 590 m which are dominated by sporopolypyrrium assemblage with a range of 54.2%–97.1% (average 86.8%). Algae for fluvial and lacustrine environments were not counted for this section. Marine dinoflagellates are in continuous existence varying between 2.9% and 45.8% (average 13.2%).

There are 10 Enping Formation samples extracted from the section of 4 245 m to 4 610 m of Well Z7, which are predominated by palynium assemblage with the content of 78.6% to 98.5% (average 91.2%). Content for algae indicating fluvial and lacustrine facies (mostly *Pediastrum*) is low but of continuous existence, accounting for 0–12.4% (average 6.0%). No marine dinoflagellates are observed in this section.

5 Sedimentary environment

The deep-water area of the northern SCS experienced complex tectonic evolution and corresponding transgression-regression processes during the Paleogene, which significantly affected sedimentary environment of the Baiyun Depression. Environmental shift from terrestrial to ocean took place within individual regions of the Baiyun Depression. Based on palaeoecological evidence of palynophyte assemblages, it is promising to reconstruct sedimentary environment of different regions in deep-water areas from the Eocene to early Miocene.

5.1 Wenchang Formation (Lower and Middle Eocene)

Wenchang Formation is the lowermost sedimentary succession in the Baiyun Depression during the early and middle Eocene. Due to deep burial and difficulty in sampling, the Baiyun Depression is only obtained with Well Z3 and Well Z5 with high contents of palynopore fossils drilled in southeastern zone and southern uplift belt, separately. Well Z3 contains low but continuously existing algae for fluvial and lacustrine facies, mainly freshwater *Pediastrum*, and is rarely observed with marine dinoflagellates (Fig. 4). This palynalgal assemblage pattern implies a dominance of freshwater lacustrine environment during this time. Well Z5, on the other hand, does not contain algae fossils, thereby indicating a fan delta environment (Fig. 4).

During the deposition of the Wenchang Formation, the northern SCS generated large-scale faults under the influence from the Zhuqiong Movement. The Baiyun Depression was characterized by multiple terrestrial faulted basins, depositional centers and extensive lacustrine sediments during the rift stage. In more detail, the main sag of the Baiyun Depression developed medium-deep lacustrine sediments, while its margin formed fan delta sediments. In general, the Baiyun Depression has experienced multi-stage evolution of initial basin formation, semi-deep lacustrine – deep lacustrine sedimentation with active fault and subsidence, and final stage of shallow lacustrine deposition (Zhu, 2010; Xiang et al., 2024). According to previous studies, the Wenchang Formation in the Baiyun Depression is generally enriched in freshwater algae assemblage dominated by discostrans and chlorella, and indicates a freshwater lacustrine environment (Shi et al., 2017). Therefore, the Baiyun Depression was mainly under terrestrial environment and was not affected by transgression when it was initially formed during the early and middle Eocene.

5.2 Enping Formation (Upper Eocene)

IODP367, 368 results indicate that the SCS was originated in

the late Eocene, and coastal-shallow marine facies were formed on the edge of SCS oceanic crust where sites U1501 and U1504 were located (Jian et al., 2019). At this time, the Baiyun Depression was experiencing fault-sag transition processes characterized by detachment fault structures. The northeastern sag of the Baiyun Depression is dominated by palypollen and marine dinoflagellate fossils with extremely low content of algae for fluvial and lacustrine facies (Fig. 4), which suggest a shallow marine continental shelf environment. At the same time, a large number of marine dinoflagellate fossils as a signal of transgression are also observed in the southeastern part of the Baiyun Depression (Fig. 4) and suggest that the sedimentary environment shifted from the previous terrestrial freshwater lacustrine to shallow marine facies during the late Eocene. The southern uplift zone of the Baiyun Depression was dominated by palynopore assemblage and rarely generated marine dinoflagellates during the early deposition of the Enping Formation. Algae indicating fluvial and lacustrine facies appear continuously, and gradually transition from freshwater dinoflagellates to freshwater-brackish water granular chlorella. However, a large group of marine dinoflagellates are found to exist continuously within the upper Enping Formation and suggest a strong impact of the transgression process. Correspondingly, the overall sedimentary environment of the Baiyun Depression shifted from freshwater lacustrine to marine transitional facies. The western Baiyun Depression are dominated by palynopore assemblage with a relatively low content of algae for fluvial and lacustrine facies and the non-existence of marine dinoflagellates under a sedimentary environment with braided river delta (Fig. 4). It is apparently shown that the Baiyun Depression experienced significant sedimentary environmental changes during the late Eocene. On the one hand, eastern and southern sags were initially deposited with marine sediments under a shallow marine continental shelf environment during this time. The northwestern region was not affected by transgression and remained dominated by terrestrial deposition.

It was during the late Eocene that the SCS initially formed, and the Baiyun Depression was transitioned from rift to fault under the overall tectonic background of continental break-up and detachment. The entire depression was experiencing continual subsidence, resulting in a large scale of sedimentation and connection among separate sub-sags. The Baiyun Depression exhibited a topographic pattern with higher elevation in the northwest and lower in the southeast. In more detail, its eastern and southeastern parts were influenced from transgression by generating coastal and shallow marine sediments, while the western region received abundant terrigenous clastic materials transported by eastward flowing Kontum-Ying-Qiong River and developed extensive braided river deltas and delta plains (Shao et al., 2019; Cui et al., 2019).

It is more likely that the eastern or southeastern Baiyun Depression originally developed marine sediments during the late Eocene in contrast to the terrestrial environment dominating the northwest. In another word, our study suggests initial transgression largely taking place from the eastern or southeastern depression (instead of the southern area) and exhibiting a westward progression of seawater invasion. In addition, geophysical data compilation also consistently suggests that the Dongsha Uplift was formed during the late Miocene due to drastic the Dongsha Movement (Zhao et al., 2012).

5.3 Zhuhai Formation (Oligocene)

The Zhuhai Formation is uniquely characterized by widespread generation of marine dinoflagellates, but their distribution and contents vary greatly among different regions. The east-

ern and southeastern regions of the Baiyun Depression are dominated by palynopore assemblage with extremely low contents of algae for fluvial and lacustrine facies and significant decrease of marine dinoflagellates (Fig. 4). Marine dinoflagellates are of highest content at the continental shelf with a depth of 50–200 m, and show decreasing trends towards both land and sea regions (Mamet and Copeland, 1982). Given that the eastern and southeastern Baiyun Depression had already been influenced by a shallow marine environment during the late Eocene, these areas might have deepened into a continental slope setting. Located at the southern region of the Baiyun Depression, Wells Z5 and Z4 share similar spore-algal assemblage patterns to that of the underlying Enping Formation. In more detail, there is an abundance of palynopore assemblage, continuous existence of algae for fluvial and lacustrine facies as well as an increase of marine dinoflagellates. This pattern is largely linked to frequent seawater ingress and limited terrigenous input from fluvial system under a transgression-impact delta environment with transitional marine-terrestrial facies. The southern region of the Baiyun Depression is observed with continuous appearance of algae for fluvial and lacustrine facies and sporadic distribution of low-content marine dinoflagellates within Upper Oligocene sediments. It is speculated that this area was dominated by a terrestrial setting and less influenced from transgression. The western sag of the Baiyun Depression is mainly composed of palynopore assemblage with minor marine dinoflagellates during the Oligocene. Given the extensive development of large river systems (Xiang et al., 2024), this area was probably dominated by transitional marine-terrestrial facies.

The Baiyun Depression shifted from a fault-sag to a sag basin during Oligocene due to the widespread impact of SCS initiation. The entire basin was experiencing large-scale subsidence and strong transgression processes. Both ancient Kontum-Ying-Qiong River from the west and Paleo-Pearl River from the north provided the Baiyun Depression with large abundance of terrestrial materials (Shao et al., 2019; Cui et al., 2021; Xiang et al., 2024). Correspondingly, the overall environment was mainly transitional marine-terrestrial, coastal and shallow marine facies with relatively shallow water depths.

5.4 Zhujiang Formation (Lower Miocene)

There is a significant increase of marine dinoflagellates in both the northwestern sag and southern uplift zone of the Baiyun Depression during early Miocene (Fig. 4), indicating a shallow marine environment on a continental slope with deepening water depths than previous scenarios. Marine micropaleontological fossil records are widely identified in the eastern and southeastern Baiyun Depression. The existence of nummulitic limestones largely indicates a semi-abyssal environment (Wu et al., 2013). It is thereby suggested that the overall depression was dominated by a semi-abyssal setting on a continental slope with deepening water depths while only limited regions, including western sag and southern uplift belt, were deposited with shallow marine sediments.

6 Transgression process and sedimentary environment evolution in the northern SCS

Re-cycled and re-deposited marine fossils of Eocene ages were first revealed in the Oligocene sediments from Site ODP 1148 situated in the northern SCS, and indicated the earliest formation of SCS (Wang et al., 2003). Sites U1501 and U1504 of IODP 367–368 are located at the continental-oceanic boundary identified with coastal and shallow marine sediments of Upper

Eocene depositional ages, while Site U1502 drilled farther to the south is featured by deep marine deposits. Jian et al. (2019) thereby indicated a trend of shallowing in water depth from south to north. Combined with the latest updates from scientific ocean drillings, this study aims to provide a refined reconstruction of transgression-regression processes and sedimentary environment of the deep-water area of northern SCS during the early Cenozoic (Fig. 5).

During the early-middle Eocene when the Wenchang Formation was formed, the overall Baiyun Depression was dominated by fluvial and lacustrine environment before impacted from transgression (Fig. 5a). During the late Eocene when the Enping Formation was deposited, eastern and southeastern regions initially transitioned into shallow marine environment on a continental shelf influenced by the early transgression process. The southern uplift zone remained dominated by freshwater lacustrine facies during early depositional stage of the Enping Formation, but subsequently shifted into a transitional terrestrial-marine environment due to transgression. The western sag of the Baiyun Depression has been continuously influenced by a delta environment with braided rivers and were unimpacted from transgression (Fig. 5b). The eastern and southeastern regions were deposited with shallow marine sediments in a continental shelf setting during early stage of the Zhuhai Formation, followed by deep marine sedimentation in a continental slope environment in later interval. Western sag and southern uplift zones were dominated by a transitional terrestrial-marine environment with frequent transgression processes. In particular, western sag generated successions of braided river and delta sedimentation under the transitional environment (Fig. 5c). During the early Miocene when the Zhujiang Formation was formed, the entire Baiyun Depression evolved into a marine environment, where most areas were dominated by deep-marine setting on a continental slope and western sag and southern uplift zone were shallow marine environment due to progressive extension of SCS oceanic crust and eustatic level rise (Fig. 5d).

It was previously suggested that transgression took place in a direct northward direction within the Baiyun Depression during the Paleogene (Liu et al., 2007; Li, 2013). Our study has revealed that transgression first occurred in eastern and southeastern Baiyun Depression. The southern area was not impacted by transgression evolving into a transitional environment until the late Eocene, before shifting into a shallow marine environment during the early Miocene. Therefore, it is reasonable to restore a westward transgression process in deep-water basin, which also shows a great consistence with the gradual expansion pattern of the SCS.

7 Conclusions

In this study, palynalgal analyses are conducted on seven boreholes in an effort to provide a better understanding of the sedimentary environment evolution and transgression processes of the Baiyun Depression in the northern SCS deep-water area. Our study also makes a significant contribution to the application of plant ecology to sedimentary environmental reconstruction. Several key conclusions are obtained in this research:

(1) Prior to the initial formation of the SCS, the northern SCS area was dominated by lacustrine deposits yielding a dominant content of palynopore assemblage and large abundance of algae indicating fluvial and lacustrine facies during the early and middle Eocene. With the initiation of SCS in the late Eocene, eastern and southeastern the Baiyun Depression transitioned into a shallow marine environment on a continental shelf with

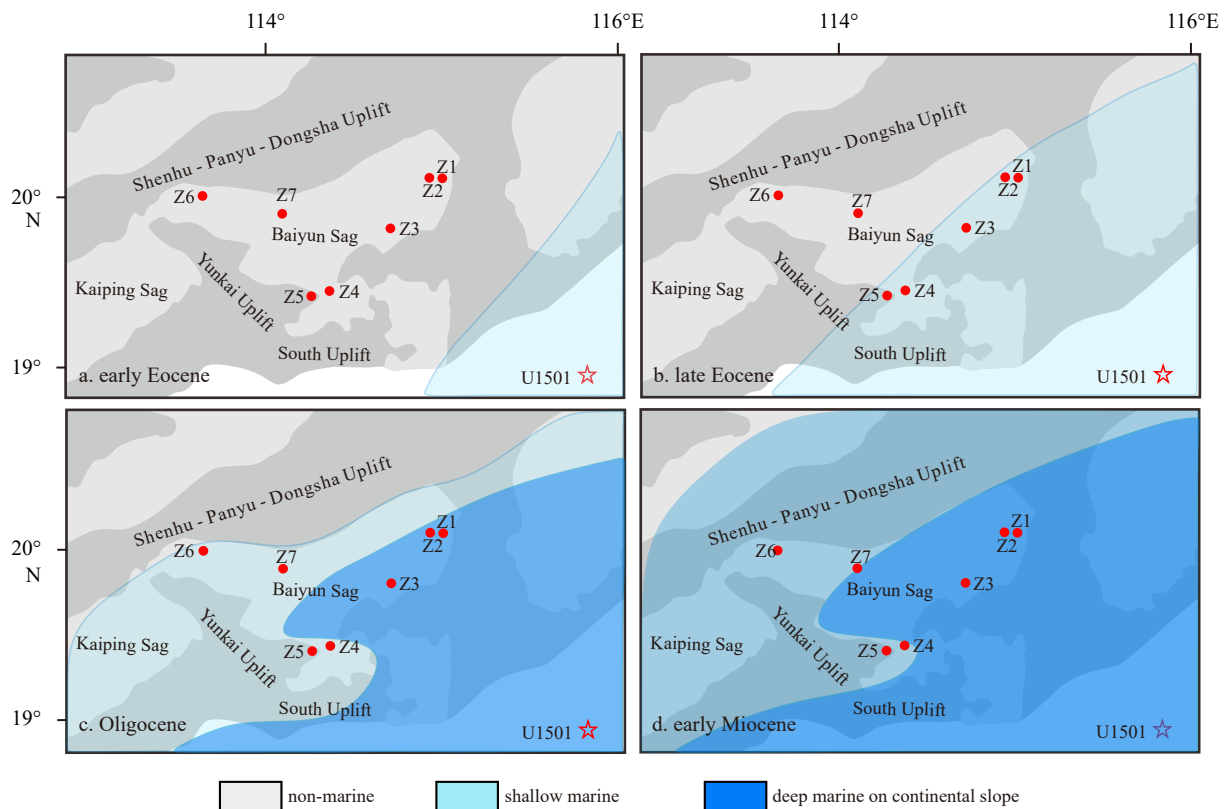


Fig. 5. Transgression process of the Baiyun Depression in Paleogene. a. Wenchang Formation, b. Enping Formation, c. Zhuhai Formation (high water stage shown in the figure), d. Zhujiang Formation

plentiful marine dinoflagellates. The southern uplift zone simply generated palynopores and algae for fluvial and lacustrine facies during early stage of the late Eocene, which indicate a freshwater lacustrine environment. It changed into a transitional setting during a later stage by forming both algae for fluvial and lacustrine facies and marine dinoflagellates. However, the western and northwestern areas remained lack of marine dinoflagellates implying a dominance of the terrestrial environment. During the Oligocene when the SCS progressively enlarged to the west, eastern and southeastern Baiyun Depression were largely deepened and shifted into a deep marine environment on a continental slope, while the northwestern sag and southern uplift zone were commonly dominated by transitional facies. The southwestern sub-basin was open during the early Miocene due to the sudden shifting of the SCS spreading axis. The Baiyun Depression experienced further subsidence, where most of the area was under a deep marine environment on a continental slope with limited shallow marine facies observed at the continental shelf in the northwestern sag and southern uplift zone.

(2) Transgression process of the Baiyun Depression shows a westward progression, which is in great consistence with the opening and expansion of the SCS. Compared to eastern and southeastern sags, the southern uplift zone of the Baiyun Depression initially subsided and generated marine successions during the late stage of the late Eocene. In addition, the Dongsha Uplift located at the eastern Baiyun Depression largely formed after the Miocene.

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