

The sedimentary facies and dynamic environment of the Diaokou lobe in the modern Huanghe River Delta of China

GAO Wei^{1,2}, LIU Shihao^{3*}, LIU Jie^{1,2}, XU Yuanqin^{1,2}, LI Ping^{1,2*}

¹ Key Laboratory of Marine Sedimentology and Environmental Geology, The First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China

² Laboratory for Marine Geology, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao 266061, China

³ Research Center for Islands and Coastal Zone, The First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China

Received 24 May 2018; accepted 12 June 2018

© Chinese Society for Oceanography and Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

The Huanghe River captures the Diaokou River in 1964 and forms a deltaic lobe in the subsequent 12 a. The progradational process of the Diaokou lobe is associated with complicated evolution of riverine sheet flooding, merging, and swinging. On the basis of 11 borehole cores and 210 km high resolution seismic reflection data set, the sedimentary sequence and dynamic environment of the Diaokou lobe (one subdelta lobe of the modern Huanghe River Delta) are studied. The stratigraphy of the lobe is characterized by an upward-coarsening ternary structure and forms a progradational deltaic clinoform. Totally six seismic surfaces are identifiable in seismic profiles, bounded six seismic units (SUs). These SUs correspond to six depositional units (DUs) in the borehole cores, and among them, SUs 4–6 (DUs D to F) consist of the modern Diaokou lobe. Lithological and seismic evidences indicate that the delta plain part of the Diaokou lobe is comprised primarily by fluvial lag sediments together with sediments from sidebanks, overbanks, fluvial flood plains and levees, while the delta front part is a combination of river mouth bar sands (majority) and distal bar and deltaic margin sediments (minority). As a result of the high sedimentation rate and weak hydrodynamic regime in the Huanghe River Delta, the sediments in the delta front are dominated by fine-grained materials. The grain size analysis indicates the Huanghe River hyperpycnal-concentrated flow shows the suspension, transportation and sedimentation characteristics of gravity flow, and the sediment transportation is primarily dominated by graded suspension, while uniform suspension and hydrostatic suspension are also observed in places. The strength of the hydrodynamic regime weakens gradually offshore from riverbed, river mouth bar, sidebank, distal bar subfacies to delta lateral margin and flooding plain subfacies.

Key words: modern Huanghe River Delta, sedimentary facies, sediment dynamics, grain size

Citation: Gao Wei, Liu Shihao, Liu Jie, Xu Yuanqin, Li Ping. 2018. The sedimentary facies and dynamic environment of the Diaokou lobe in the modern Huanghe River Delta of China. *Acta Oceanologica Sinica*, 37(11): 40–52, doi: 10.1007/s13131-018-1332-z

1 Introduction

Fluvial delta is a comprehensive sedimentary system; its sedimentation, suspension and reworking of the sediments are heavily influenced by both river system (Coleman and Wright, 1975) and marine forces (e.g., tide and wave) (Wright et al., 1986a; Wang et al., 2010). As formed and evolved in the coastal area, a transition of the marine and terrestrial environments, the fluvial delta is sensitive to the global environmental change (Bianchi and Allison, 2009). Deltaic sedimentary and geomorphological processes are dominated by both marine (wave and tide) and fluvial forces (Wright, 1985; Wang et al., 2007). During the regressive period, the fluvial clinoform migrated into the prior neritic and littoral settings, resulting in a series of different sedimentary facies. Therefore, the deltaic sequence stratigraphic study can reveal the sedimentary evolution as well as the geomorphology that

is associated with the sediment dynamics of the regressive delta. A grain size is an important environmental proxy for such studies; its distribution characteristics is a result of sedimentary input sources and hydrodynamic (both fluvial and marine forces) regimes (Visher, 1969). Particularly, the distribution characteristics of the grain size are related to the difference of transportation and sedimentation mechanism in different geological surroundings (Stevenson et al., 2014). Studies (Yamaguchi et al., 2005; Flood et al., 2015) that adopted a grain size analysis to reveal the sediment transportation mechanism, source of sediment input, sedimentation process as well as sediment dynamic conditions have been widely reported.

The modern Huanghe River Delta is a representative hyperpycnal-dominated delta in the world (Li et al., 1998a, 2000; Liu et al., 2004, 2016; Necker et al., 2005). The sedimentary characterist-

Foundation item: The National Program on Global Change and Air-sea Interaction of China under contract No. GASI-GEOGE-05; the NSFC-Shandong Joint Fund for Marine Science Research Centers of China under contract No. U1606401; the Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology of China under contract No. MGQNLN-KF201715; the National Natural Science Foundation of China under contract No. 41206054.

*Corresponding author, E-mail: liping@fio.org.cn; liushihao@fio.org.cn

ics of the modern Huanghe River Delta can be generalized as the following four points: (1) the deltaic clinoform is consisted mainly of silty sediments, and most of which originated from the Loess Plateau (Gao et al., 2014a); (2) the water depth in the Huanghe River subaqueous delta is too shallow to form completely-developed deltaic sequences by the hyperpycnal concentrated flow; (3) vertical and/or oblique tidal currents, gyres near the estuary, shear front as well as the orbital (wave) effects contribute to a unique hydrodynamic environment that strongly impacts on the development of the deltaic sequence (Wright et al., 1986b; Li et al., 1998b; Yang et al., 2011; Ramirez and Allison, 2013); (4) the above conditions and the wide deltaic elongation range result in a special deltaic structure, where various deltaic and/or estuarine sedimentary facies were formed and developed (Li et al., 1998a, 2000).

The modern Huanghe River Delta has been formed since June 1855, after a prior channel valley rechanneled from the Ji-ansu Province, the southern Yellow Sea, to its modern position with the vertex at the Tongwaxiang County, Lanyang, Henan Province. A subaerial delta plain was generated in the Lijin County, Dongying, Shandong Province (Fig. 1a) (Zhou, 1987; Pang and Jiang, 2003a, b; Qiao et al., 2011). Since 1855, totally 11 major tail swings of the Huanghe River have been observed on the modern Huanghe River Delta, forming eight large sub-deltas

(Fig. 1b) (Fan et al., 2006). Averagely, the evolution of a single sub delta fan is 16 a, which is much faster than the Mississippi sub deltas (≈ 115 –175 a in average) (Wells and Coleman, 1987; Meade and Moody, 2010). After 1949, strong artificial impact reduced the frequency and influence range of the channel tail swings. The top of the swing fan was limited into the vicinity of the Yuwa County (Fig. 1b).

The Diaokou lobe of the modern Huanghe River Delta was a sub delta fan that formed and evolved between 1964 and 1976 (i.e., No.7 subdelta, Fig. 1b). Its evolution was dominated by natural process with limited artificial influences (Gao et al., 2014b), and it kept a nearly intact sedimentary sequence of a sub delta (nearly all the sub deltaic facies can be observed in the Diaokou lobe) (Cheng and Xue, 1997), making it an ideal research area to study (1) the sedimentary and dynamic evolution of the Huanghe River sub deltas, and (2) how the hyperpycnal flow influences the sedimentation of the Huanghe River sub deltas. Although the downcore distributions of lithological facies and grain size characteristics have been reported by many previous studies (e.g., Liu et al., 2009, 2014, 2016; Zhou et al., 2016), less emphasis have been made on the study of the modern (since 1855) sedimentary and dynamic evolution of the Huanghe River Delta. A comprehensive seismic and borehole survey is of importance to further reveal the post-glacial evolutionary mechanism (particularly, the

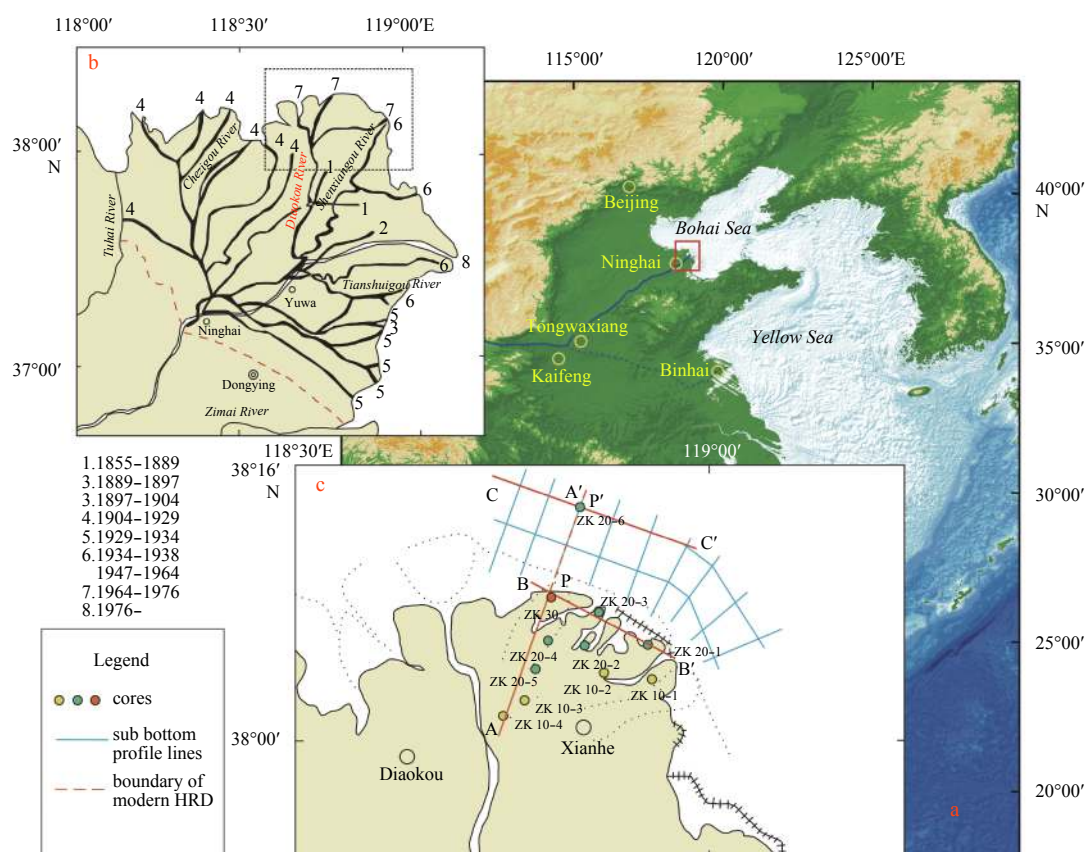


Fig. 1. Map for the modern Huanghe River Delta (HRD) on the China's eastern coast (a); distribution of the modern Huanghe River sub-delta lobes since 1855 (after Cheng and Xue, 1997) (b); and location for the borehole cores in the sub bottom seismic reflection profiles in and near the Diaokou lobe (c). In Panel a, the red box stands for the location of our study area. In Panel b, the orange dashed line indicates the boundary of the modern HRD. The river channels with numbers marked on the top indicate the stages of the Huanghe River's rechanneling; the age of each stage is shown below Panel b. In Panel c, the blue lines show the seismic survey track, while the orange lines indicate the representative seismic profiles that shown in Fig. 2. Yellow, green and red circles indicate the location of the borehole cores analyzed in this study.

modern mechanism) of the Huanghe River Delta.

2 Materials and methods

2.1 Sub bottom seismic reflection data

The sub bottom seismic survey of the Diaokou lobe was conducted by using a GeoChirp sub bottom profiler (Geoacoustics, INC, British). A total of 210 km seismic data set was collected within the subaqueous deltaic lobe (Fig. 1c). The profiler was fired at a power level of 60 J, and a frequency of 16 Hz, resulting in a vertical resolution of 10 cm. The seismic interpretation was conducted by using Triton's perspective software (Triton Imaging, INC, USA); time-varied gains, bandpass filtering, and swell filtering were applied to all data. The correlation between seismic and borehole data and different bandpass, stack, and other filtering (e.g., sea floor smoothing) methods was conducted to improve the interpretation accuracy.

2.2 Borehole core samples

A total of 11 borehole cores with overall 190 m in length were collected in the subaerial and subaqueous delta within the Diaokou lobe. The locations and basic descriptions are exhibited in Fig. 1c and Table 1, respectively. In the laboratory, the cores

Table 1. Basic information of borehole cores derived in this survey

No.	Core name	Location	Core length/m
1	ZK 10-1	38°04'37.7"N, 118°54'28.6"E	8.7
2	ZK 10-2	38°04'30.0"N, 118°51'23.0"E	10.0
3	ZK 10-3	38°03'06.3"N, 118°46'24.8"E	8.4
4	ZK 10-4	38°01'59.8"N, 118°44'50.1"E	10.2
5	ZK 20-1	38°05'33.1"N, 118°54'51.6"E	20.3
6	ZK 20-2	38°05'45.0"N, 118°50'39.1"E	20.5
7	ZK 20-3	38°07'07.9"N, 118°51'00.2"E	21.0
8	ZK 20-4	38°05'38.2"N, 118°48'34.3"E	20.7
9	ZK 20-5	38°04'19.2"N, 118°47'33.9"E	19.2
10	ZK 20-6	38°19'42.3"N, 118°51'47.8"E	18.6
11	ZK 30	38°08'20.0"N, 118°48'29.7"E	30.2

were split, described and photographed. Since the original split sediment surface is too fuzziness to reveal the small-scale sedimentary structure. Therefore, before photograph and description, all the core surfaces were smoothed and all the contaminants were removed.

The borehole cores were resampled in 5 cm interval (totally 3 372 samples) for a grain size analysis. The measurement was conducted by using a Mastersizer 2 000 laser particle analyzer (Malvern Inc, British) with a measure range of 0.02–2 000 μm . The grain size was analyzed following Liu et al. (2016) after pre-treating the samples with 10% H_2O_2 and 0.1 mol/L HCl to remove organic matter and biogenic carbonate. To reduce systematic and artificial errors, the measure was repeated until such error is less than 3%.

The calculation of grain size parameters, i.e., medium diameter (Md), mean size (Mz), sorting coefficient (σ), skewness (Ski) and kurtosis (Kg), was obtained after Folk and Ward (1957). In order to address relative hydrodynamic condition, the distribution curves and probability accumulative curves of each sample were established by the software.

2.3 Bathymetric data

Bathymetric data sets were derived from 1959, 1966, 1968, 1972, 1974, 1976 topographic charts for the last 50 a topographic evolution of the Diaokou lobe. The correlation between the topographic change and the subsurface structure (established by seismic and borehole data sets) is subsequently adopted to analyze the sedimentary evolution of the Diaokou lobe.

3 Results

3.1 Seismic and sedimentary stratigraphy

Totally six seismic surfaces were interpreted in the shallow stratigraphy within 30 m below sea floor (Seismic line P–P' in Fig. 1), corresponding T3, T3', T2, T1, T1' and T0 from the oldest to the youngest, respectively (Fig. 2). Therefore, six seismic units (SUs), SU1 to SU6 from top to bottom, were identifiable among these surfaces. Besides, we also interpret six depositional units (DUs),

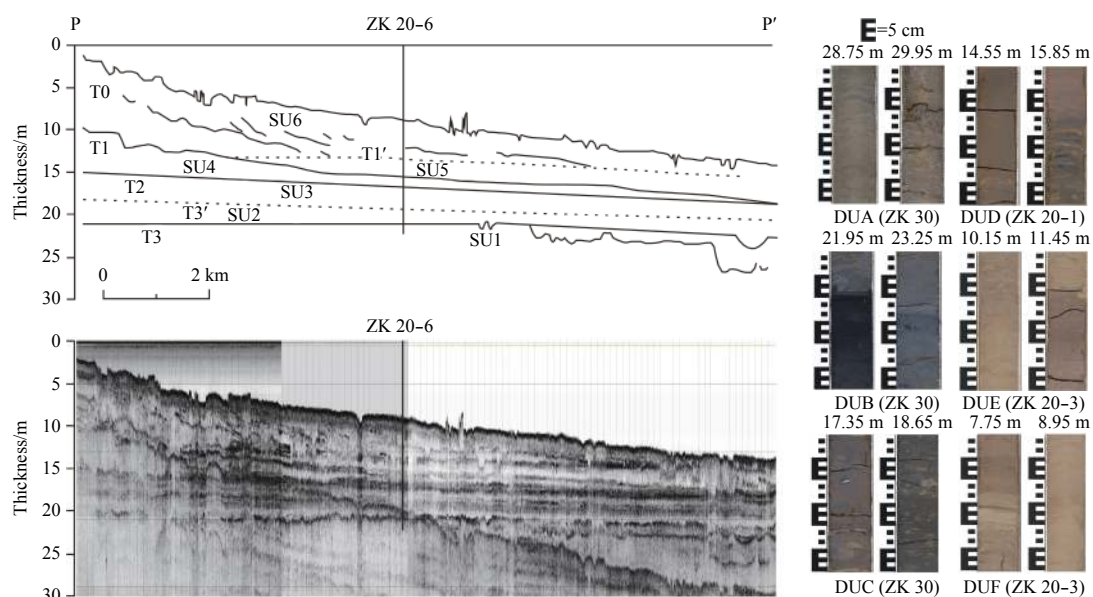


Fig. 2. Interpreted (top) and uninterpreted (bottom) seismic reflective profile along the dip direction on the Diaokou lobe (Fig. 1). The inset on the right exhibits representative DUs in the boreholes.

DUA to DUF from bottom to top, in the borehole cores. The correlation between DUs and the SUs are also exhibited in Fig. 2.

T3 is characterized by high-amplitude, less than 0.5 relief, continuous reflectors. SU1 was truncated and bounded above by this surface, but its bottom surface is not identifiable in our seismic profiles. SU1 is dominated by seismic transparent materials with some chaotic reflectors in places. Several cut-and-fill structures are observable in SU1 (Fig. 2). SU1 corresponds to DUA, which is characterized by pyknotic yellowish brown sediments with scattered shell fragments and calcareous concretions. On the basis of the above correlations as well as previous stratigraphic studies reported by Liu et al. (2009, 2014, 2016), and Zhou et al. (2016), we interpret DUA/SU1 as the lowstand (most probably formed during or near the last glacial maximum (LGM)) fluvial/lacustrine deposits.

SU2 consists of medium- to high-amplitude, stratified acoustic materials, bounded below by T3 and above by T3'. T3' is a high-amplitude, low-relief, sub-horizontal, continuous surface, and it is approximately parallel to T3 (Fig. 2). SU2 corresponds to DUB, which is dominated by yellowish and grey brown slit with scattered fish-bone structures and organic muds. Radioactive carbon-14 dating results of two samples in DUB are 8 800 and 10 210 a BP, respectively. We interpreted SU2/DUB as the tidal flat deposits that formed during post-LGM transgression.

SU3 is a medium-amplitude, semi-transparent acoustic package that overlies SU2, bounded above by T2, which is a high-amplitude, continuous, seaward-dipping surface. Therefore, SU3 consists of a seaward-dipping wedge (Fig. 2). This unit corresponds to DUC in the borehole cores, which is characterized by grey brown slit with scattered grey black clay and grey brown fine sand and plenty of shell fragments. We interpreted SU3/DUC as the combined neritic and deltaic deposits that formed since Mid-Holocene, and thus T2 probably corresponds to the maximum flooding surface (MFS).

SU4 also consists of a seaward-dipping wedge but with a

steeper gradient than SU3. It is characterized by medium- to high-amplitude, semi-transparent to chaotic reflectors, and some stratified reflections in places (Fig. 2). It is bounded above by a medium-amplitude, high-relief, continuous surface (T1) with the steepest dipping gradient within the subsurface. SU4 corresponds to DUD in the borehole cores, which is dominated by grey brown slit with 1–2 cm thick yellowish slit and scattered shell fragments. Given the Huanghe River shifted its main course into the southern Yellow Sea, and our study area at time experienced erosive mechanism, an erosion unconformity surface is widely recognized within or near this region (e.g., Liu et al., 2016), which probably corresponds to the bottom boundary of SU4. Thus, we are confident to interpret SU4/DUD as the modern Huanghe River deposits that formed between 1855 and 1964, i.e., the deltaic deposits before the formation and evolution of the Diaokou lobe.

On the basis of the above interpretation, we interpret that the combination of SUs 5 and 6 as the front deltaic deposits of the Diaokou lobe that has formed since 1964. SU5 situates on the bottom of the Diaokou lobe deposits, characterized by medium- to low-amplitude, semi-transparent, acoustic materials. It corresponds to DUE, a red-brown-slit-dominated slit with a distinguished upward-coarsening structure. SU6 is a progradational clinoform located on the top, dominated by seaward-dipping, cross bedding, and wavy bedding reflectors to chaotic reflectors (Fig. 2). SU6 corresponds to DUF, which is dominated by yellowish grey fine sand and yellowish brown slit with some red brown clayey laminas. T1' is a low-amplitude, sub-horizontal acoustic transition that separates such two units. It is discontinuous in places in the distal of the Diaokou lobe deposits. We hypothesize that it probably corresponds to the flooding events in 1967.

3.2 Subdivision of Diaokou lobe deposits and their grain size characteristics

On the basis of downcore distribution of grain size parameters (e.g., Xue, 1994; Liu et al., 2014) as well as lithological (e.g.,

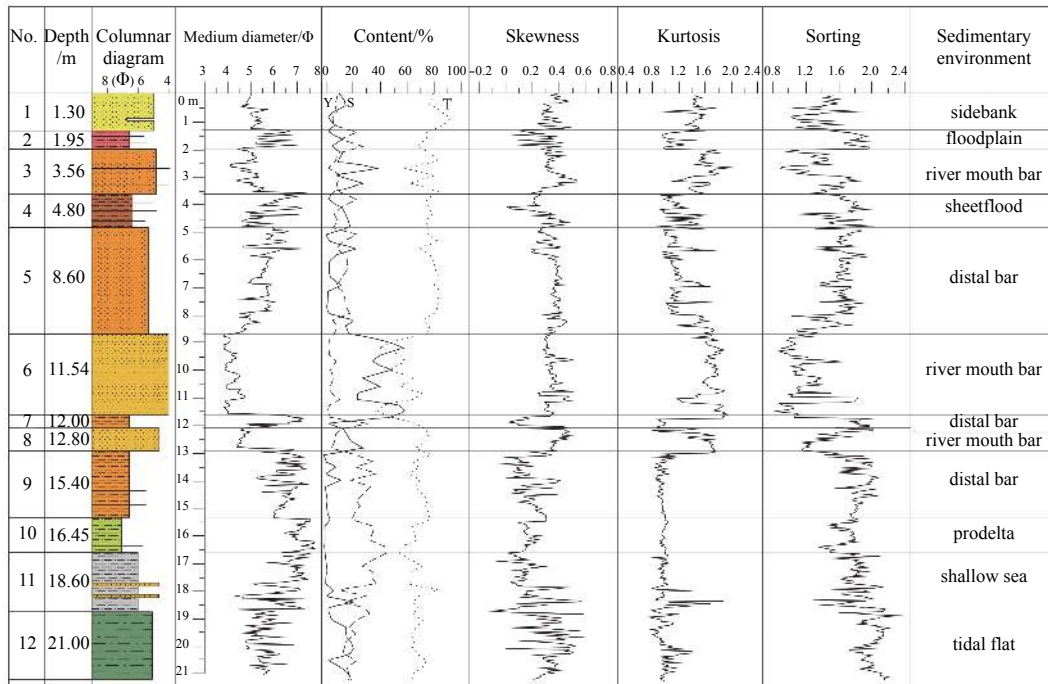


Fig. 3. Downcore distribution of the grain size parameters in Core ZK 20-3. Y, S and T in the content column indicate the clay, silt and sand components, respectively.

color, small-scale structures) characteristics (Fig. 3), the Diaokou lobe deposits of the modern Huanghe River Delta (i.e., the DUF/SU5 and SU6) can be further subdivided into three sedimentary facies (SFs). They are the delta plain facies, the delta front facies, and the prodelta facies (e.g., Xue, 1994). Within them, eight subfacies are identifiable. The grain size characteristics are detailed described in the descriptions of each subfacies.

3.2.1 Delta plain facies

The delta plain facies keep the most intact structure in the Diaokou lobe among the entire Huanghe River Delta system. In the borehole cores, its average thickness is approximately 5 m. A binary lithological structure (coarser sediment on the bottom and finer sediments on the top) (Fig. 4) can be observed, indicating that it was presumably a result of fluvial vertical and lateral accretion which preserved within riverbed and flood plain environments, respectively. On the basis of a lithological analysis as well as well-established sedimentary mode of the delta plain facies in literatures (e.g., Tye and Coleman, 1989; Xue, 1994; Allison et al., 2003), the facies can be further divided into four subfacies, which were interpreted as the riverbed sediments (e.g., Fig. 4), the overbank sediments, the flood plain sediments and the natural levee sediments, respectively.

The riverbed subfacies is relatively coarse in the binary structure, consists of very fine sand and coarse silt with some red- to brown-clayey silt interlayers. Scattered charcoals, plant frag-

ments and a few shell fragments are common. We identified a parallel bedding structure and overlying these fine-grained sediments consist of a cross bedding structure, indicating a high-velocity of fluvial depositional environment. Such structure is bounded below by a significant unconformity surface (Fig. 4). We observed a “flame” structure overlies those structures. Specifically, the “flame” structure is characterized by tongue-shape clay layers that penetrates into the overlying sandy layers (Fig. 4). We hypothesize that such structure is formed with the lateral migration and gradual accumulation of the fluvial channel. The fluvial towing effect makes the underlying clayey silt deform. The axis direction of such “flame” is an indicator of the direction of fluvial flow. On the basis of previous borehole survey onshore and near-shore of the HRD, the stratified fine sand layer and the “flame” structure are indicative of the sedimentation in the channel axis which represents the riverbed environment (Gao et al., 2014b).

The sediments on the river base within the riverbed subfacies are primarily characterized by very fine sand; the components of sand, silt and clay account for 58.0%, 37.0% and 5.0% of the total sediments, respectively. The sediments were poorly sorted with a sorting coefficient of 1.01–1.90 and the median grain size varies from 3.4Φ to 4.0Φ . The sediments on the flanks of the same subfacies exhibit slightly different grain size characteristics. They are mainly composed of sandy silt and silty sand. Sand, silt and clay account for 35.0%, 57.0% and 8.0%, respectively. Among these sediments, the average contents of coarse silt and fine silt are

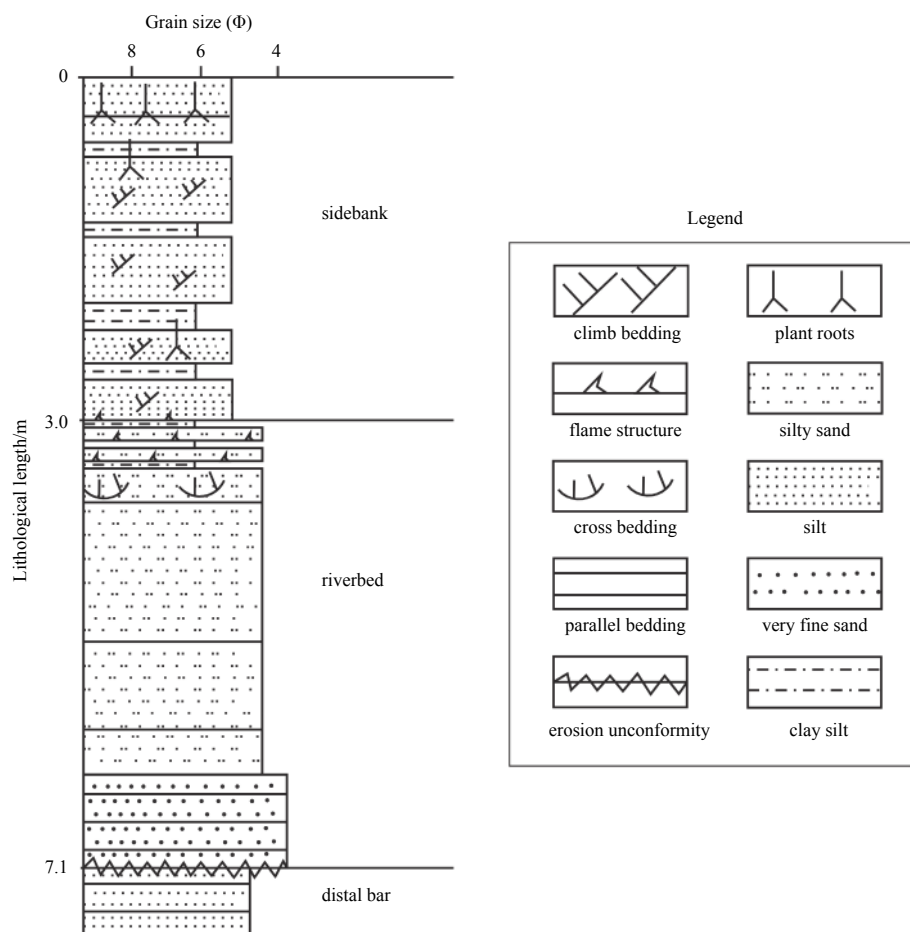


Fig. 4. Representative binary lithological structure (coarser riverbed sediments on the bottom and finer sidebank sediments on the top) of the delta plain facies in Core ZK 10-1. Representative small-scale downcore structural features (e.g., climb bedding, flame, cross bedding) are indicated. See Fig. 1 for the core location.

47.0% and 10.0%, respectively. The median diameter varies from 3.6Φ to 4.7Φ , which is a little finer than channel basement sediments, although their sorting coefficient is identical.

The overbank subfacies is mainly composed of coarse silt, with clayey silt laminations scattered. The subfacies is characterized by fine-grained sediment (e.g., silt) with climbing bedding structures. The average contents of sand, silt and clay are 14.0%, 76.0% and 10.0%, respectively. Among them, coarse silt and fine silt account for 59.0% and 17.0% of the entire sediment components, respectively. The median grain size varies from 4.5Φ to 5.5Φ , and the standard deviation (i.e., sorting coefficient) ranges from 1.20 to 1.80, indicating poor sorting. According to the criteria modified by [Zhu \(2008\)](#), the subfacies below are all marked by poor/extremely poor sorting. On the basis of the binary structure of the grain size characteristics and the scattered climbing bedding, we interpret this layer as the overbank subfacies because such features were often observable at the transition of the riverbed and floodplain. The thickness of subfacies varies between 1.0 and 3.0 m. Generally, thicker part was observed in the channel axis while thinner part in the channel flanks. Four to five sedimentary cycles with approximately 0.2 to 0.5 m thick were identified in the subfacies, each of the cycle is characterized by a coarse silty interlayer with the scattered climbing bedding, parallel bedding structure and plant roots, and approximately 2 mm thick, yellowish brown, clayey silt laminations. We hypothesize that the parallel beddings and the climbing beddings are indicators of a rapid depositional process that driven by a hyperpycnal flow during the flooding period. On the top of the subfacies, we observed a 2–5 cm thick, red-brown layer that dominated by silty clays or clayey silts with scattered plant roots. On the basis of the pervious hypothesis, we presume that it is result of weak hydrodynamic (presumably lenitic) condition after flooding event and consists of top boundary of the overbank sediments.

The flood plain subfacies is mainly composed of clayey silt, of which the average contents of sand, silt and clay are 5.0%, 73.0%

and 22.0%, respectively. The median diameter varies from 5.8Φ to 7.6Φ , and the standard deviation ranges from 1.6 to 1.9. The thickness of this subfacies changes generally between 0.15 and 1.10 m. Two types of lithological combinations are identifiable. One is observed within shallower depression (e.g., Cores ZK 20–4 and ZK 10–4) and occasionally exposed subaerially. Its thickness varies between 0.15 and 0.50 m, characterized by red-brown clayey silt with some light yellowish silt and horizontal beddings scattered. Another is usually observed in the deeper depressions near the fluvial channel (e.g., Cores ZK 20–1 and ZK 20–2). Its thickness is usually over 1.0 m, and it is characterized by a multiple-cycles structure, as known as positive rhythm structure (e.g., [Shi et al., 2016](#)), where the bottom of each cycle is dominated by light yellowish silt with the parallel beddings and the clay content increases upward. The top layer is characterized by red-brownish sandy clay with the horizontal beddings, indicating the layer was deposited within the flood plain environment. This subfacies generally overlies the riverbed subfacies and is underlied by the sidebank subfacies (Fig. 5). We hypothesize that it is result of the abandoning and rechanneling of fluvial distributaries which contribute to depression morphology in the previous place.

The natural levee subfacies is usually exposed subaerially and formed a bulge/crest. On the basis of the outcrops, they can be easily recognized as the natural levee sediments. In the Diaokou channel, such sediments are mainly characterized by yellow silt or clayey silt and several-centimeter thick silty clay interlays ([Wang and Ye, 1990](#)). The median diameter of the levee sediment varies from 5.0Φ to 6.5Φ . Near the main channel valley, such subfacies is averagely 1.1 m in thickness, and almost composed by 100.0% silt with cross bedding and climbing bedding structures; on the flank away from the valley, the thickness of the subfacies decreases gradually and eventually truncated by the flooding depression deposits. The levee sediments usually overlie the sidebank or riverbed subfacies.

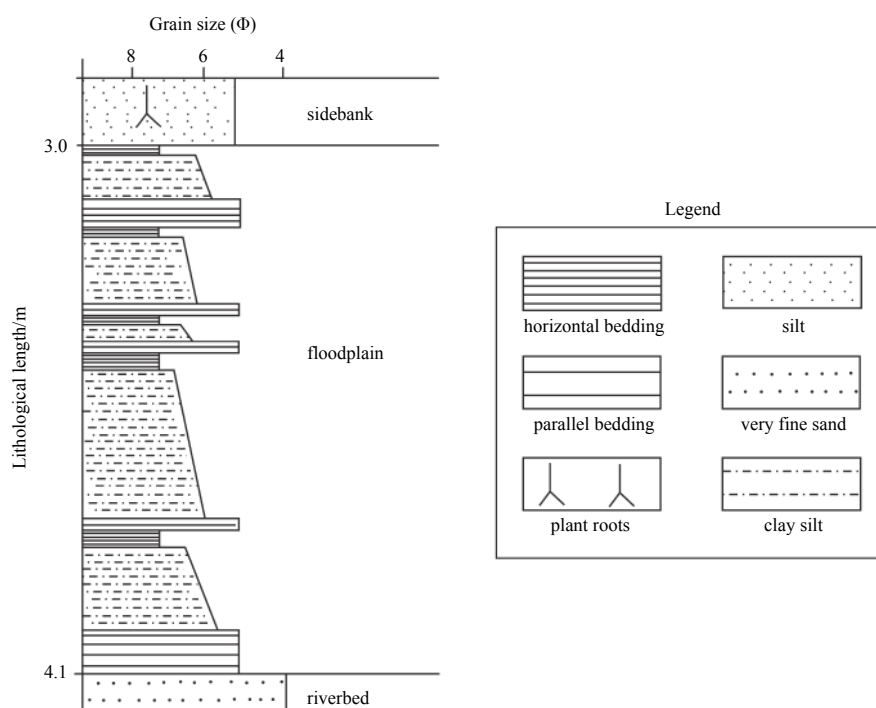


Fig. 5. Lithological characteristics of the flood plain subfacies in Core ZK 20-2.

3.2.2 Delta front facies

In the early stage of the Huanghe River rechanneling, the river was in the wandering state. The shallow water resulted in frequent change of the channel valley, and the location and scale of the river mouth estuary was not stable during that time, causing the frequent variation of the sedimentary environment as well as the hydrodynamic condition, which resulted in a complicated sedimentary delta front structure. In the borehole cores, the delta front facies in the Diaokou lobe deposits can be further divided into the sheet flood subfacies, river mouth bar subfacies, distal bar subfacies and delta lateral margin subfacies.

The sheet flood subfacies is characterized by silt and clayey silt with many sporadic-distributed sedimentary beddings and structures (e.g., parallel beddings, convolute beddings and flame structures). The down-core grain size distribution changes dramatically in this subfacies. The average content of sand (ranges from 2.6% to 70.2%), silt (ranges from 27.6% to 77.5%) and clay (ranges from 2.1% to 31.6%) are 15.7%, 69.9% and 14.4%, respectively. The median diameter ranges from 3.7Φ to 7.2Φ , and the standard deviation varies between 1.00Φ and 2.00Φ . We interpret it as the sheet flood subfacies because the identification of several thin beddings and structures as well as the superposition of the subfacies itself. Its underlying strata are usually the delta lateral margin subfacies or the distal bar subfacies that presumably formed in the Shenxiangou channel during the early stage of the Diaokou lobe evolution. The sheet flood subfacies is covered by the riverbed, the river mouth bar, and/or the distal bar deposits that probably accumulated along the estuary of the Diaokou channel.

The river mouth bar subfacies is mainly composed of very fine sand and silt with yellow-brown clayey silt laminations, and parallel beddings and small cross beddings are common. The average contents of sand, silt and clay are 29.0%, 64.0% and 8.0%, respectively. The median diameter ranges from 4.2Φ to 5.5Φ , and the majority vary between 4.2Φ and 4.8Φ . The sediments become finer off the estuary. The standard deviation varies from 1.10 to 1.80. Its lithological characteristics is mostly similar to the distal bar subfacies, but we can interpret it as the river mouth bar subfacies due to the water depth it developed, particularly the identification of plant root is an important marker for this subfacies.

The distal bar subfacies is usually observed on the distal (toward the sea) flank of the river mouth bar. The distal bar dips slightly toward the impounded basin. The sediment is finer than that in the estuary. It is mainly composed of silt with small amount of clay which forms several clayey silt layers. Vertically, the subfacies is covered by the river mouth bar subfacies, and they jointly consist of an upward-coarsening delta accretion sequence. The average contents of sand, silt and clay are 10.0%, 75.0% and 15.0%, respectively. The median diameter ranges from 4.5Φ to 6.5Φ with the majority varying from 5.0Φ to 5.5Φ . The standard deviation varies from 1.20 to 1.80. We observed interbeds of coarse-grained layers and fine-grained layers in the subfacies, which is probably caused by the migration of the estuary as well as the alternation of the flood and drought. A transition of such structure occurred as the clayey silt with silt laminations changed into silt with clayey silt laminations along the seaward direction of the river mouth.

The delta lateral margin subfacies is mainly composed of clayey silt and silty clay with silt layers that presumably driven by storm surge (Fig. 6). Since the Huanghe River is characterized by high sediment flux, the lateral margins were usually very thick and impacted seriously the storms. Thus, with the thickness and

grain size characteristics of this subfacies, we can interpret it as the delta lateral margin sediments. The average contents of sand, silt and clay are 4.0%, 70.0% and 26.0%, respectively; in the silt component, the coarse and fine silt accounts for 34.0% and 36.0% of the entire subfacies. Such grain size content probably indicates weak hydrodynamic conditions (e.g., Xu et al., 2013). The median diameter ranges from 5.2Φ to 7.6Φ with the majority are more than 6.0Φ . The standard deviation varies from 1.34 to 2.15, indicating poor to extremely poor sorting.



Fig. 6. Representative photograph of the delta lateral margin subfacies (ZK 20-2) (thickness unit: cm).

3.2.3 The prodelta facies

The prodelta subfacies, as its definition (e.g., Xue, 1994), is usually observed in the external part of the Diaokou lobe within 12–16 m water depth, below the wave base. The average contents of sand, silt and clay are 2.0%, 70.0% (30.0% of coarse silt and 40.0% of fine silt) and 28.0%, respectively. The median diameter ranges from 6.5Φ to 7.8Φ . The standard deviation varies from

1.58 to 1.95. The prodelta facies is characterized by red-brown to gray-brown clayey silt and silty clay with scattered light yellowish silt laminations; it is most probably originated from suspended fine-grained mud. The parallel beddings are common, and the thickness of such structure is usually over 3 m, indicating a high sedimentation rate and a weak dynamic condition. A significant color boundary is noticeable on the bottom of subfacies which separates the prodelta from the underlying dark-gray neritic facies (Fig. 7).

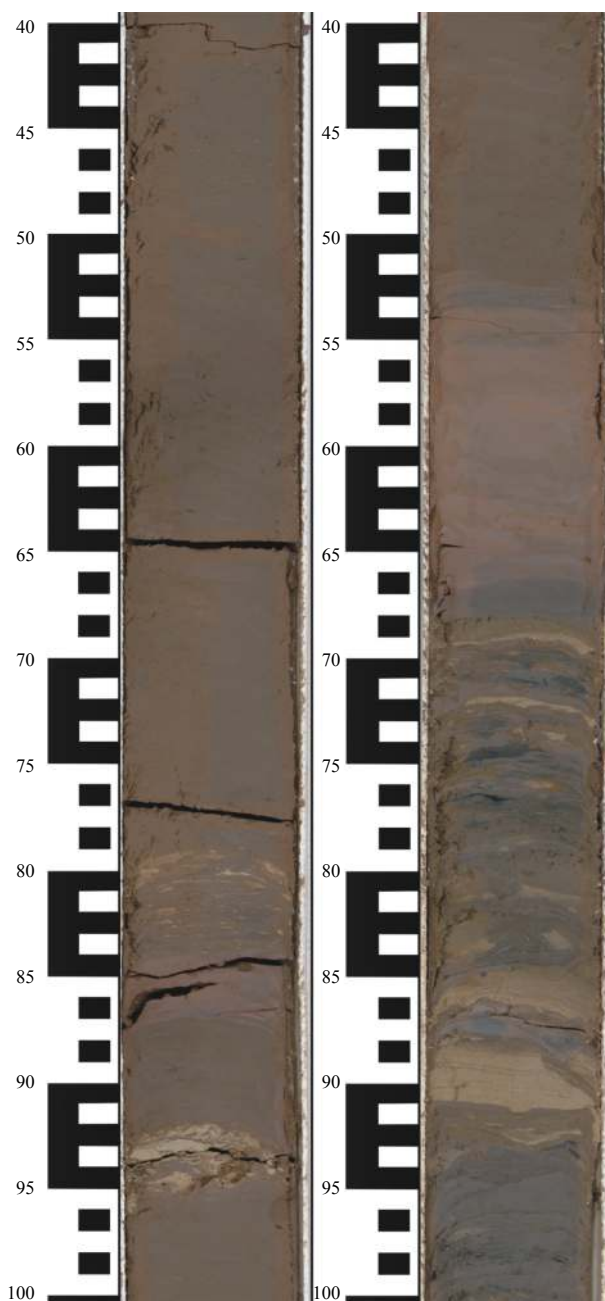


Fig. 7. Representative photograph of the prodelta facies and the shallow sea facies (ZK 20-1) (thickness unit: cm).

4 Discussion

4.1 Distribution and evolution of sedimentary facies/subfacies

The basement of the modern Huanghe River deltaic sediments is well defined in literatures (e.g., Liu et al., 2009, 2016;

Zhou, 2016). In the nearshore area, the basement is approximately 16 m below sea level, which consists of our interpretation of the dark gray neritic facies (SU2/DUC and SU3/DUD) (Fig. 2). Such facies are abundant with shell fragments (Liu et al., 2006); its thickness is usually more than 2.0 m and dips gradually seaward. As noted previously, the Diaokou lobe primarily received sediments from the Shenxianggou channel during 1934–1964, and from the Diaokou channel during 1964–1976. It also received fine-grained input from these channels during 1855–1889 and 1964–1976 (Xue et al., 2009; Wu et al., 2015). The Diaokou lobe experienced a complicated deltaic evolution, including sheet flooding, merging, braiding and swinging, and thus resulted in spatial distributions of facies/subfacies. In many analogs (Fan et al., 2001), the riverbed subfacies were mainly deposited along the river channel. The overbank subfacies is located on both sides of the riverbed subfacies, while the out of which, the flood plain subfacies is deposited. Generally, the proximal delta plain is comparatively narrow due to the stability of the river channel, while the distal delta plain is wide because the frequent swing of the distributary channel. The delta front subfacies and the prodelta subfacies are widely deposited in the subaqueous delta (Blair and McPherson, 2008). Since our dense seismic and core data covered the majority regions of the Diaokou lobe, both dip and strike distribution of the sedimentary subfacies (Fig. 8) are analyzed to construct a working hypothesized facies evolution of the Diaokou lobe (Purkait and Majumdar, 2014).

Along the dip direction (along the channel valley), we observed the sedimentary facies/subfacies are distributed as the riverbed, the river mouth bar, the distal bar and the prodelta from proximal to distal (AA' profile in Fig. 8). The evolutionary process of facies/subfacies is hypothesized as following.

In the early stage of the Huanghe River rechanneling during 1964 to 1966, the river was characterized by overflowing and/or wandering with a shallow and wide valley. A large amount of riverine inputs were deposited in the depressions and embayment of the channel valley, creating many sand sheet structures. At the breaking point, many fine-grained materials were deposited, forming a couple of subfacies associated with the sheet flooding. After 1967, the prior estuarine embayment was buried and a steep deltaic shoreface (deepest part is 12 m below the sea level) formed off the river mouth. With such process, the sands were transported to the distal part and formed the river mouth subfacies. Subsequently, the river mouth bar extended gradually seaward and covered on prodelta facies. The gradient of the delta front facies was steep (usually more than 0.002). Owing to the rapid extension of the river mouth, the delta lateral margin subfacies was formed in the circulation region of the estuary, and was mainly composed of fine-grained materials (Wang et al., 2010). During the flood period, the riverbed facies was deposited rapidly that contributed to the flooding of the main channel and thus resulted in the flood plain subfacies at the top of the Diaokou lobe.

Along the strike (perpendicular to the channel valley) direction, we interpreted (1) the fine sediment formed the first lobe that deposited during 1855–1889, (2) the fourth lobe that deposited during 1904–1929 and (3) the Shenxianggou lobe that formed during 1953–1964. They jointly formed the prodelta facies within water depth of 14–16 m below the sea level. Behind the prodelta facies, we observed the distal bar subfacies and the river mouth bar subfacies that are probably associated with the Shenxianggou River input. We interpreted the overlying structures as the Diaokou lobe deposits that have probably deposited since 1964. Since the majority accumulation spaces have been occupied by

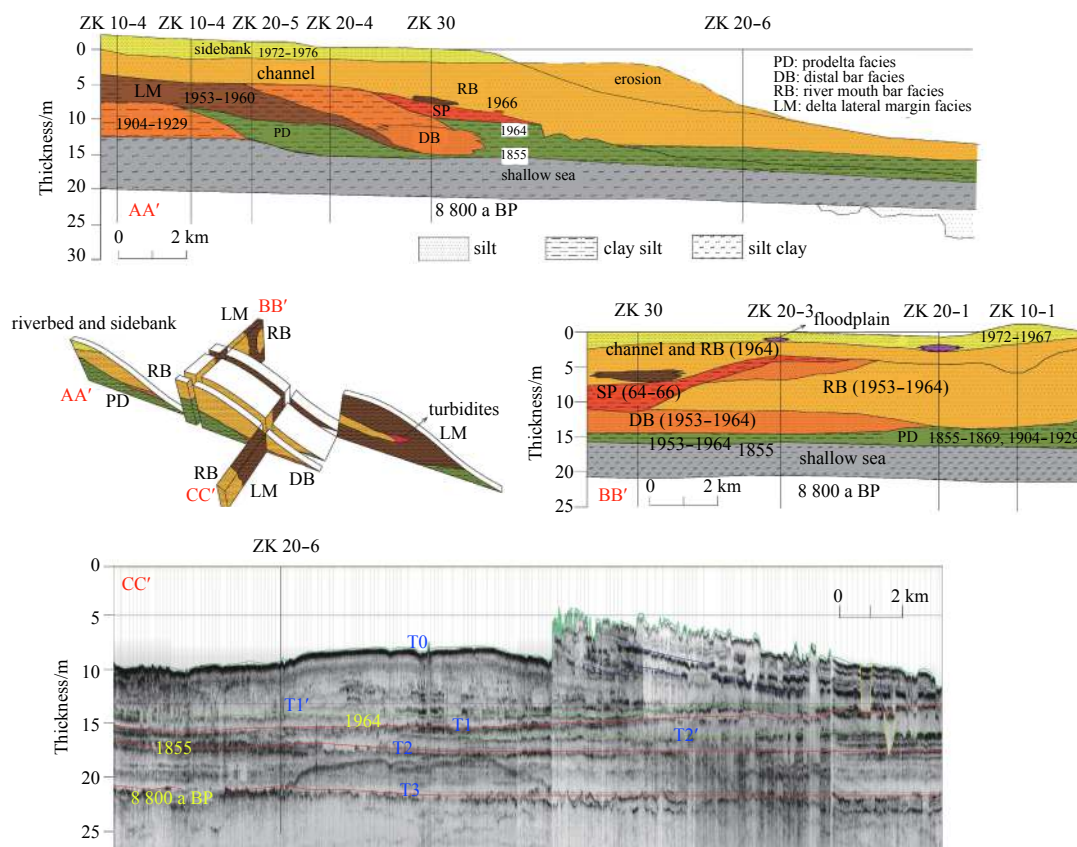


Fig. 8. Distribution of sedimentary facies/subfacies and sedimentary pattern in the Diaokou lobe.

the Shenxiangou deposits, the Diaokou lobe is comparatively thin (less than 5 m) on its southeast flank (BB' profile in Fig. 8). Within the subaqueous delta, the lobe is thin and its slope is gentle, probably because such lobe is far away from the estuary and therefore experienced strong erosion. We observed prodelta facies and delta lateral margin subfacies in the distal part while thicker distal bar subfacies and river mouth bar subfacies in the proximal area. Since the Diaokou channel was abandoned in 1976, we hypothesize that the external part of the Diaokou lobe has been seriously reworked and erode by marine forces (CC' profile in Fig. 8) (Gao et al., 2014a; Ma and Li, 2010).

An upward-coarsening structure was identified as the vertical distribution of facies/subfacies is marked by the prodelta facies (clayey silt) on the bottom, the delta front facies (silt) in the middle, and the subaerial delta plain facies (coarse silt with some very fine sands). Along the strike direction, the river mouth bar subfacies is absent in places probably due to the frequent swing of the river channel. Besides, the delta lateral margin subfacies accounted for the majority accumulation space, indicating the Diaokou lobe is dominated by fluvial impacts (Dalrymple et al., 2012).

4.2 Grain size distribution and sedimentation of the Diaokou lobe

The delta plain facies are usually approximately 5 m in thickness. It is a result of the fluvial vertical and lateral accretion and is characterized by a binary grain size structure. As noted previously, the median diameter of the delta plain facies varies from 3.5Φ to 5.5Φ , marked primarily by silty (particularly coarse silty) sediments, presumably caused by the low gradient and high sedimentation rate of the Huanghe River's downstream. As a result,

the riverbed lifted fast and frequently led to overflow flooding during the flood period. The rechanneling of distributary channel valley usually occurred every 2 a during the evolution of the Diaokou lobe (Cheng and Xue, 1997), leading to the formation and development of the overbank subfacies. After the channel was abandoned, the depression areas of the channel valley provided sufficient spaces for these clayey silts.

The delta front facies are characterized by the greatest sedimentation rate and the largest amount of heavy minerals in the delta system. As developed in neritic environment with a water depth between 3 and 16 m, the delta front facies can be further divided into two types of micro-sequences: (1) a vertical sequence of the river mouth bar, and (2) a vertical sequence of the estuarine sand sheet to delta lateral margin, and consisted primarily of distal bars, river mouth bars, and/or delta lateral margin sediments. As noted above, the median diameter of the delta front sediment ranges mainly from 4.5Φ to 5.5Φ , marked by coarse silt; the median diameter of the lateral margin sediments is greater (more than 6.0Φ), marked by clayey silt. We hypothesize that such grain size distribution is a result of the Huanghe River's high sedimentation rate in the river mouth areas. Given that the river mouth extends seaward and is dominated by a long and narrow beak shape, the riverine input sediments diffuse to the two side as such process continued, and finer sediments are deposited in these regions due to the weaker hydrodynamic conditions there.

The prodelta facies is characterized by clayey silt, with a median diameter from 6.5Φ to 7.8Φ . We hypothesize that such grain size characteristics is a result of special dense flow of the Huanghe River. Instead of the diffuse of the fine particles that ob-

served in other places, the dense flow of the Huanghe River presumably kept high density and suspended load even after the deltaic deposition. During the flooding period, the dense fluid extended into the prodelta and probably contributed to an approximately 3 m thick silty and clayey silty package.

4.3 Hydrodynamic environments of sedimentary facies

The Huanghe River hyperpycnal flow is a representative gravity flow, and thereby the most samples exhibit gravity flow characteristics in the C-M plot (the letters C and M denote the grain size corresponding to the cumulative 1% and the median grain size, respectively), i.e., all the spots located approximately paral-

lel to the C-M line (Fig. 9) (Heller and Dickinson, 1985; Wright et al., 1988). Besides, the C-M plot (e.g., Liu et al., 2015) indicates the Huanghe River Delta sediments also differ from the representative turbidity flow and mud flow (Nittrouer et al., 2012; Gao et al., 2014a; Maren, 2015). We can interpret from the C-M plot (Fig. 9) that (1) the transportations of the sediments from the riverbed, the river mouth bar and the sidebank subfacies are dominated by graded suspension, (2) those from the distal bars, the delta lateral margin subfacies and the prodelta facies are dominated by the uniform suspension, and (3) those from flood plains and sidebank (or overbank) subfacies are driven by the lenitic suspension. Graded suspension indicates that the grain sizes of the suspended sediments decrease from lower to upper, while uniform and lenitic suspension indicates that the grain size of suspended sediments turned smaller than their original status (Gao et al., 2014b). Thus, our observation indicates that the dynamic conditions weaken gradually offshore. With the progradation (seaward migration) of the Huanghe River Delta sediments, the transportation/migration modes of the sediments transform from grade suspension into uniform suspension.

The cumulative probability plot (Fig. 10) (e.g., Endo et al., 1996; Yuan et al., 2003) indicates that the Diaokou lobe sediments primarily consist of saltation and suspension components, while traction components are seldom observed. With the variation of the current strength and the water depth, we observed the saltation and suspension components start to mutually transfer. The sediments from all the subfacies/facies exhibit arch cumulative curves and the section points of the finer-grained materials are characterized by smooth curves instead of intersected lines, probably indicating turbulence and gravitational differentiation (Wang and Ye, 1990) are driven factors for the sedimentation of the suspended sediments. Since those factors have impacted less on the coarse-grained materials and only keep finer

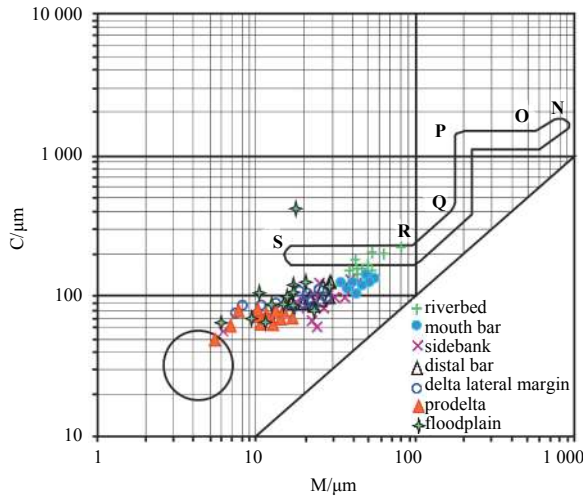


Fig. 9. C-M plot of the sediments from representative sedimentary facies/subfacies in the Diaokou lobe.

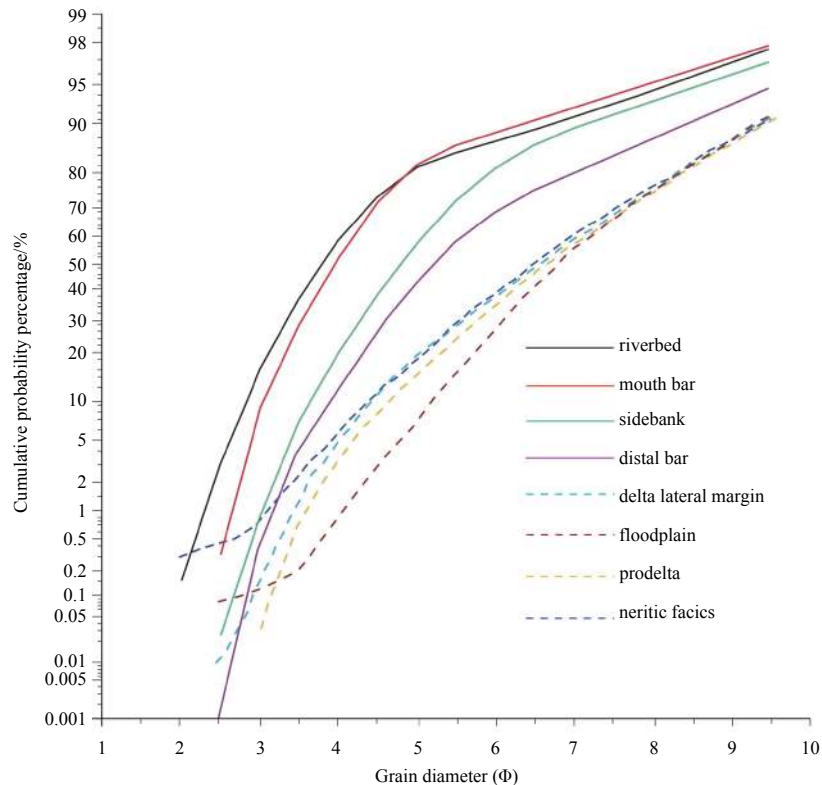


Fig. 10. The cumulative probability plot of the sedimentary facies/subfacies in the Diaokou lobe.

sediments suspending and drifting, the accumulative plot thereby exhibits steeper curves for the coarser components whereas gentle and smooth curves for the finer components.

On the basis of the grain size cumulative plot (Fig. 10) as well as the distribution plot (Fig. 11), the Diaokou lobe sediments can be further divided into two sedimentary types: (1) sediments de-

posited in strong hydrodynamic regimes (i.e., seriously impacted by fluvial forces), represented by the riverbed, river mouth bar, sidebank and distal bar subfacies; and (2) sediments deposited in comparatively weaker dynamic regimes, represented by the flood plain, delta lateral margin subfacies as well as the prodelta and neritic facies.

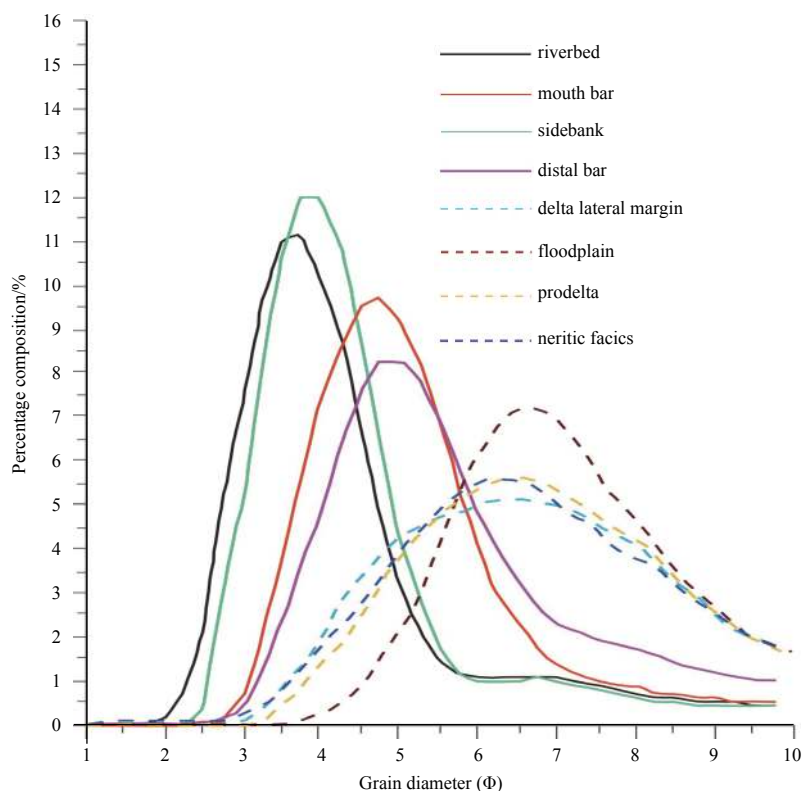


Fig. 11. The grain size distribution plot of the sedimentary facies/subfacies in the Diaokou lobe.

We observed in the cumulative plot (Fig. 10) that the sediments deposited in the strong dynamic regime (Type-1 sediments) are characterized by saltation and suspension loads. The saltation curves of those sediments are steeper with a dipping gradient of 60° – 68° , indicating that such sediments are well sorted and the distribution of the grain size is concentrated. The suspension curves are much gentler with a dipping gradient of 11° – 18° and the cumulative probabilities varied from 7.0% to 30.0%. The median grain size (Φ) increases gradually from the riverbed, river mouth bar, sidebank subfacies to the distal bar subfacies. Compared with sediments from other major river deltas (Lee Caldwell, 2013), the values of the fine materials' intercept points in the Diaokou lobe are much greater. The distribution plot (Fig. 11) reveals that Type-1 sediments are characterized by a prominent single-peak curve with coarse grain size, very leptokurtic and very coarse skewness, probably indicating that they are driven by unitary, strong dynamic regimes and/or their input sources are single and unitary (e.g., Visher, 1964).

Not surprisingly, Type-2 sediments (those deposited in weaker dynamic regimes) are dominated by clayey materials with the dipping gradient usually stayed in 45° (Fig. 10), presumably because they are deposited far away from the river mouth and the hyperpycnal flows turn weaker (Li et al., 1998b). In the distribution plot (Fig. 11), although they are also dominated by single-peak curves, the gentler peak-shape and mesokurtic and coarse

skewness indicate weak and uniform dynamic regimes.

5 Conclusions

The modern Huanghe River Delta is generally characterized by an upward-coarsening to ternary progradational delta, while a normal graded (downward-coarsening) bed sequence was observed at the edge of the delta. The grain size and lithological evidences indicate that the sedimentary mode of the Diaokou lobe can be divided into several categories: (1) vertically, the mode dominated by the river mouth bar and the delta lateral margin is observable, and (2) horizontally, the main steam valley and distributary valley types are observable. In the cross section, we identified the stack of river mouth bar, and delta lateral margin units. The front of the delta is characterized by fine-grained materials; the grain size analysis indicates that such area is dominated by fluvial regimes, and jointly influenced by the hyperpycnal flow and the marine forces.

The Huanghe River Delta plain is primarily comprised by fluvial lag sediments, sidebanks and overbanks subfacies, together with flood plains and natural levees subfacies. The delta front facies mainly consists of the river mouth bar and distal bar subfacies with delta margin deposits on its both flanks. With the progradation of the Huanghe River Delta during the regressive settings, we identified clayey-silt prodelta sediment, silty and high-moisture delta front sediments and silty to fine sandy delta plain

sediments from bottom to top. Although the Huanghe River keeps a wedge form like other deltas in the world, our survey within the Diaokou lobe indicates that the edge of the delta is dominated by a special clayey-silt delta lateral margin subfacies.

As a result of the high sedimentation rate and weak/lenitic hydrodynamic regime in the Huanghe River Delta, the sediments there are dominated by fine-grained materials and marked as clayey silt and silt. These sediments exhibit poor sorting, very coarse skewness and leptokurtic, indicating that the sedimentation in the Huanghe River Delta is dominated by single provenance that from the Huanghe River. Grain size distribution plots and accumulation plots indicate that the Diaokou lobe sediments are mainly composed of saltation and suspension components, but the lack of bedload components. The C-M plot indicates that (1) the Huanghe River hyperpycnal flow shows the suspension, transportation and sedimentation characteristics of gravity flow, and (2) the sediment transportation is primarily dominated by graded suspension, while uniform suspension and hydrostatic suspension are also observed in places. The strength of the hydrodynamic regime weakens gradually offshore from the riverbed, river mouth bar, sidebank, distal bar subfacies to the delta lateral margin and flooding plain subfacies.

References

- Allison M A, Khan S R, Goodbred Jr S L, et al. 2003. Stratigraphic evolution of the late Holocene Ganges-Brahmaputra lower delta plain. *Sedimentary Geology*, 155(3–4): 317–342
- Bianchi T S, Allison M A. 2009. Large-river delta-front estuaries as natural “recorders” of global environmental change. *Proceedings of the National Academy of Sciences of the United States of America*, 106(20): 8085–8092, doi: [10.1073/pnas.0812878106](https://doi.org/10.1073/pnas.0812878106)
- Blair T C, McPherson J G. 2008. Quaternary sedimentology of the Rose Creek fan delta, Walker Lake, Nevada, USA, and implications to fan-delta facies models. *Sedimentology*, 55(3): 579–615, doi: [10.1111/j.1365-3091.2007.00913.x](https://doi.org/10.1111/j.1365-3091.2007.00913.x)
- Cheng Guodong, Xue Chunting. 1997. *Sedimentary Environment and Sediments of the Modern Huanghe River Delta* (in Chinese). Beijing: China Geological Publishing House, 49–65
- Coleman J M, Wright L D. 1975. Modern river deltas: variability of processes and sand bodies. In: Broussard M L, ed. *Deltas: Models for Exploration*. Houston: Houston Geological Society, 99–150
- Dalrymple R W, Mackay D A, Ichaso A A, et al. 2012. Processes, morphodynamics, and facies of tide-dominated estuaries. In: Davis Jr R A, Dalrymple R W, eds. *Principles of Tidal Sedimentology*. New York: Springer, 79–107
- Endo N, Masuda F, Yokokawa M. 1996. Grain-size distributions of sediment carried by single transportation modes in an experimental microdelta system. *Sedimentary Geology*, 102(3–4): 297–304
- Fan Dejiang, Chen Zhangrong, Luan Guangzhong. 2001. Riverway sedimentation over the Yellow River Delta: II. The sedimentation mechanism of the Jianlin sediment bar. *Journal of Ocean University of Qingdao* (in Chinese), 31(2): 237–242
- Fan Hui, Huang Haijun, Zeng T Q, et al. 2006. River mouth bar formation, riverbed aggradation and channel migration in the modern Huanghe (Yellow) River delta, China. *Geomorphology*, 74(1–4): 124–136
- Flood R P, Orford J D, McKinley J M, et al. 2015. Effective grain size distribution analysis for interpretation of tidal-deltaic facies: West Bengal Sundarbans. *Sedimentary Geology*, 318: 58–74, doi: [10.1016/j.sedgeo.2014.12.007](https://doi.org/10.1016/j.sedgeo.2014.12.007)
- Folk R L, Ward W C. 1957. Brazos river bar: a study in the significance of grain size parameters. *Journal of Sedimentary Research*, 27(1): 3–26, doi: [10.1306/74D70646-2B21-11D7-8648000102C1865D](https://doi.org/10.1306/74D70646-2B21-11D7-8648000102C1865D)
- Gao Wei, Li Guangxue, Cao Lihua et al. 2014a. Formation mechanism of seafloor instability in the modern Yellow River Delta. In: *Proceedings of the Twenty-fourth International Ocean and Polar Engineering Conference*. Busan: ISOPE, 289–293
- Gao Wei, Li Guangxue, Wang Xiangdong, et al. 2014b. Sedimentary characteristics of the hyperpycnal flow in the modern Yellow River Delta. *Indian Journal of Geo-marine Sciences*, 43(8): 1438–1448
- Heller P L, Dickinson W R. 1985. Submarine ramp facies model for delta-fed, sand-rich turbidite systems. *AAPG Bulletin*, 69(6): 960–976
- Lee Caldwell R. 2013. *The effect of grain size on River Delta process and morphology* [dissertation]. Boston: Boston College University Libraries.
- Li Guangxue, Wei Helong, Han Yeshen, et al. 1998a. Sedimentation in the Yellow River delta, part I: flow and suspended sediment structure in the upper distributary and the estuary. *Marine Geology*, 149(1–4): 93–111
- Li Guangxue, Wei Helong, Yue Shuhong, et al. 1998b. Sedimentation in the Yellow River delta, part II: suspended sediment dispersal and deposition on the subaqueous delta. *Marine Geology*, 149(1–4): 113–131
- Li Guangxue, Zhuang Kelin, Wei Helong. 2000. Sedimentation in the Yellow River delta. Part III. Seabed erosion and diapirism in the abandoned subaqueous delta lobe. *Marine Geology*, 168(1–4): 129–144
- Liu Shihao, Feng Aiping, Du Jun, et al. 2014. Evolution of the buried channel systems under the modern Yellow River Delta since the last glacial maximum. *Quaternary International*, 349: 327–338, doi: [10.1016/j.quaint.2014.06.061](https://doi.org/10.1016/j.quaint.2014.06.061)
- Liu Shihao, Feng Aiping, Li Peiying, et al. 2015. High-resolution grain size distribution and evolution of the sediment-dynamic environment in the modern Yellow River Delta since the Latest Pleistocene. *Quaternary Sciences (in Chinese)*, 35(2): 291–306
- Liu Shihao, Li Peiying, Feng Aiping, et al. 2016. Seismic and core investigation on the modern Yellow River Delta reveals the development of the uppermost fluvial deposits and the subsequent transgression system since the postglacial period. *Journal of Asian Earth Sciences*, 128: 158–180, doi: [10.1016/j.jseae.2016.07.009](https://doi.org/10.1016/j.jseae.2016.07.009)
- Liu Jingpu, Milliman J D, Gao Shu, et al. 2004. Holocene development of the Yellow River's subaqueous delta, North Yellow Sea. *Marine Geology*, 209(1–4): 45–67
- Liu Jian, Saito Y, Wang Hong, et al. 2009. Stratigraphic development during the Late Pleistocene and Holocene offshore of the Yellow River Delta, Bohai Sea. *Journal of Asian Earth Sciences*, 36(4–5): 318–331
- Liu Shengfa, Zhuang Zhenye, Lü Haiqing, et al. 2006. The strata and environmental evolution in the late quaternary in the Chengdao area and modern Yellow River Delta coast. *Transactions of Oceanology and Limnology (in Chinese)*, (4): 32–37
- Ma Yanyan, Li Guangxue. 2010. Evolution history and trend of the modern Huanghe River Delta. *Acta Oceanologica Sinica*, 29(2): 40–52, doi: [10.1007/s13131-010-0020-4](https://doi.org/10.1007/s13131-010-0020-4)
- Maren D S V, Winterwerp J C, Vroom J. 2015. Fine sediment transport into the hyper-turbid lower Ems River: the role of channel deepening and sediment-induced drag reduction. *Ocean Dynamics*, 65(4): 589–605, doi: [10.1007/s10236-015-0821-2](https://doi.org/10.1007/s10236-015-0821-2)
- Meade R H, Moody J A. 2010. Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007. *Hydrological Processes*, 24(1): 35–49
- Necker F, Härtel C, Kleiser L, et al. 2005. Mixing and dissipation in particle-driven gravity currents. *Journal of Fluid Mechanics*, 545: 339–372, doi: [10.1017/S00222112005006932](https://doi.org/10.1017/S00222112005006932)
- Nitttrouer J A, Shaw J, Lamb M P, et al. 2012. Spatial and temporal trends for water-flow velocity and bed-material sediment transport in the lower Mississippi River. *Geological Society of America Bulletin*, 124(3–4): 400–414
- Pang Jiazhen, Jiang Mingxing. 2003a. On the evolution of the Yellow River estuary (Part II). *Transactions of Oceanology and Limnology (in Chinese)*, (4): 1–13
- Pang Jiazhen, Jiang Mingxing. 2003b. On the evolution of the Yellow River estuary (I)-I. Hydrographic characteristics. *Transactions of Oceanology and Limnology (in Chinese)*, (3): 1–13

- Purkait B, Majumdar D D. 2014. Distinguishing different sedimentary facies in a deltaic system. *Sedimentary Geology*, 308: 53–62, doi: [10.1016/j.sedgeo.2014.05.001](https://doi.org/10.1016/j.sedgeo.2014.05.001)
- Qiao Shuqing, Shi Xuefa, Saito Y, et al. 2011. Sedimentary records of natural and artificial Huanghe (Yellow River) channel shifts during the Holocene in the southern Bohai Sea. *Continental Shelf Research*, 31(13): 1336–1342, doi: [10.1016/j.csr.2011.05.007](https://doi.org/10.1016/j.csr.2011.05.007)
- Ramirez M T, Allison M A. 2013. Suspension of bed material over sand bars in the Lower Mississippi River and its implications for Mississippi delta environmental restoration. *Journal of Geophysical Research Earth Surface*, 118(2): 1085–1104, doi: [10.1002/jgrf.20075](https://doi.org/10.1002/jgrf.20075)
- Shi Peibing, Chu Qingzhong, Chen Xiaozhe, et al. 2016. Sedimentary facies and formation model of Honghe River delta. *Journal of Chongqing University of Science and Technology: Natural Sciences Edition* (in Chinese), 18(2): 18–21, 26
- Stevenson C J, Talling P J, Masson D G, et al. 2014. The spatial and temporal distribution of grain-size breaks in turbidites. *Sedimentology*, 61(4): 1120–1156, doi: [10.1111/sed.12091](https://doi.org/10.1111/sed.12091)
- Tye R S, Coleman J M. 1989. Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi Delta Plain. *Journal of Sedimentary Petrology*, 59(6): 973–996
- Visher G S. 1964. Fluvial processes as interpreted from ancient and recent fluvial deposits. *AAPG Bulletin*, 48(2): 550
- Visher G S. 1969. Grain size distributions and depositional processes. *Journal of Sedimentary Petrology*, 39(3): 1074–1106
- Wang Houjie, Bi Naishuang, Wang Yan, et al. 2010. Tide-modulated hyperpycnal flows off the Huanghe (Yellow River) mouth, China. *Earth Surface Processes and Landforms*, 35(11): 1315–1329, doi: [10.1002/esp.2032](https://doi.org/10.1002/esp.2032)
- Wang Houjie, Yang Zuosheng, Li Yunhai, et al. 2007. Dispersal pattern of suspended sediment in the shear frontal zone off the Huanghe (Yellow River) mouth. *Continental Shelf Research*, 27(6): 854–871, doi: [10.1016/j.csr.2006.12.002](https://doi.org/10.1016/j.csr.2006.12.002)
- Wang Aihua, Ye Zhizheng. 1990. Framework, developing processes and sedimentary model of the modern Huanghe River delta. *Marine Geology & Quaternary Geology* (in Chinese), 10(1): 1–12
- Wells J T, Coleman J M. 1987. Wetland loss and the subdelta life cycle. *Estuarine, Coastal and Shelf Science*, 25(1): 111–125, doi: [10.1016/0272-7714\(87\)90029-1](https://doi.org/10.1016/0272-7714(87)90029-1)
- Wright L D, Wiseman W J, Bornhold B D, et al. 1988. Marine dispersal and deposition of Yellow River silts by gravity-driven underflow. *Nature*, 332(6165): 629–632, doi: [10.1038/332629a0](https://doi.org/10.1038/332629a0)
- Wright L D, Yang Z S, Bornhold B D, et al. 1986a. Hyperpycnal plumes and plume fronts over the Huanghe (Yellow River) delta front. *Geo-Marine Letters*, 6(2): 97–105, doi: [10.1007/BF02281645](https://doi.org/10.1007/BF02281645)
- Wright L D. 1985. River deltas. In: Davis R A, ed. *Coastal Sedimentary Environments*. New York: Springer, 25–36
- Wright L D, Yang Z S, Bornhold B D, et al. 1986b. Short period internal waves over the Huanghe (Yellow River) delta front. *Geo-Marine Letters*, 6(2): 115–120, doi: [10.1007/BF02281647](https://doi.org/10.1007/BF02281647)
- Wu Xiao, Bi Naishuang, Kanai Y, et al. 2015. Sedimentary records off the modern Huanghe (Yellow River) delta and their response to deltaic river channel shifts over the last 200 years. *Journal of Asian Earth Sciences*, 108: 68–80, doi: [10.1016/j.jseaes.2015.04.028](https://doi.org/10.1016/j.jseaes.2015.04.028)
- Xu Taoyu, Shi Xuefa, Wang Guoqing, et al. 2013. Sedimentary facies of the subaqueous Changjiang River delta since the late Pleistocene. *Chinese Journal of Oceanology and Limnology*, 31(5): 1107–1119, doi: [10.1007/s00343-013-2281-1](https://doi.org/10.1007/s00343-013-2281-1)
- Xue Chunting. 1994. Comparison of two classifications of clastic sediments. *Marine Geology & Quaternary Geology* (in Chinese), 14(2): 109–113
- Xue Chunting, Ye Siyuan, Gao Maosheng, et al. 2009. Determination of depositional age in the Huanghe Delta in China. *Haiyang Xuebao* (in Chinese), 31(1): 117–124
- Yamaguchi M, Sugai T, Fujiwara O, et al. 2005. Depositional process and landform of the Kiso River Delta, reconstructed from grain size distributions, and accumulation rate of sediment cores. *The Quaternary Research*, 44(1): 37–44, doi: [10.4116/jaqua.44.37](https://doi.org/10.4116/jaqua.44.37)
- Yang Zuosheng, Ji Youjun, Bi Naishuang, et al. 2011. Sediment transport off the Huanghe (Yellow River) delta and in the adjacent Bohai Sea in winter and seasonal comparison. *Estuarine, Coastal and Shelf Science*, 93(3): 173–181, doi: [10.1016/j.ecss.2010.06.005](https://doi.org/10.1016/j.ecss.2010.06.005)
- Yuan Jing, Du Yumin, Li Yunnan. 2003. Probability cumulative grain size curves in terrigenous depositional environments of the Paleogene in Huimin Sag. *Petroleum Exploration and Development* (in Chinese), 30(3): 103–106
- Zhou Yongqing. 1987. Characteristic of the channel shifting and its mechanism of formation in the Yellow River Delta. *Marine Geology & Quaternary Geology* (in Chinese), 7: 41–46
- Zhou Liangyong, Liu Jian, Saito Y, et al. 2016. Modern sediment characteristics and accumulation rates from the delta front to prodelta of the Yellow River (Huanghe). *Geo-Marine Letters*, 36(4): 247–258, doi: [10.1007/s00367-016-0442-x](https://doi.org/10.1007/s00367-016-0442-x)
- Zhu Xiaomin. 2008. *Sedimentary Petrology* (in Chinese). 4th ed. Beijing: China Petroleum Industry Press, 64–79