Quaternary Sedimentary and Palaeoenvironmental Evolution of the Southern Yangtze River Delta in China since the Pleistocene

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Abstract: In order to study the stratigraphic division of the southern wing of the Yangtze River Delta in Quaternary and its coupling relationship with the palaeoenvironmental evolution, the Quaternary borehole BK01 (237.80m in depth; rate of core recovery > 96%) located in the southern wing of the Yangtze River Delta was taken as the research sample; sediment sporopollen analysis, micropalaeontology identification, granularity content analysis and isotopic dating were carried out. Combining with lithologic strata information revealed by the borehole, this paper discussed the palynological assemblages, the palaeoenvironmental evolution, the sedimentary sequence and palaeoclimate characteristics since the Pliocene epoch. The results showed that the study area has undergone many environmental changes since Pleistocene. There were 17 species of foraminifera belonging to 11 genera found in this area, including 16 benthic foraminifera and 1 plank tonic foraminifera. There were 8 species of Ostracod belonging to 8 genera. Pollen analysis showed that there were 37 species, including 18 species of arboreal pollen, 11 species of herbaceous plant pollen, and 8 species of fern spore. In the sporopollen assemblage, woody plant content was the highest, accounting for 85. 1%; fern spores accounted for about 8.7%; herbaceous pollen accounted for only 6.3%. According to borehole lithology, grain size, sporopollen assemblage and micropalaeontology analysis, the sedimentary environment records can be divided into 18 sporopollen assemblage zones and seven palaeoclimate cycles.

1. Introduction

Due to the interaction of the Yangtze Estuary and the Hangzhou Bay, sea level changes in Quaternary recorded abundant information of sedimentary environment evolution in the southern wing of the Yangtze River Delta. [1-4] Climate and sea-level changes in the Yangtze River Delta since the last glacial period have attracted much attention from scholars. Some hot issues include the number and extent of transgression of sea, as well as sea-level changes since the last glacial period. [5-7] Methods such as granularity, palaeomagnetism, sporopollen and microorganism analysis have been widely used in palaeoenvironment studies. [8-9] Previous researchers have done a lot of work and achieved many important results in the study of the Yangtze River Delta Plain, which laid a foundation for further study of sedimentary characteristics, sequence stratigraphic analysis and palaeoenvironmental evolution since the Quaternary, especially since the Holocene, [10-13] and also provides a more detailed basis for the Quaternary evolution of the Yangtze River Delta. However, due to the limitations of drilling depth, sampling technology as well as testing and analysis skills, previous studies on the Holocene palaeoenvironment are relatively in-depth, but related studies of the Pleistocene, especially on the basement rocks are relatively weak. [14-15]

The borehole BK01 locates in the southern wing of the Yangtze River Delta. It records a complete and continuous Quaternary stratigraphic and sedimentary sequence since the Pleistocene, and can well represent the Quaternary transgression of sea as well as palaeoclimate changes in the

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plain area of the Yangtze River Delta. Based on the systematic analysis of foraminifera and Ostracod fossils as well as sporopollen assemblages with high resolution in the sediments of borehole BK01, combined with grain size, dating and magnetic data, the sedimentary facies can be divided and the chronological framework can be established. The evolution characteristics of palaeovegetation, palaeoclimate and sedimentary environment in the plain area of the Yangtze River Delta were studied in this paper, which could provide basic information for the Quaternary stratigraphic division and comparison of the southern wing of Yangtze River Delta since the Pleistocene.

2. Sample Collection and Research Methods

Borehole BK01 (30º44'45"N, 120º53'59"E) is located in Nanhu District, Jiaxing City (as show in Figure 1). The depth is 237.80 m, of which bedrock is below 236.50 m. The drilling cores were cut longitudinally from the center, trimmed and lithologically described. 104 sediment microfossils (foraminifera and Ostracod) and 104 sporopollen analysis samples, 184 grain size analysis samples, 175 palaeomagnetic samples and 11 isotope dating samples were collected. The sampling interval was generally 1 m.

Figure 1. Location of BK01 borehole

(Data of boreholes XZK169,YG 01 and SG7 comes from references 16 and 17)

Micropalaeontological analysis included species identification and quantitative statistics of foraminifera and Ostracod. Each pollen sample weighs 50g. After acid-alkali treatment and gravity flotation, the flotation material containing sporopollen was extracted and made into slices. The percentage content was identified, counted and calculated under a microscope. Specific test methods could refer to references.[18-20] Grain sizes in sediment of 184 samples were analyzed, and measured by Mastersizer 2000 laser particle size analyzer. Test methods in reference 21 were used. Palaeomagnetism was measured by 2G-760 U-Channel rock superconducting magnetometer. Test methods in reference 22 were used. Eight samples of sediment containing carbon debris were selected and packed in sealed package. The optical stimulated luminescence dating (OSL) of eight samples was commissioned by Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The OSL/OSL-DA-20 thermoluminescence/photoluminescence instrument produced by Risø laboratory in Denmark was used to complete the OSL dating. Micropalaeontology analysis, sporopollen analysis, particle size analysis and the palaeomagnetism analysis were entrusted to the Department of Earth Sciences, Sun Yat-sen University.

3. Research Results

3.1 Chronological sequence

Isotope ages measured by ^{14}C and OSL methods are shown in Figure 2. The ages measured at the depths of 14.2m, 19.0m and 20.0m are 33904-34558ka, 35229-36163ka and 38888-39929ka respectively. The ages of OSL at depths of 24.0m, 29.0m and 59.0m are 60.5 ± 3.3ka, 74.8 ± 3.8ka and 120.6 ± 8.9ka respectively. The stratigraphic ages of all samples belong to Late Pleistocene. The OSL age at depths of 90.2m is 142.7 ± 9.6ka, which belongs to the Middle Pleistocene. The OSL ages at 108.5m, 129.0m and 138.2m are all over 150 ka.

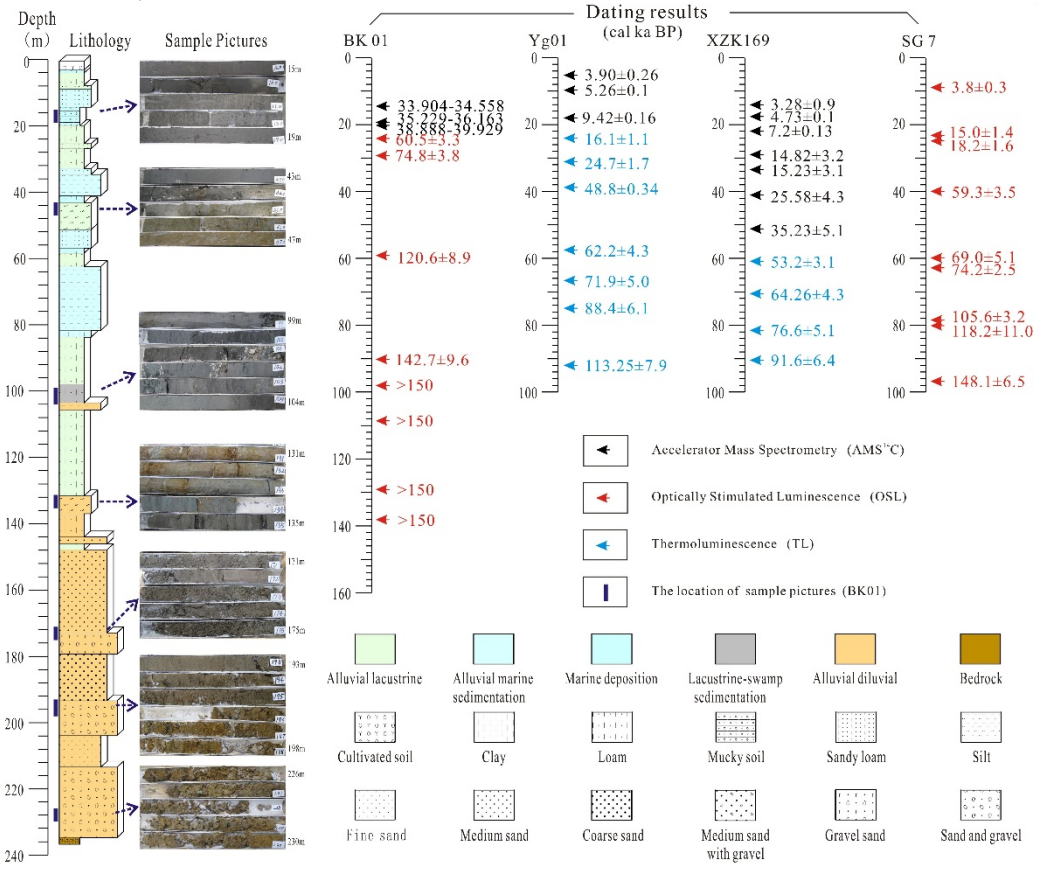

Figure 2. Lithological stratification characteristics and dating results of borehole BK01

3.2 Sporopollen

A total of 37 sporopollen types are identified in 104 sporopollen samples from borehole BK01, including 18 arboreal pollens, 11 herbaceous plant pollens and 8 fern spores. Among the sporopollen assemblages, woody plants habe the highest content, about 85.1%; ferns spores account for about 8.7%; pollen of herbaceous plants accounts for only 6.3%. According to the change of sporopollen types and the characteristics of assemblage, 18 sporopollen assemblage zones can be divided (Figure 3).

P1 (235-212 m): The average sporopollen concentration is 104 grains per gram; the pollen of ferns is the absolute dominant, with average of 85.5%. Polypodiaceae, trilete spore and Pterisisporites are the most abundant. P2 (212-166.5m): The average sporopollen concentration is 9.3 grains per gram. P3 (164.8-160m): The average sporopollen concentration is 58 grains per gram. The arboreal pollen is the absolute dominance, with average content of 79.5%. The pollen of coniferous plants such as Pinus and Quercus are dominant. P4 (157-137m): The total sporopollen concentration is zero. P5 (135-131m): The average sporopollen concentration is 69 grains per gram, all of which are fern spores. P6 (129-105m): the total sporopollen concentration is zero. P7 (103-99m): The total sporopollen concentration is high, with average concentration of 16,445 grains per gram. The arboreal pollen is the absolute predominance, with average content of 92.9%. Pinus

and other coniferous plants are the main pollens. P8 (97-93m): The average sporopollen concentration is 102 grains per gram. The dominant pollen content of woody plants is 65.5%. P9 (91-80m): The total sporopollen concentration is high, with the average concentration of 2776 grains per gram. The pollen content of woody plants is absolutely dominant, with average content of 85.8%. P10 (78-75m): The average sporopollen concentration is 169 grains per gram, and the arboreal pollen is the absolute dominant, with the average content of 87.6%. P11 (73-69m): The total sporopollen concentration is high, with the average concentration of 1039 grains per gram. The pollen content of woody plants is absolutely dominant, with average content of 94.9%. P12 (66-62m): The average sporopollen concentration is 297 grains per gram, and the pollen content of woody plants is the absolute dominant, with average content of 74.6%. P13 (60-58m): The total sporopollen concentration is high, with the average concentration of 2847 grains per gram. The arboreal pollen content is absolutely dominant, with average content of 79.1%. P14 (57-42m): The sporopollen concentration is low. P15 (38.4-35m): The average sporopollen concentration is 190 grains per gram, and the arboreal pollen is the absolute dominant, with average content of 73.7%, of which Pinus is the most abundant. P16 (32-21m): The average sporopollen concentration is 37 grains per gram, and fern spores are the absolute dominant, with average content of 91%. P17 (20-14m): The total sporopollen concentration is high, with the average concentration of 3247 grains per gram. The arboreal pollen content is absolutely dominant, with average content of 74.2%. P18 (12.6-3.5m): The average sporopollen concentration is 109 grains per gram, and fern spore content is the absolute dominant, with the average content of 68.1%.

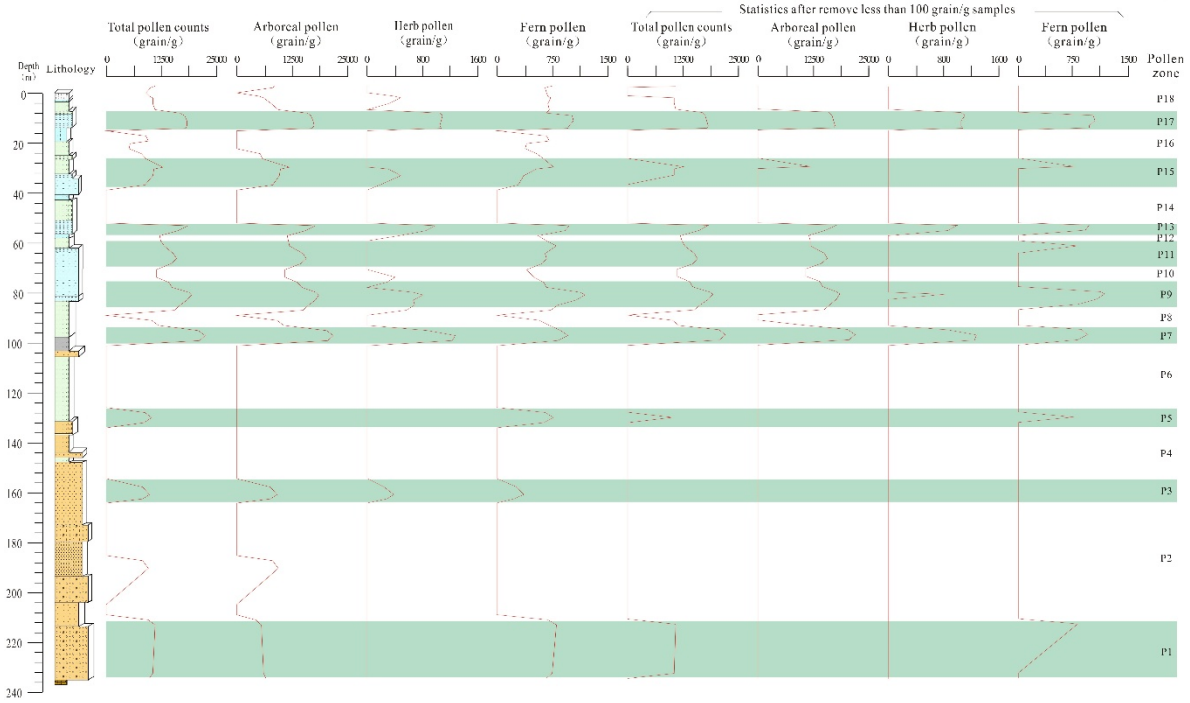

Figure 3. Pollen assemblage zones of borehole BK01

3.3 Foraminifera and Ostracod

A total of 104 foraminifera and Ostracod samples are found in pore BK01. Among them, 17 species in 11 genera of foraminifera are identified, including 16 benthic foraminifera and 1 plank tonic foraminifera, with 0 to 497489 foraminiferal shells per 100g sediment. 8 species of 8 genera of Ostracod were found, with 0-125569 Ostracod shells per 100g sediment. The total abundance, diversity and generic depth distribution of foraminifera and Ostracod are shown in Figure 4; photographs of foraminifera and Ostracod are shown in Figure 5.

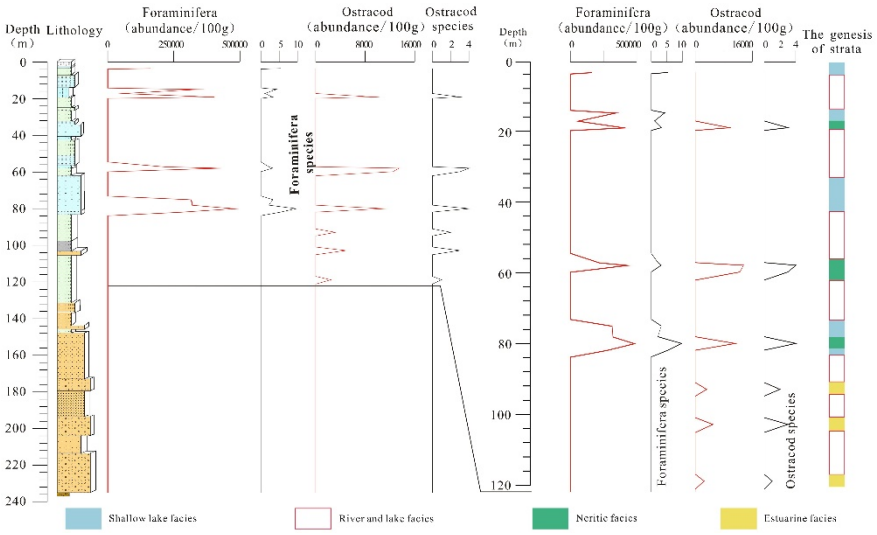

Figure 4. Abundance and differentiation distribution of foraminifera and Ostracod in BK01 and stratigraphic genesis speculation

Figure 5. Foraminifera (1-6) and Ostracod (7-12) found in BK01 borehole

1-2, Ammonia beccarii, 78cm. 3-4, Florilus decorus, 106cm. 5-6, Cribrononion subincertum, 78cm. 7-8, Neomonoceratina dongtaiensis, 31cm. 9-10, Sinocytheridea impressa, 106cm. 11-12, Pistocythereis bradyformis, 41cm.

3.4 Granularity

The grain size curve of BK01 pore (Figure 6) shows that the grain size characteristics of 0-85m sediments are complex, including sTable fluvial-lacustrine deposits and coarse fluvial deposits. The frequent changes of sedimentary environment show the influence of the interaction among marine deposits, alluvial-marine deposits and lacustrine deposits. Sediments at 85-150 m are mainly in the form of coarse-grained rivers. The shape of grain-size curve is relatively single; the sedimentary environment is relatively sTable. The 150-236m sediments are mainly composed of fine-grained sediments. It is inferred that most of the sediments are alluvial-proluvial and the coarse-grained sediments formed in the river environment.

4. Discussion

Previous studies have shown that the sedimentary facies of different horizons can be distinguished by the information provided by grain size, micropalaeontology and other indicators. [23] Palaeoclimate characteristics of different periods and palaeoclimate changes can be studied by analyzing information about sporopollen and foraminifera. [24] The strata revealed by the hole BK01 are depositional records with a depth of 236.5m. Based on the stratigraphic characteristics of lithology, sedimentary facies, sporopollen, foraminifera and ostracods, as well as the frequency curve of grain size distribution, the sedimentary environment of the borehole is

comprehensively analyzed, and the model of multi-stratigraphic division of hole BK01 is established (Figure 6).

4.1 Early Pleistocene (147.0-236.5m)

The hole reveals that the early Pleistocene strata corresponded to sporopollen P1- P3 and the early stage of P4 zones, and the lower segment is al(pl)N-Qp_1j^2. According to the lithological characteristics and grain size analysis curve, the sedimentary environment is inferred as fluvial facies with a thickness of 31.1m. The total sporopollen concentration is slightly lower at 104 grains/g; the average fern spore content is 85.5%. According to sporopollen assemblage, the vegetation type should be temperate monsoon climate. The climate is warm, cool and slightly wet, so we infer that it corresponds to The Third Warm Period. The upper section is al(pl)N-Qp_1j^3. The lithological characteristics of the sediments are medium sand, medium-coarse sand and gravel. The sedimentary environment is inferred to be fluvial facies with a thickness of 57.1m. The total sporopollen concentration is low and dominated by arboreal pollen. According to sporopollen assemblage, the vegetation type should be temperate continental climate. The climate is warm, cool and slightly humid, and can be inferred as The Fourth Warm Period. 147.0-148.3m is al-lN-Qp_1j^3, the sediment is hard plastic sub-clay layer with high iron and manganese oxides. It is inferred that the sedimentary environment is river-lake facies. The total concentration of sporopollen is zero; foraminifera and ostracods are not found. According to sporopollen assemblage, the vegetation type revealed should be cold and dry climate, and it can be inferred as The Fourth Cold Period in short term. According to the periodic law of alternation of warm and cold periods, it is revealed that BK01 hole underwent two climatic cycles in the early Pleistocene.

4.2 Middle Pleistocene (84.0-147.0m)

The boreholes reveal that the Middle Pleistocene strata correspond to the late stage of the sporopollen P4 zone and the P5-P9 zone. The sediments are mostly sub-clay and sub-clay with sandy soil. It is revealed that the Middle Pleistocene underwent two palaeoclimatic cycles. The lower part is mainly composed of alQp_2q^1, lhQp_2q^1 and al-lQp_2q^1 strata. It is presumed that the sedimentary environment is fluvial facies, shallow lake facies and river-lake facies. The alluvial genetic strata are 9.7m thick. The total sporopollen concentration is low, with the average concentration of 69 grains/g. All of them are fern spores. The vegetation type reflected by sporopollen assemblage should be temperate monsoon climate. It is inferred that the period corresponds to The Fifth Warm Period of palaeoclimatic stage. The stratum thickness of fluvial alluvial and alluvial lakes is 31.0m. The vegetation type reflected by sporopollen assemblage represents cold and dry climate. It is inferred that it corresponds to The Fifth Cold Period.

The upper part is mainly composed of lhQp_2q^2 and al-lQp_2q^2 strata. It is presumed that the sedimentary environment is lacustrine and fluvial facies deposits, corresponding to the sporopollen P7-P9 zone. The OSL age measured at 90.2m hole depth is 142.7 ± 9.6ka; the stratum age belongs to the Middle Pleistocene. Among them, the stratum of lacustrine-marsh deposit is 5.7m thick. The total sporopollen concentration is high; the average concentration is 16445 grains/g and dominated by arboreal pollen with the average content of 92.9%. According to sporopollen assemblage, the vegetation type should be subtropical coniferous forest. The climate is warm and dry; it can be inferred as The Sixth Warm Period. The alluvial-lake stratum is 16.6m thick. The total sporopollen concentration is low; the average is 102 grains/gram. The average arboreal pollen is 65.5%. The sporopollen assemblage reveals that the vegetation type should be subtropical mixed forest, and the palaeoclimate is cold and humid. It is inferred that it corresponded to The Sixth Cold Period.

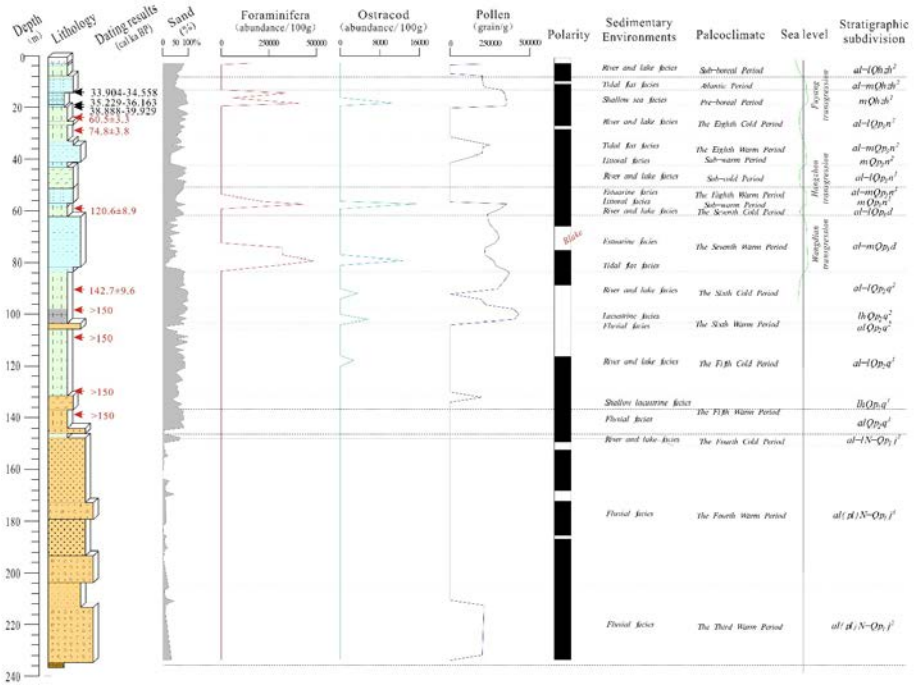

Figure 6. Multiple stratigraphic division and comparison of borehole BK01 on the North bank of Hangzhou Bay

4.3 Late Pleistocene (19.6-84.0m)

Multiple stratigraphic comparisons show that P10-P16 sporopollen zone of pore BK01 corresponds to the Late Pleistocene strata, reflecting that the Late Pleistocene underwent three climatic cycles. The OSL ages at 24.0m, 29.0m and 59.0m depth are 60.5 ± 3.3ka, 74.8 ± 3.8ka and 120.6 ± 8.9ka respectively. The stratigraphic age should be Late Pleistocene.

The Dongpu Formation corresponds to the Wangdian transgression period of sea level change, mostly consisting of silt layers with sub-sandy soil and sub-clay interbedding. The early stage is in estuarine sedimentary environment and al-mQp_3d stratum. The palaeoclimate stage corresponds to The Seventh Warm Period. The total sporopollen concentration is high at the depth of 58-60m, with average concentration of 2847 grains/g. The arboreal pollen content is the absolutely dominant. The vegetation type of this combination should be subtropical coniferous forest; the climate is warm and humid. Large numbers of foraminifer can be found in this period. There are 384-109354 foraminiferal shells in 100g sediments; Ammonia beccarII and Cribrononion subincertum are the most abundant. Ostracods are relatively abundant at the depth of 80m. There are 7483 Ostracod shells in 100g sediments; Sinocytheridea impressa and Neosinocythere elongata are the most abundant. Late Dongpu Formation consists of sub-clay and sub-sandy soil layers, revealing the sedimentary environment of river-lake facies and alluvial-lacustrine strata. Palaeoclimate stages correspond to The Seventh Cold Period. The total sporopollen concentration is low and ostracods are abundant. There are 125569 Ostracod shells per 100g of sediments. Sinocytheridea impressa, Neomonoceratina dongtaiensis, Loxoconcha ocellata, Sinocythere sinensis and Bicorncythere leizhouensis are the most abundant. Sedimentary environment and sporopollen assemblage reflect the cold and dry climate of this period.

The first section of Ningbo Formation corresponds to the early stage of Hangzhou transgression. It is mainly composed of al-mQp_3n^1 and al-lQp_3n^1 strata. The lithological features include sub-clay layer as well as sub-clay with sub-sandy soil layer. It is inferred that the sedimentary environment of estuarine and lacustrine facies corresponds to The Eighth Warm Period and a short sub-cold period. The second section of Ningbo Formation corresponds to the later stage of Hangzhou transgression. The main strata are mQp_3n^2,al-mQp_3n^2 and al-lQp_3n^2. The lithological features include sub-clay layer and partially sandy layer. The total sporopollen concentration is slightly higher; the average concentration is 190 grains/g. The arboreal pollen is the absolutely dominant,

with the average content of 73.7%. The sporopollen assemblage reveals that the vegetation type should be temperate coniferous forest, which is warm, cool and humid. There are few foraminifera and ostracods in that period. The sedimentary environment is inferred to be estuarine facies and lacustrine facies. The palaeoclimate period corresponds to the sub-warm period of the late Eighth Warm Period and the Eighth Cold Period.

4.4 Holocene (0-19.6m)

The Holocene experienced one climatic cycle. In the early Holocene, sea level rose and transgression intensified sharply. Corresponding to the change of sea level in the early stage of Fuyang transgression, the strata are al-mQhzh^{1} and mQhzh^{1}. The sedimentary environment is tidal flat facies, belonging to the early stage of post-glacial period; the palaeoclimate corresponded to The Atlantic Period. The lithology is mainly muddy sub-clay and sub-sandy soil. The total sporopollen concentration is high at 14.0-19.6m, with the average concentration of 3247 grains/g. The arboreal pollen is absolutely dominant, with the average content of 74.2%. The vegetation type of this combination should be subtropical mixed forest. The climate is warm and wet. The total sporopollen concentration of 12.6-3.5m is slightly lower, with the average concentration of 109 grains/g, and fern spores are the absolutely dominant. The average content is 68.1%. The vegetation type of this combination should be the humid temperate marine climate. Ostracod fossils are found at a depth of 19m. There are 1890 Ostracodl shells in 100 g of sediments, mainly include Sinocytheridea impressa, Loxoconcha ocellata and Bicorncythere leizhouensisa. Foraminifera are found at the depth of 15-19 m; 5 to 58321 foraminiferal shells could be found in 100 g sediments, mainly include Ammonia beccar II and Cribrononion subincertum.

The late Holocene corresponds to the late period of Fuyang transgression, which has the alluvial-lacustrine stratum of al-lQhzh^{2}. The sedimentary environment is fluvial-lacustrine facies belonging to the late glacial stage; the palaeoclimate should be the Sub-boreal Period. The lithological features include sub-clay layer and miscellaneous filling layer. The total sporopollen concentration is low. Only a few foraminifers can be found at about 3.5 m. 83 foraminiferal shells are found in 100 gram of sediment, dominated by Ammonia and Elphidium. The sporopollen assemblage reflects that the palaeoclimate of this period is cold and dry.

5. Conclusion

Based on sporopollen analysis, micropalaeontology identification, granularity content analysis and isotopic dating, the Quaternary stratigraphic division and the correlation framework of BK01 hole in the south wing of the Yangtze River Delta are established. From bottom to top, the boreholes can be divided into bedrock Changhe Formation of carbonaceous mudstone (Ech), Jiaxing Formation (N-Qp$_1$j), Qian'gang Formation (Qp$_2$q), Dongpu Formation (Qp$_3$d), Ningbo Formation (Qp$_3$n) and Zhenhai Formation (Qhzh) strata since early Pleistocene.

Sedimentary environment records can be divided into 18 sporopollen assemblage zones and seven palaeoclimatic cycles according to borehole lithology, grain size, sporopollen assemblage and the micropalaeontology analysis. Among them, the Holocene period is dominated by tidal flat facies and fluvial lake facies, corresponding to the Atlantic Period and the Sub-boreal Period. The Late Pleistocene period is dominated by estuarine facies, lake-river facies and littoral facies, corresponding to the palaeoclimate cycles of The Seventh Warm Period to The Eighth Cold Period. The Middle Pleistocene is dominated by river facies, lake facies and river-lake facies, revealing two palaeoclimate cycles from The Fifth Warm Period to the Sixth Cold Period; the Early Pleistocene has fluvial and lake facies deposits, revealing two palaeoclimate cycles from The Third Warm Period to The Fourth Cold Period.

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