Transgressive Events since the Late Pleistocene in the Yellow River Delta: Grain-size Distribution and Palynological Results

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Abstract: This study deals with the relationship between sea-level changes and paleoclimatic fluctuations based on the analysis of stratigraphy, grain sizes, palynology, and radiometric dating of the Yellow River delta since the Late Pleistocene. Evidence from the sedimentary record, grain sizes, and pollen provides a paleoenvironmental history of the Late Pleistocene from the boreholes of the delta. Based on a combination of grain-size analysis with lithological studies, marine deposit units contain the intervals of 13.85–16.9, 18.5–19.69, 27.9–34.8, 36.4–37.2, 48.4–51.6, and 54.1–55.9 m, and transitional facies units contain the intervals of 10.25–13.85, 16.9–18.5, 19.69–27.9, 34.8–36.4, 37.2–48.4, 51.6–54.1, and 55.9–60 m, compared with fluvial (terrestrial facies) deposit units (3.36–10.25 m). Based on pollen analysis and pollen assemblages, there were three warm-wet periods from 9.1–0.16 ka BP, 16.1–60 ka BP, and 90.1–94.6 ka BP. From the top to the bottom of the borehole, the paleoclimate has an evident fluctuation: warm and moist (Holocene Optimum) — cool and dry (Younger Dryas Event) — mild semi cool — cool and dry — warm and moist. There were three warm-wet periods from 9.1–0.16 ka BP, 16.1–60 ka BP, and 90.1–94.6 ka BP, respectively. The warm period allowed monsoonal evergreen and broadleaved deciduous forests that corresponded to the Holocene hypsithermal climatic conditions and the Late Pleistocene climatic Optimum. Three warm-wet periods occurred in marine deposit units from 9.1–0.16 ka BP, 60.1–16.1 ka BP, and 94.6–90.1 ka BP. These periods correspond to the Cangzhou transgression, Xianxian transgression, and Huanghua transgression, respectively. From 90.1–60.1 ka BP, 17.5–9.1 ka BP, and 0.16 ka BP–1855 AD, three dry and cold phases are recognized. The phases indicate the fluvial (flood plain) sedimentary environment, corresponding to cooler and mild dry periods based on palynological results and grain-size distribution.

Key words: transgression, grain-size, Pollen, Late Pleistocene, Yellow River Delta

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1 Introduction

The global climate has undergone tremendous changes during the Earth’s history. One of the most significant changes is global cooling and warming marked by the origin and expansion of sea-level (Zachos et al., 2001). Sea-level change and its effect on the climate and environment are important issues in Earth science.

The Yellow River is generally thought to have been formed at the end of the Late Pleistocene (Zhang, 1989; Xue, 1993; Wang et al., 1983). The Yellow River presently flows into the Bohai Sea, but during the period 1128–1855 AD, the river flowed into the western South Yellow Sea. It is the fifth largest river in the world in terms of length and sediment discharge and is one of the best examples showing sea-level change, transgression, and delta progradation (Milliman, 1983; Li et al., 2013; Gao et al., 2015; Gao et al., 2018). Event deposits are preserved widely in sedimentary successions on Shandong Peninsula and in the surrounding seabed. These sedimentary sequences provide important information about sea-level rise, transgression, and progradation (Rea et al., 1998; Cheng et al., 2010; Chen et al., 2016; Cheng et al., 2019). The Yellow River delta sedimentary deposits are regarded as sensitive parameters to Quaternary sea-level fluctuations.

Relative to other parts of the Shandong Peninsula, the margin of the Bohai Sea is an ideal place to study the relationship between climate and sea-level change (Xu et al., 1994). Many borehole cores have been investigated in...
the Bohai Sea and its coastal plain, some of which contain sedimentary records from the early Quaternary. The sedimentary sequences in many cores provide important records of sea-level changes and transgression. Studies of boreholes have found three transgressions around the Bohai Sea, deposited during the Holocene and in Marine Isotope Stage 3 (MIS 3) and MIS 5 (Zhuang et al., 1999; Liu et al., 2007; Wang et al., 1980; Wang et al., 1981).

Sediments deposited during various stages of the Neogene and Quaternary show great spatial differences in grain-size and thickness, which have been ascribed to the complex neotectonic structure of the Bohai Basin. The considerable differences in sediment thickness make it difficult to make stratigraphic comparisons and thus correlate marine sediments among the cores, which complicates age assessment of Quaternary transgressive events. During the last few decades, the formation and evolution of the delta in relation to both sea-level change and delta progradation have been important topics for scientific research on the coast of China, and a number of sedimentological studies on the Yellow River Delta have been carried out (Milliman et al., 1987; Saito et al., 2000; Saito et al., 2001; Liu et al., 2008; Liu et al., 2009).

Palynological analysis is a method to understand the past climate or environmental history and is still a popular and important method (Wang, 1993; Cheng et al., 2018). Few palynological investigations that can potentially provide a better understanding of the depositional environment and the evolution of both climate and vegetation have been conducted in the Yellow River Delta area, even though many studies have been done elsewhere in China (Jiang et al., 1999; Liu et al., 2004). With the initiation of the Deep Sea Drilling Project, the potential of palynological analysis was explored for Quaternary sediments (Montade et al., 2012; Yang et al., 2019). Pollen in the delta is derived from terrestrial vegetation and the surrounding area. Studies on pollen assemblages provide not only information on coastal vegetation but can also recognize sea level change and transgression. However, few palynological investigations provide a better understanding of the depositional environment and the evolution of both climate and transgression, even though many studies have been conducted near the Delta (Yi et al., 2003; Yang et al., 2019).

Spatial and temporal variations of grain-size represent transgressive successions and contain many sedimentary characters that provide a high-resolution chronostratigraphic framework for paleoenvironment change. The grain-size distribution of sediment is influenced by sedimentary dynamics and the environment. It is crucial to set up a well-constrained chronology of the transgression-regression series for better geological understanding. Paleomagnetic dating results showed that three transgressive phases (T-1, T-2, and T-3 from top to bottom) occurred in the Bohai Coast (Yao et al., 2014; Yi et al., 2015; Liu et al., 2016).

In order to provide a better understanding of the sedimentary environmental changes and Quaternary transgression-regression cycles, more case studies of sedimentary records around the Bohai Sea are needed to establish high-resolution regional proxies of investigations. We drilled core YRD-1101 from the northern coast of the modern Yellow River delta that lies on the western margin of the Bohai Sea. Well-constrained chronologically and high-resolution analyses of environmental proxies in such cores are still rather scarce. This core was previously shown by paleomagnetic measurements to cover the last Pleistocene. Grain-size analysis was combined with lithological studies and age dates (AMS 14C and OSL age) to identify the timing and characteristics of depositional events documented by the core.

In this study, we carried out a detailed investigation of the core sediments, analyzed environmental proxies (grain-size and pollen) at relatively high resolution, and refined the chronology of the core. Our aim was to clarify the sedimentary evolution during the last Pleistocene in this area and the various factors that affect the sedimentary record. The purpose of this study was to reconstruct the paleoenvironments of the Later Pleistocene on the basis of palynofloras recovered from the boreholes obtained from the Yellow River Delta. We also focused on the timing of the first Quaternary marine transgression and of subsequent (Late Pleistocene and later) transgressions.

2 Geological Background

The Yellow River Delta originated mainly in the depression period in the Neogene and Quaternary, and subsidence occurred overall. Three transgressions occurred on the southwestern coast of the Bohai Bay in the late Quaternary, corresponding to the stages of deep sea oxygen isotopes (MIS5, MIS3 and MIS1) (Yao et al., 2012; Yao et al., 2014; Yao et al., 2017; Zhou et al., 2014).

The study site has prograded seaward more than 40 km since 1855 AD. The Old Yellow River emptied into the South Yellow Sea and formed a large subaqueous delta from 1128 to 1855 AD. Seawater first entered the northern Yellow Sea and Bohai Sea area at around 11.6 cal kyr BP and 10.5 cal kyr BP, respectively, after the Last Glacial Maximum. During the maximum Holocene transgression, at about 6-7 cal kyr BP, the western coastline of the Bohai Sea was 50–90 km west of the present coastline. At the same time, the Yellow River delta began to develop on the western shore of the Bohai Sea (Xue, 1993). The Bohai Bay Basin, which began to develop on the Archean basement of the North China Craton in the Late Cretaceous, experienced episodic rifting from the Paleogene to the end of the Oligocene, which was followed by post-rift thermal subsidence from the Miocene to the Recent (Han et al., 2001; Lan et al., 2010; Guo et al., 2016).

At present, the Yellow River Delta and the surrounding area is a lowland region with mean altitude 200-500 m and a warm humid temperate climate affected by the Asian monsoon. The precipitation is concentrated in the warm and humid summer, and it is cool and dry in winter.

The region has also been extensively used for agriculture and is now covered by various crops and a few seminatural shrub forests. In the hills, the lower montane vegetation is temperate to subtropical broad-leaved deciduous forest, which is composed mainly of species
belonging to Fagaceae, Magnoliaceae, Euphorbiaceae, and Hamamelidaceae (Yi et al., 2003; Li et al., 2017; Liu et al., 2004; Xu et al., 2015).

Borehole YRD-1101 was collected on the coast of the modern Yellow River Delta at 38°02'08.97" N, 118°36'25.88" E using a rotary drilling method in July 2011 (Fig. 1). The core was more than 200 m long, and the average recovery of muddy and sandy sediments exceeded 90% and 85%, respectively. The core was split lengthwise, photographed, and described directly after core opening. On the basis of lithological characteristics and sedimentary phenomena, the sediments in the core were recognized as three types: fluvial deposits, marine deposits, and littoral deposits (Fig. 2).

3 Samples and Methods

3.1 Sample collection

We obtained samples for the various analyses and tests from core YRD-1101. The uppermost core from 0–3.36 m is artificial fill, but the part below 3.36 m consists of natural, undisturbed sediments.

For grain-size analysis of bulk sediments, 443 samples were collected from the core, mainly at 10 cm internals. For microfossil identification, 260 samples were collected from the core, mainly at 15 to 22 cm internals.

3.1.1 Sample age test

Seven samples from foraminifera were tested for AMS $^{14}$C data. The data were obtained by Beta Analytic Inc., Miami, Florida, USA. We also sent 20 samples for OSL dating to the Testing Center of Qingdao Institute of Marine Geology using a Daybresk 2200 TL/OSL reader. The age model of core YRD-1101 was described previously (Liu et al., 2016). Additional age markers, such as the occurrence of the Younger Dryas cooling event were also used as controls. We obtained the age data in Figure 2 modified from previous studies (Sun et al., 2014; Brauer et al., 1999; Boulay et al., 2004; Liu et al., 2016; Yue et al., 2019).

3.1.2 Grain-size test

Grain-size analysis was performed at the Testing Center of Qingdao Institute of Marine Geology, using a Malvern MAM5005 laser particle size analyzer. The instrument has a measurement range of 0.05–2000 μm, and the measurement error is better than 3%. Prior to analysis, the samples were pre-treated with 10% H$_2$O$_2$ to remove organic matter and 10% HCl to remove carbonates. Sediment classification was conducted following the scheme of Folk et al. (1970).

Fig. 1. Schematic map of geotectonic units and the location of core YRD-1101 (modified from Li, 2016).
Fig. 2. Lithology of core YRD-1101 showing sampling horizons and ages (modified from Li, 2016; Liu et al., 2016; Yue et al., 2019).
The percentage of sand, silt and clay components was determined based on the analyzed data. The average grain-size and sorting were calculated based on the logarithmic method (Folk et al., 1957). The sorting values were used to categorize the sediments. The sorting for each sample was determined according to the criteria as follows: < 0.35, very well sorted; 0.35–0.50, well sorted; 0.50–0.70, moderately well sorted; 0.70–1.00, moderately sorted; 1.00–2.00, poorly sorted; 2.00–4.00, very poorly sorted; > 4.00, extremely poorly sorted (Blott et al., 2001).

3.1.3 Pollen in sample test

Pollen analysis of the samples was conducted using the standard treatment method. Samples were processed for pollen using a modification of the protocols reported by Faegri and Iverson (1989), including treatments with hot 10% HCl and 10% KOH, hot 55% HF (successful hot HF treatments were used if necessary to remove all silicates, sieving (250 μm), and acetylation for 10 min. Pollen samples were mounted on microscope slides using silicone oil. At least 300 arboreal pollen grains were counted per sample using a Nikon Imager microscope.

In total, 260 spore-pollen samples from YRD-1101 were processed by acids and alkalis and then rinsed with water until neutral. Finally, samples were placed in test tubes and slides were made, followed by counting under a biological microscope.

3.2 Results

3.2.1 Grain-size characteristics and sedimentary lithology

Lithologically, the core is dominated by brown to gray sandy mud and sand interlayered with sandy silt (Fig. 3). The mud layers are homogeneous and are dominated by silt (9.8–70.1%), clay (5.5–78.5%) and sand (9.1–33.2%), representing stable fluvial deposits that have experienced weak hydrodynamic conditions. The sandy mud layers are mainly composed of silt (26.3–61.2%), clay (3.1–24.5%), and sand (8.1–39.7%), with occurrences of sandy silt layers. These layers differ significantly from the adjacent sediment in texture. For example, reddish and yellowish mottles are common, as well as moderate and locally strong bioturbation.

Event deposits usually show significant grain-size variability. Within an event depositional sequence, high variability is related to sediment processes (Wang et al., 2007; Li et al., 2019). From the grain-size analysis, the sediments of the core are dominated by the alternation two distinct facies (marine deposits and fluvial deposits), and littoral deposits can be found at the bottom. The average size of all sediment samples is 3.12–7.48 φ, with an average value of 5.38 φ.

The standard deviation (δ) of the samples is 0.2–2.1, denoting poor to well sorting. Skewness (SK) is a measure of the asymmetry of the probability distributions of the grain sizes. The data show the skewness of the samples ranges from -0.15–0.6 within the symmetrical distribution range, while some coarse grain layers fall within the positive distribution grades.

Based on the distributional characteristics of the grain-size frequency curves, marine facies were identified. The fluvial (terrestrial facies) deposit unit (3.36–10.25 m) was dominated by silt and sand, given the progradation history, and it reflects rapid sedimentation at or around the river mouth. Modern Yellow River Delta sediments deposited since 1855 AD were formed in a weak-to-medium sedimentary dynamic environment. Transitional facies units contain the intervals of 10.25–13.85, 16.9–18.5, 19.69–27.9, 34.8–36.4, 37.2–48.4, 51.6–54.1, and 55.9–60 m. The average size and standard deviation are lowest in the core, while the skewness falls within the positive distribution grades. The individual grain-size frequency indicates that the average size and standard deviation are low, while some coarse grain layers fall within the negative distribution grades. Clay dominates the marine-continental transitional facies that are easily distinguished from open seas, river mouths and gulfs, lagoons, littoral zones, and fresh water. Marine deposit units contain the intervals of 13.85–16.9, 18.5–19.69, 27.9–34.8, 36.4–37.2, 48.4–51.6, and 54.1–55.9 m. The individual grain-size frequency signifies normality; both the average size and standard deviation are high, while some coarse grain layers fall within the positive distribution grades. The clay contents are the lowest in the marine transgressions strata, which caused sea-water invasions along river valleys.

3.2.2 Palynomorph analysis

Pollen and spores are abundant between the depths of 13.9–60 m, while only 11 samples contain sufficient pollen grains, spores, and algae above the depth of 13.9 m. In total, 56 palynoflora taxa, i.e., 21 tree and shrub taxa, 23 herbs, six ferns, and six types of algae, were extracted from the core section. The dominant palynomorphs were identical throughout the section, Artemisia and Chenopodiaceae pollen were predominant. A pollen diagram showing the percentage values was produced. The whole section was divided into six zones based on the results of cluster analysis. The palynomorphs and their percentages in each zone are shown in Fig. 4.

(1) Pollen Zone I (3.36–13.9 m, 0.16 ka BP–1855 AD)
Pollen assemblage: Artemisia-Chenopodiaceae-Gramineae-Pinus

From 0–3.36 m, no palynofloras were recorded with the very fine (artificial fill layer) sand composing this sedimentary succession. It is impossible to interpret the palaeoclimate from palynological assemblages.

The interval from 3.36–13.85 m is mainly composed of common deciduous, evergreen broad-leaved pollen, including Quercus, Castanopsis, Ulmus, and Moraceae. Herbs (42.5–53.1%) and hardwoods (19.2–41.2%) had high percentages, followed by pteridophyta (9.5–25.5%). Upland herb pollen was composed primarily of Gramineae, Artemisia, Chenopodiaceae, Cyperaceae, Compositae, and Ephedra; Potamogeton and Lilaeae appeared to be rare, indicating forest grassland vegetation. Pteridophyta included Polypodiaceae, Pteridium, and Selaginella, similar to modern analogs drawn from boreal forests and woodlands in northern Asian. The palaeoclimate was cool and dry.

(2) Pollen Zone II (13.9–19.7 m, 9.1–0.16 ka BP)
Pollen assemblage: Quercus-Pinus-Ulmas-Typha
Fig. 3. Lithology and downcore variations of grain-size parameters from YRD-1101.
This zone is represented by increasing pollen concentrations and pollen. It is distinguished by high diversity. In general, the frequency of herbaceous (45.1–62.3%) and hardwood (23.1–48.6%) species increases while that of pteridophyta (6.5–19.5%) decreases. Overall, herbaceous and hardwood species are prominent among all taxa. The assemblages are presented by a sudden increase in both aquatic and warm taxa including *Quercus*, *Typha*, *Cyperaceae*, *Potamogeton*, and *Pteridium*. Marine algae are also present in this zone. The pollen assemblage suggests a warmer and more humid climate than zone I that probably corresponds to the Holocene Optimum. The Holocene thermal optimum is implied by the presence of monsoonal evergreen forest associated with diverse broadleaved deciduous taxa and the abrupt decrease in the herbaceous taxa, conifers, *Pinus*, and *Fagus* found among the palynological assemblages. The vegetation of the Yellow River Delta area may have been composed of both monsoonal evergreen and broadleaved deciduous forests.

During the Holocene thermal optimum, which was characterized by high precipitation, transgression occurred, and seawater invaded the previous fluvial region, creating estuarine and prodelta environments, as indicated by aquatic plants and marine algae as well as by diverse and abundant herbs and evergreen and deciduous broadleaved trees during Pollen zone II.

(3) Pollen Zone III, (20-26.9 m, 9.1-13.28 ka BP)
Pollen assemblage: *Pinus-Picea-Artemisia-Gramineae*

This zone is characterized by the lowest pollen concentrations and total pollen sum. The frequency of hardwoods (28.2–53.7%) increases upward, but that of herbaceous species (21.3–49.8%) decreases. The interval from 23 m to 27 m is mainly dominated by pollen grains derived from conifers and thermophilous trees in association with abundant herb pollen. Thermophilous hardwood tree and shrub taxa, conifers, and herbaceous taxa are present throughout the interval. Arboreal pollen includes *Pinus, Picea, Abies* and *Betula*, as well as some *Tsuga, Salix*, and *Larix*. Herbaceous pollen is composed primarily of *Gramineae, Artemisia, Chenopodiaceae, Cyperaceae*, and *Compositae*. The pteridophytic spores include common *Polypodiaceae*, *Bryophyta*, and *Pteridium*. A short part in the pollen assemblage showing *Artemisia* dominance may reflect a short-term climatic deterioration, comparable to the Younger Dryas Event in the North Atlantic region (Alley et al., 1993; Andreev et al., 1997; Severinghaus et al., 1998). Among all taxa, *Pinus, Gramineae*, and *Artemisia* are predominant. Xerophytic herb pollen belongs to *Gramineae, Artemisia*, and *Cyperaceae*, which indicate low-open grasslands. Together with these results, the pollen assemblage suggests coniferous woodlands and grasslands, indicating cooler and drier climatic conditions than Pollen Zone II. The cool, dry conditions probably caused the contraction of deciduous forest, coniferous forest, and steppe grasses. The period of climate deterioration undoubtedly occurred throughout much of the world corresponding to the Younger Dryas.

(4) Pollen Zone IV (26.9–38.3 m, 13.28–60.1 ka BP)
Pollen assemblage: *Artemisia-Quercus-Gramineae*
This zone is distinguished by high pollen concentrations and dinoflagellate abundance. The frequency of pteridophyta (12.7–48.5%) and hardwoods (26.1–41.5%) increases while herb (32.1–48.3%) decreases. *Artemisia*, Chenopodiaceae, *Pinus*, Cruciferae, Compositae, and *Quercus* pollen is predominant throughout the interval. Pteridophytic spores include common Polypodiaceae, Selaginella, and *Pteridium*. This zone yields the highest abundance and greatest diversity of palynomorphs encountered in the borehole.

Thermophilous hardwood taxa (29.3–47.7%) increased negligibly during this period, while conifers and herbaceous taxa (19.5–42.1%) decreased. The increase in pollen grains derived from the thermophilous hardwood trees and shrubs was concomitant with a decrease in herb pollen percentages. The change reflects the northward migration of trees and shrubs in response to climate warming during the intervals. The pollen assemblage suggests a huge increase in precipitation during the interval, with a sudden return of aquatic life (Hydrophytes increased) and the development of vegetation, indicating a warm and humid period. The pollen profile indicates marine deltaic deposition, probably in a stable environment.

**5) Pollen Zone V (38.3–48.4 m, 60.1–90.1 ka BP)**

Pollen assemblage: *Pinus-Picea-Artemisia-Typha*

This zone is characterized by the abundance of herb pollen together with a decline in pollen derived from thermophilous trees. The frequency of herb (38.4–63.7%) pollen increases downward, whereas conifer pollen (7.8–28.4%) generally increases upward. Pteridophytic species played an important role during this zone and increased much more in Pollen Zone IV. *Artemisia* and Gramineae predominate among herb pollen. Broadleaved deciduous tree pollen (including *Quercus*, *Carpinus*, and *Ulmus*) is rare. At the same time, conifer pollen such as *Pinus*, *Picea*, and *Tsuga* increased. Pteridophytic spores include common Polypodiaceae, Selaginella, and *Pteridium*. Algae include *Pediastrum* and *Zygnema*. The pollen assemblage indicates a dominant grassland vegetation reflecting a cool and dry climate.

**6) Pollen Zone VI (48.4–60 m, 90.1–94.6 ka BP)**

Pollen assemblage: Chenopodiaceae-*Quercus*-Betula-Artemisia

There are significant differences in the average pollen percentages of Pteridophyta (32.3–45.1%), shrubs, herbs (30.7–41.1%), and hardwoods (29.8–39.4%) in the borehole. Marine algae and thermophilous trees (including *Artemisia*, Chenopodiaceae) predominate among all pollen taxa. There is a sharp decrease in *Typha* and Cyperaceae that delineates the lower boundary. During the interval, increased marine taxa are associated with reduced representation of aquatic plants. Algae include *Hystrichosphaera*, *Pediastrum*, and *Zygnema*. The pollen profile indicated a marine deposition environment and suggests warmer and more humid climatic conditions than zone V. The percentages of Hydrophytes, Pteridophyta, and algae increase more sharply than in Zone IV, which likely indicates a higher sea-level than that in Zone IV.

## 4 Discussion

### 4.1 Identification of event deposits

From grain-size analysis combined with lithological study, three types of deposit facies (marine, transitional and terrestrial facies) were identified in core YRD-1101 (Fig. 3). The coarse-grained component is high, indicating that sedimentary material from a nearshore shelf environment was under tidal influence. Marine units (13.85–19.7, 29.2–35.6, 36.4–37.2, 48.5–51.4 and 53.9–55.8 m) are characterized by alternations of silt to clayey silt and fine to medium sands, containing benthic foraminifera and the ostracod assemblage of euryhaline and brackish water species.

The foraminiferal assemblages are generally dominated by *A. beccarii* var.s., *E. magellanica*, and *P. tuberculatum*, with secondary species including *E. advenum* and *C. subincertum*. The ostracod assemblages have lower simple diversities and dominant species *N. chenae, S. impressa* and *K. bisanensis* (Liu et al., 2016; Li et al., 2019; Lii et al., 2020). Reddish and yellowish mottles are common in units (48.5–51.4 m and 53.9–55.8 m), as well as moderate and locally strong bioturbation.

The 13.85–19.7 m interval consists of dark gray to brown-gray clayey silt, intercalated with silt and fine-sand beds, and shows tidal bedding. Heavy bioturbation is common, and shell fragments and shelly layers are scattered throughout the unit. This part is interpreted as having been deposited from the middle to late Holocene in a coastal to nearshore shelf environment under tidal influence. The heavy bioturbation with high abundance and simple diversities of the foraminiferal and ostracod assemblages in this unit suggest that the sedimentation rate was low (Liu et al., 2016; Qiu et al., 2017). In this unit, the benthic foraminiferal assemblages have abundances mostly between 5,000 and 20,000, and the simple diversities are the highest among all units of the core. The assemblages are dominated by *A. beccarii* var.s., *E. magellanica*, and *P. tuberculatum*, and secondary species include *C. subincertum* and *E. advenum*. Similar to the foraminiferal assemblages, the simple diversities of the ostracod assemblages, which range between 8 and 17, are also the highest units of the core. Ostracod abundances are relatively high, mostly between 800 and 10,000, and they are dominated by *N. chenae, S. impressa*, and *K. bisanensis* (Liu et al., 2016). On the basis of the lithofacies, grain-size, benthic foraminiferal, and ostracod assemblages, in conjunction with the dates, this unit is interpreted as having been deposited from the middle to late Holocene in a coastal to nearshore shelf environment under tidal influence.

During the intervals (35.6–36.4 m and 51.4–53.9 m), both the benthic foraminiferal and ostracod assemblages exhibit high abundances and diversities. High clay contents in both intervals may be because of heavy bioturbation. Euryhaline species including *A. beccarii* var.s. and *E. magellanica* dominate in the two units (Liu et al., 2016), as well as high clay and low silt. We regard the intervals as marine-continental transitional (lagoons)
facies deposit units according to the algae pollen that dominated at the same time. The slight saline lagoons facies are very common in Bohai Sea’s Holocene stratigraphy (Wang et al., 1981).

Fluvial deposit units (3.36–13.85 m, 19.7-29.2 m, 37.2–48.5 m, and 55.8–60 m) are characterized by alternations of yellowish gray to grayish yellow clayey layer, interbedded with abundant clayey and silty laminations, and tidal bedding. The unit (3.36–13.85 m) is dominated by euryhaline littoral species such as *A. beccarii* vars., *E. magellanicum*, and *P. tuberculatum*. The ostracod assemblages have abundances averaging 360, and an average diversity of 5; *N. chena* is the dominant species, and secondary species include *S. impressa*, *P. bradyformis*, and *K. bisanensis*. This is interpreted as deposits given the progradation process of the modern (since 1855 AD) Yellow River Delta. The fine sediments are relatively well sorted compared to the coarser sediments, suggesting a low-energy hydrologic environment. The cyclic grain-size variation indicates several waning discharge periods for the delta. No bioturbation is evident. Both the benthic foraminiferal and ostracod assemblages exhibit low abundances and diversities. The absence of bioturbation and the low abundance diversities of the benthic foraminifera reflect rapid sedimentation around the river mouth (Craddock et al., 2010; Yi et al., 2012; Liu et al., 2016; Liu et al., 2020).

**4.2 Paleovegetation and climatic implications**

The pollen, granularity, sea-level change curves and transgressions provide a scientific basis for the study of the ancient climate and environment in the Yellow River Delta, which provide the standards for the establishment of a Quaternary stratigraphic framework (Fig. 5). Quaternary vegetation is the direct ancestor of modern flora, and modern phytogeographical distributions are the result of the historical development of past vegetation; comparisons between modern and Quaternary pollen assemblages help to increase our understanding of the evolution of both vegetation and climate (Birks et al., 1980; Yi et al., 2003).

In Pollen Zone I (3.36–13.9 m) of the core, the data reveal that conifers such as *Pinus*, *Picea* and *Tsuga*, with lowland trees and herbs, including *Chenopodiaceae*, *Gramineae* and *Artemisia*, are common. Broadleaved deciduous trees are rare, indicating a cool and dry climate from 0.16 ka BP to 1855 AD. This period responds to the environment after the Huanghua transgression in which major terrestrial facies were caused by fluvial deposits on the flood plain.

Pollen Zone II (13.9–19.7 m) represents the Holocene thermal optimum between 9.1 and 0.16 ka BP. The stage is implied by the presence of monsoonal evergreen forest associated with diverse broadleaved deciduous taxa and the abrupt decrease in the herbaceous taxa, conifers, *Pinus*, and *Tsuga* found among the palynological assemblages. Enhanced monsoonal precipitation and moist conditions are also inferred from the common pterido phytic spores. The vegetation of the Yellow River delta area is composed of both monsoonal evergreen and broadleaved deciduous forests, which correspond to early MIS 1 and the stage of sea-level rise. Grain-size analysis and the sedimentary environment evolution reflect the basic similarity and generally the Huanghua transgression.

From 13.28 to 9.1 ka BP in Pollen Zone III, climatic cooling is observed by an abrupt reduction of monsoonal evergreen and broadleaved deciduous trees and a rising frequency of herbaceous taxa *Artemisia*, with *Chenopodiaceae* and Gramineae. Conifer pollen includes *Fagus* and *Tsuga*, and rare thermophilous hardwood taxa include *Quercus* and *C. stanopsis*. The abrupt cooling event was indicated by the expansion of coniferous forest and sea level lowering in eastern China. The changes in pollen assemblages may indicate a gradual climatic transition from warm, wet to cold, and dry conditions. This shows *Artemisia* dominance may reflect a short-term climatic deterioration, comparable to the ‘Younger Dryas’ event. Evidence for the Younger Dryas climate oscillation has also been identified in the distinct changes in benthic foraminifera faunas in the core (Yi et al., 2003; Liu et al., 2016; Li et al., 2017). The pollen assemblages may indicate a Younger Dryas short-term climatic deterioration that is corresponds to the lowest sea-level stage.

Pollen zone IV, from 13.28–60.1 ka BP, is another warm climatic phase, suggested by the increase in representatives of monsoonal evergreen and broadleaved deciduous trees, with low frequencies of conifer pollen (*Pinus* and *Picea*) throughout the internal the zone. Abundant dinoflagellates indicate an aquatic environment with humid and warm conditions during this stage. This event is characterized by a warm and humid environment with algal taxa compared with the sea level rise and transgression that correspond to early MIS 3 and the stage of sea-level rise. Grain-size analysis and sedimentary environment evolution reflect the basic similarity with the Xianxian transgression.

From 90.1–60.1 ka BP, the pollen zone V climatic cooling event is identified by an increase in the occurrence of conifers, combined with a remarkable decrease in evergreen and broadleaved deciduous forest and the expansion of grassland. From the δ18O record, the cooling period has a sharp drop in temperature and humidity (Raymo et al., 1992; Liu et al., 2004; Wan et al., 2007; Guo et al., 2016). Sedimentary facies are dominated by a transition that reflects the Cangzhou transgression, and the sea level rose rapidly compared with MIS 5a. The pollen assemblage expresses the paleoenvironment that was cool and dry, the particularity and hysteresis of plant growth may be a reason.

The Pollen VI zone from 90.1–94.6 ka BP is the warmest period and is dominated by evergreen forest and broadleaved deciduous trees. The warm and humid phase indicates the development of a hypsithermal and is the warmest during the whole core, comparable to MIS 5b marine sedimentation based on the grain-size results. The vegetation may have comprised both monsoonal evergreen and broadleaved deciduous forests. Grain-size analysis and the sedimentary environment evolution reflect basic similarity and are generally consistent with the Cangzhou transgression.

The six pollen assemblage zones identified provide a basis to understand the paleovegetation and climatic
The characteristics of different pollen types can represent the different climate types, from the Late Pleistocene onwards, and division into six pollen zones. The sporopollen in assemblages express the warm-moist to cold-dry to mild-semi dry to cool-dry to warm-moist and mild dry alternating type of climate changes; the sedimentary environment evolution and particle size reflect the basic similarity and are generally consistent with the Cangzhou transgression, Xianxian transgression, and Huanghua transgression.

### 5 Conclusions

(1) Based on a combination of grain-size analysis with lithological studies and stratigraphy, 14 sedimentary units have been identified. These correspond to deposition stages, including the fluvial (terrestrial facies) deposit unit (3.36–10.25 m), transitional facies units (10.25–35 m, 35–40 m, 40–45 m, 45–50 m, 50–55 m, 55–60 m), and marine facies units (25–30 m and 30–35 m). The sedimentary facies and climatic type are shown in the table and figure below.

#### Table: Sedimentary Facies, Climatic Type, and Transgression Event

<table>
<thead>
<tr>
<th>Age (ka)</th>
<th>Depth (m)</th>
<th>Main oxygen isotope stages (MIS)</th>
<th>Relative sea level(m)</th>
<th>Sedimentary facies</th>
<th>Climatic type</th>
<th>Transgression event</th>
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Fig 5: Sedimentary facies, climatic type and transgression event of the Yellow River Delta since the Late Pleistocene (Modified from Chappel et al., 1996; Lambeck et al., 2002).
16.9–18.5, 19.69–27.9, 34.8–36.4, 37.2–48.4, 51.6–54.1, 55.9–60 m, and marine deposit units (13.85–16.9, 18.5–19.69, 27.9–34.8, 36.4–37.2, 48.4–51.6, 54.1–55.9 m). The marine deposits are characterized by coarse grain sizes, poor sorting, wide kurtosis, bimodal frequency, and clear depositional variations. The transitional deposits are dominated by fine grains from a basic normal distribution.

(2) Based on the palynological analysis of the core, we divided the palynological diagram into six pollen zones and reconstructed the past vegetation and climate. Based on pollen analysis and pollen assemblages, there were three warm-wet periods from 9.1–0.16 ka BP, 13.28–60 ka BP, and 90.1–94.6 ka BP. The sporopollenin assemblages indicate the palaeoclimate that had an evident fluctuation: warm and moist → cool and dry → mild semi→cool and moist (Holocene Optimum) → mild dry.

(3) There are three transgression-regression events and evolutions of the sedimentary environment based on sea-level changes since the Late Pleistocene in the Yellow River Delta, China. We recognize the sedimentary procession of the delta since the Late Pleistocene. The procession can be divided into two regression and three transgression events, corresponding to two cool periods and three warm periods based on pollen assemblages. From 9.1–0.16 ka BP, 60.1–16.1 ka BP and 94.6–90.1 ka BP, three warm-wet periods occurred. The periods correspond to the Cangzhou transgression, Xianxian transgression, and Huanghua transgression, respectively. From 90.1–60.1 ka BP, 16.1–9.1 ka BP, and 0.16 ka BP–1855 AD, three dry and cold phases are recognized. The phases indicate the fluvial (continental) sedimentary environment, corresponding to cold-dry periods based on palynological results and grain-size distribution.

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