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Sediment distribution characteristics and environment evolution within 100 years in western Laizhou Bay, Bohai Sea, China

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A B S T R A C T

This study is about the reconstruction of fluvial origins based on the grain size distribution of sediment deposits in the western Laizhou Bay, Bohai Sea, China. Thirteen sediment cores were selected to research sediment characteristics using the Sahu discriminant formula, *C-M* diagram, and Folk method. The results showed: (1) Bounded by the Guangli River estuary, the north sediment was affected by the water and sand flowing from the Yellow River during different periods. The south sediment came from multi-source rivers under the influence of the Xiaoqing River, Mihe River, and other coastal rivers; (2) the deposited sediments were dated by a clear historical record of the branched channel oscillation combined with the characteristics of the diversion channel, erosion, and regression. The subaqueous delta overlapped during several Yellow River channel runs (1897–1904, 1929–1934, 1938–1947, 1947–1953, 1976–1996) and the deposited sediment facies changed (the north tidal flat-abandoned subaqueous delta-lateral delta-delta front); (3) the deposited sediment characteristics can be revealed by studying the branched diversions of the Yellow River and coastal multi-rivers of the past one hundred years.

1. Introduction

Multisource rivers play important roles in transforming deposited sediment characteristics in the coastal zone. The flux of small and medium rivers, especially those of small mountainous river systems (SMRS), may have more influence on the sedimentary environment in coastal regions (Wheatcroft RA et al., 2010). The role of small and medium-sized rivers in the global cycles is of great concern to many international geoscience cooperation research projects (Kremer HH, 2004). They primarily study material migration, sedimentation, and the hydrodynamics of small and medium-sized rivers (Zhang J, 2011). Currently, studies of the rivers mainly focus on the Mekong River Basin (Liu JP et al., 2017), the western coast of the United States (Hatten JA et al., 2012), the Taiwan Island of China (Hsiung KH and Saito Y, 2017) and the eastern coast of China's Zhejiang Province (Xue CF et al., 2018).

Grain-size characteristics are usually used to reflect the sediment migration pattern because it can comprehensively explain the material source and sedimentary dynamic environment (Li T and Li TJ, 2018). There are basic marine surveys and researches but they primarily focus on the formation and evolution of the Yellow River delta, branched channel changes and sedimentation (Cui BL and Li XY, 2011; Bi NS et al., 2014; Qiao SQ et al., 2011; Wang HJ et al., 2006). The characteristics of hydrology, deposition, and coastal were changed in the Yellow River delta based on core record (Chen GD et al., 1986; Yang HR and Wang J, 1990; Pang JZ and Jiang MX, 2003). The radionuclides (^{210}Pb and ^{137}Cs) in deltaic sediment have been widely used to study modern sediment deposition, dispersal, and sedimentary processes (Kuehl SA et al., 1996; Palinkas CM and Nittrouer CA, 2007). Zhou LY et al. (2016) analyzed sediment characteristics and accumulation rates from the delta front to the prodelta of the Yellow River. However, stable sedimentary conditions (such as stable material sources, stable accumulation rates) and an unaltered sedimentary environment are required in practical application. The deposition rate can't calculate in the blank deposition area

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where it was abandoned (Xue CT et al., 2009). It is hard to confirm the dating but it is directly determined by combining historical geography with sedimentary geology at this swinging estuary.

The sedimentary characteristics of the multi-source river delta in the Laizhou Bay have been preliminarily recognized since the Holocene period (Xue CT and Ding D, 2008). This doesn 't ignore the sedimentary contributions of small and medium-sized rivers (such as the Guangli River, the Xiaoqing River, and the Mihe River) to the west of Laizhou Bay except for the Yellow River (Gao MS et al., 2019; Yin P et al., 2018). The sedimentary environment evolution of the Yellow River delta is restricted by the sediment condition and the marine hydrodynamics (Peng J and Chen CL, 2009; Wang F et al., 2019). There will be a comprehensive understanding of the deposited sedimentary evolution in the western Laizhou Bay under the influence of small and medium-sized rivers. In this study, the authors selected thirteen cores to research the deposited sediment characteristics and reconstructed sediment distribution patterns in the western Laizhou Bay.

2. Regional background

The study area is located in the western Laizhou Bay (Fig. 1; 118°57′N–119°21′N, 37°05′E–37°45′E) between the branches of the Yishu Rift. Since the Neogene, this region turns into a stable period, with few tectonic movements and peaceful deposition (Yu Z et al., 2008). In terms of physiognomy, the western of Laizhou Bay is classified as a coastal alluvial plain/marine deposition plain. Outcropped strata in this area mainly comprise of Holocene and Pleistocene alluvial and marine sediments. The thickness of the sedimentary layers increases gradually from west to east. There are clayey silt sedimentary areas of the southern lateral in the modern Yellow River delta and silty sedimentary areas of multiple rivers in the area. Some coastal rivers were also developed, such as the Xiaodao River, Yongfeng River, Guangli River, Zimai River, Xiaoqing River, Mihe River, and the Bailang River (from north to south). The clayey silt of the delta lateral is distributed on both sides of the silt (delta front). The younger delta front silt overlays the older delta lateral (interdistributary bay) with clayey silt and the younger delta lateral clayey silt overlays the older delta front silt simultaneously (Xue CT et al., 2009).

The distributary channel of the modern Yellow River delta has undergone 12 diversions since 1855 (Ye QH et al., 2007). The main distributary channel flowed to the western Laizhou

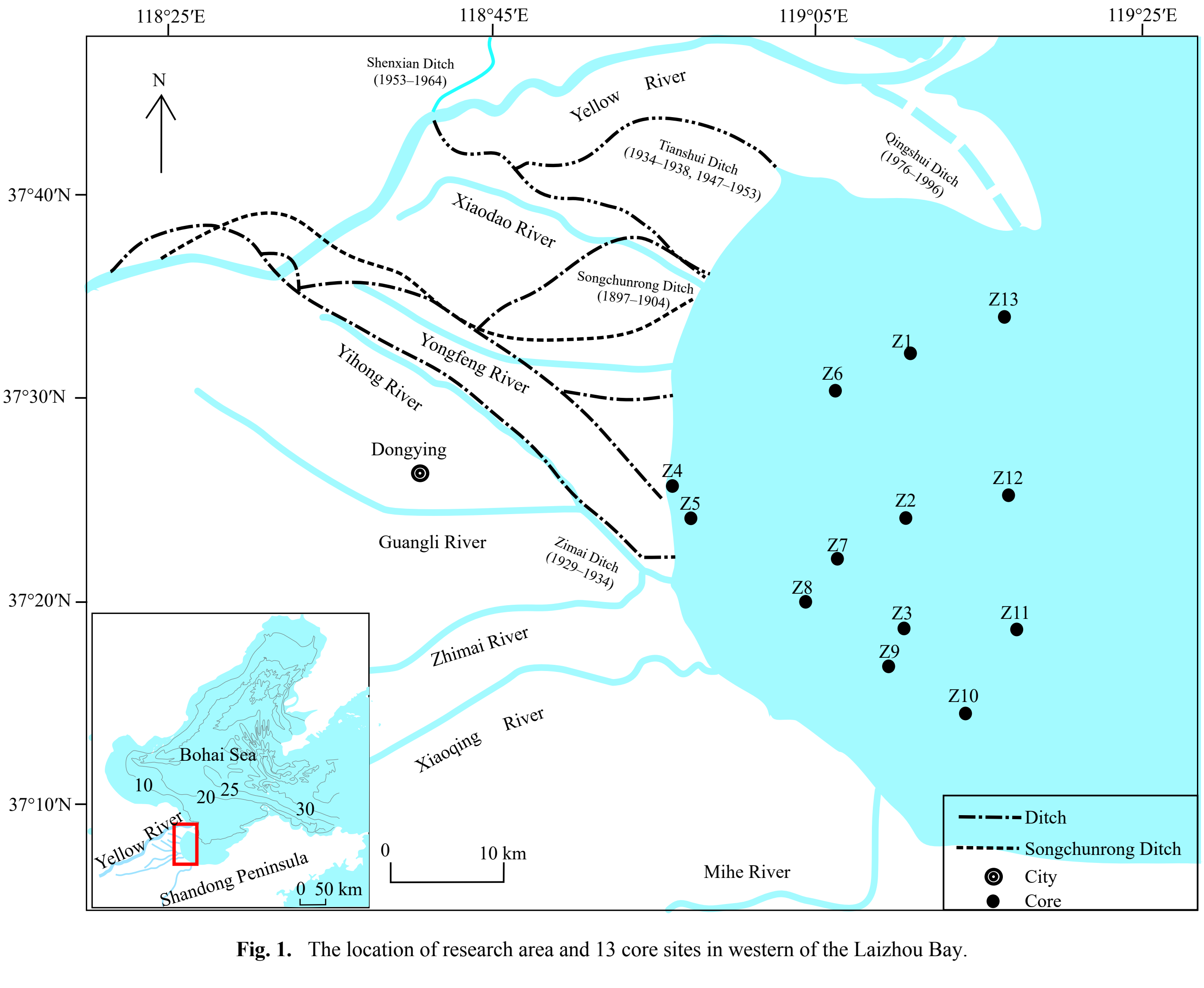

Fig. 1. The location of research area and 13 core sites in western of the Laizhou Bay.

Bay including the Zimai Ditch (1929 –1934), the Songchunrong Ditch (1897–1904), the Tianshui Ditch (1934–1938, 1947–1953) and the Qingshui Ditch (1976–1996). During these periods, the diversion channel of the Yellow River was changed to flow northward [the Diaokou River (1964–1976), and the Shenxian Ditch (1953–1964)]. The Yellow River was diverted to the east in 1976 (Fig.1).

There are two kinds of coastal rivers in the western Laizhou Bay. One is the natural river as represented by the Xiaoqing River and Mihe River. The other is represented by artificial rivers such as the Guangli River [a diversion channel of the Yellow River (1929 –1934)]. Then the river was artificially converted to a channel with flood controlling and drainage (Yang RM et al., 2005). There are tributaries (such as the Yihong River and the Zimai River) that flow down the Guangli River. As per earlier research (Xue CT et al., 2009), the sedimentary environment of the southern Laizhou Bay is more affected by the Xiaoqing River (heavy runoff) and the Mihe River (high sediment discharge). The central part of Laizhou Bay is covered with aggradational plains by a diversity of sources and complex sedimentary environments (Qin YS et al., 1985).

3. Materials and methods

Thirteen cores (Z1 –Z13) were supported by China Geological Survey project (GZH201200505) in 2013 –2015 (Fig.1; Table 1), and the sedimentary samples in the cores were collected below the sediment surface using fiber-reinforced plastic graduated tubes (with an inner diameter of 100 mm; and a wall thickness of 5 mm). During sample collections, a hand-held global positioning system (GPS) was used to identify the location of sites.

Sediment cores are 1 –3 m in length. The cores were strictly sealed after collection and transported and stored vertically. Half of each core was preserved, and the remaining half was sampled at 2 cm intervals. The sample grain size was analyzed with a Mastersizer 2000 laser grain size analyzer and divided based on the Udden-Wentworth grain size standard (McManus J, 1988). The measurement range is 0.02–2000 μm.

Quality assurance and quality control were assessed in duplicate with blank samples and standard reference materials. The quality of the analytical procedures was tested by recovery measurements based on the Chinese national geo-standards GBW07309 and GBW07429. Sample tests were completed at the Marine Geological Experimental Testing Center, Ministry of Natural Resources, China. The measurement accuracy was ±5%.

The sedimentary content of particle sizes was calculated by sample test results of sand (<4 Φ), silt (4–8 Φ), and clay (>8 Φ). A triangular diagram of the "sand-silty-clay" distribution in sediment was prepared by Folk Method (Folk RL et al., 1970). The cumulative content and corresponding particle size of the sample grain size curve was extracted, and the cumulative probability curve was plotted. Some important parameters such as Mean grain size (M_z), Sorting coefficient (S_o), Skewness (S_k), and Kurtosis (K_g) were calculated by Folk and Ward formulas (Folk RL and Ward WC, 1957).

Table 1. Location and sample records of 13 columnar deposits in the western Laizhou Bay.

Sample	Longitude/ N	Latitude/ E	Water depth/ m	Length/ cm	Sampling time
Z1	119°10′34″	37°31′53″	6	250	Aug-Nov, 2013
Z2	119°10′19″	37°23′47″	8	268	Aug-Nov, 2013
Z3	119°10′07″	37°18′21″	4	306	Aug-Nov, 2013
Z4	118°55′47″	37°25′22″	0	120	Sep-14, 2015
Z5	118°56′57″	37°23′47″	0	108	Sep-14, 2015
Z6	119°05′53.27″	37°30′00.51″	5	203	Jul-Dec, 2015
Z7	119°05′59.40″	37°21′46.42″	5	191	Jul-Dec, 2015
Z8	119°04′00.90″	37°19′39.86″	2	142	Jul-Dec, 2015
Z9	119°09′12.02″	37°16′28.72″	4	100	Jul-Dec, 2015
Z10	119°14′02.98″	37°14′11.60″	2	115	Jul-Dec, 2015
Z11	119°17′10.39″	37°18′15.42″	6	159	Jul-Dec, 2015
Z12	119°16′39.70″	37°24′56.54″	8	190	Jul-Dec, 2015
Z13	119°16′17.05″	37°33′38.26″	9	101	Jul-Dec, 2015

4. Results

The grain size distributions of sedimentary samples which are plotted in the triangular diagram are relatively concentrated in four areas (Fig. 2): Lateral delta (Z1, Z6, Z13), northern tidal (Z4, Z5), central (Z2, Z7, Z12), and southern section (Z3, Z8, Z9, Z10, and Z11). There are mainly three deposited sediment types: Silt, sandy silt, and silty sand (Fig. 3). According to the distribution of the grain size and main parameters (Figs. 2, 3), it can be described grouping sections in sediment cores by their geographical location (lateral delta, northern tidal, central, southern section) and some calculated sediment parameters such as M_z, S_o, S_k, and K_g (Table 2).

The lateral delta area: Grain sizes of the column cores (Z1, Z6, and Z13) were dominated by silt and downward-fining vertically in the modern Yellow River estuary. The grain

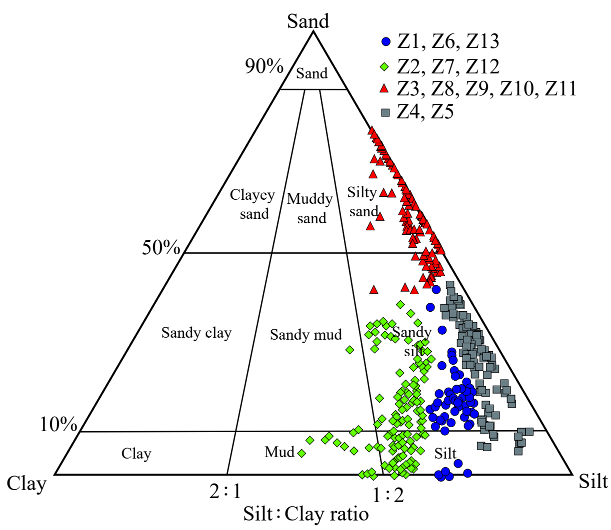

Fig. 2. Triangular diagram of sand-silt-clay in column samplings.

parameter values of S_o, S_k, K_g were 1.6, 0.4, and 1.2, respectively.

The northern tidal area: Grain size of the column core (Z4, Z5) dominated by sandy silt and changed periodically with depth in the Guangli estuary. The grain parameter values of S_o, S_k, K_g were 1.6, 0.4, and 1.2, respectively. The ranges in Z4 were divided into three sections with a depth of 55 cm and 92 cm, and the ranges in Z5 were divided into four sections with a depth of 30 cm, 52 cm, and 86 cm.

The central area: Grain size of the column core (Z2, Z7, and Z12) dominated by silty and clayey with sand content in certain depths. The highest values of sandy content were 80–140 cm depth in Z12, 100–130 cm in Z2, and the lowest value was 150 cm depth in Z7.

The southern section area: Deposited sediment in core Z3, Z8, Z9, Z10, and Z11 was dominated by silty sand on the southern coast. The main particle parameters remained stable except for individual depths.

To verify the relationship between coastal rivers and marine deposited sediments, representative columnar samples

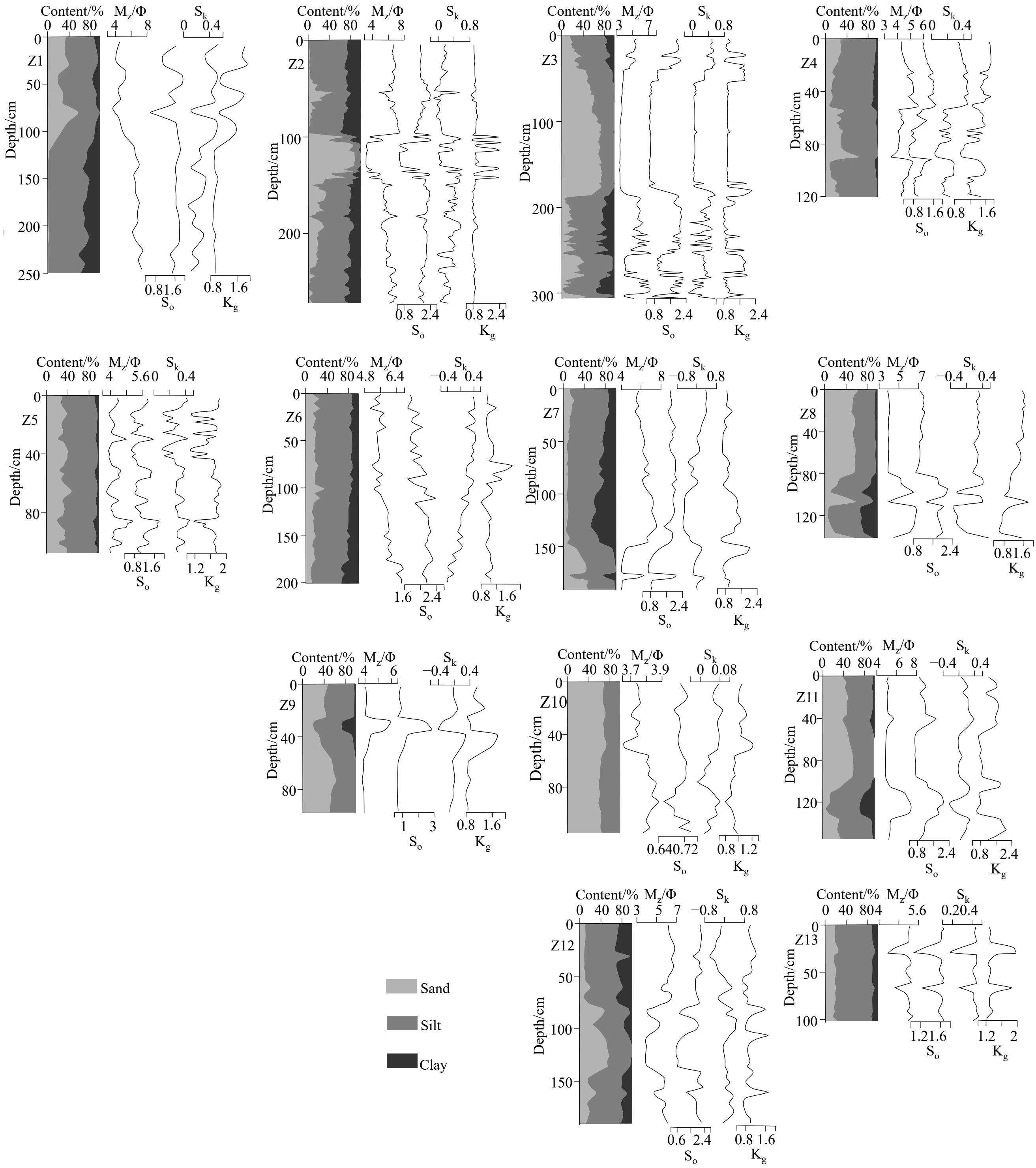

Fig. 3. Vertical grain size distribution and the main parameters in 13 cores.

Table 2. Statistics result of the main parameter in core samples.

Site	Core	Value	Sand/%	Silt/%	Clay/%	M_z	S_o	S_k	K_g	Water depth/m	Source
Delta lateral	Z1	Max	61.03	79.44	42.51	7.59	1.92	0.53	1.96	–4– –8	Yellow River
		Min	0	38.97	0	3.59	0.61	0.05	0.85		
		Average	14.14	66.13	19.73	5.804	1.59	0.31	1.18		
	Z6	Max	35.71	74.29	34.44	6.77	2.40	0.46	1.65		
		Min	7.83	51.16	10.02	5.04	1.65	–0.41	0.80		
		Average	15.80	65.83	18.36	5.79	2.02	0.14	1.05		
	Z13	Max	26.76	74.29	12.46	5.38	1.68	0.48	1.97		
		Min	13.90	66.73	4.37	4.36	1.06	0.16	1.19		
		Average	19.11	70.70	10.19	5.13	1.56	0.41	1.38		
North tidal	Z4	Max	66.38	86.68	14.24	5.63	1.74	0.48	1.76	0– –4	Guangli estuary
		Min	5.69	32.47	0.08	3.48	0.60	0.04	0.96		
		Average	21.19	72.88	5.93	4.58	1.16	0.28	1.45		
	Z5	Max	48.75	72.15	12.73	5.22	1.84	0.46	1.88		
		Min	18.52	48.58	2.22	3.79	0.62	0.10	1.05		
		Average	32.99	62.34	4.67	4.19	1.07	0.30	1.62		
Southern section	Z3	Max	77.31	78.89	39.37	7.42	2.25	0.63	2.25	–2– –6	Xiaoqing River, Mihe River
		Min	0.23	22.69	0	3.34	0.51	–0.12	0.73		
		Average	41.81	48.58	9.61	4.52	1.24	0.21	1.13		
	Z8	Max	63.43	66.34	33.58	6.83	2.18	0.55	1.86		
		Min	5.47	31.84	2.47	3.87	0.86	–0.36	0.61		
		Average	42.38	46.49	11.13	4.72	1.41	0.18	1.29		
	Z11	Max	60.21	66.68	29.50	7.54	2.17	0.40	2.11		
		Min	6.17	39.79	0	4.84	0.65	–0.26	0.65		
		Average	40.55	52.46	6.99	5.45	1.16	0.11	1.25		
	Z9	Max	64.32	62.74	26.91	6.06	2.95	0.31	1.81		
		Min	19.28	35.68	0	3.79	0.68	–0.43	0.80		
		Average	44.47	50.63	4.91	4.27	1.09	–0.03	1.05		
	Z10	Max	75.47	42.06	0	3.89	0.75	0.09	1.23		
		Min	57.94	24.53	0	3.65	0.66	–0.02	0.79		
		Average	66.02	33.98	0	3.78	0.71	0.05	0.98		
The central	Z2	Max	89.53	76.34	40.52	7.49	2.45	0.62	2.63	–6– –8	All rivers
		Min	0	10.47	0	3.11	0.50	–0.16	0.71		
		Average	23.06	55.11	21.82	5.76	1.85	0.22	0.97		
	Z7	Max	48.53	73.37	49.63	7.60	2.08	0.47	2.06		
		Min	5.22	45.15	0	4.01	0.65	–0.57	0.65		
		Average	16.59	60.77	22.64	5.92	1.65	–0.06	1.01		
	Z12	Max	58.17	91.44	36.07	6.84	2.44	0.48	1.77		
		Min	8.56	41.83	0	3.88	0.72	–0.64	0.67		
		Average	25.22	57.90	16.88	5.50	1.77	0.03	0.98		

were selected to identify the sediment environment using Sahu Discriminant Formula (Sahu BK, 1964) by the size analysis of clastic sediments. The value of the discriminant parameter (Y) can be computed by the following Eq. (1).

$$Y = 0.285M_Z - 8.76S_o - 4.893S_k + 0.048K_g \qquad (1)$$

where Y is the value of the discriminant parameter.

When Y>−7.4190, represents neritic deposit. Y<−7.4190, represents a fluvial deposit. By data statistics, Y (the average value of neritic sediment) was −5.3160, and Y (the value of fluvial deposit) was −10.4418. The discriminant value is shown in vertical distribution parameters from 13 cores (Table3; Fig. 4).

The values (−32.18, −22.74, and −35.14) of column cores (Z13, Z1, and Z6) in delta lateral were lower than the average fluvial deposit (−10.44). It appeared an extreme value (Y> −7.419) at a depth of 80 cm (Z1), indicating that the Yellow River was once a short cut (Fig. 4a). Close to fluvial deposit values, Z4 and Z5 changed in fluvial and neritic sediment, indicating that it is related to the north tidal flat which used to be the channel of the Yellow River entering the Bohai Sea (1897–1904, 1929–1934) and then the river flowed north (Fig. 4b). The calculated value (Z8, Z9, and Z10) according to 13 cores in Eq. (1) was close to fluvial deposit values, but it changed under 80 cm in Z8 indicating that the sediment transported of coastal rivers (such as the Xiaoqing River, the Mihe River) (Fig. 4c).

The sedimentary accumulation curve can explain the relationship between sediment size and transport mode (Saito Y, 2010). *C-M* patterns were proposed by Passega as a

Table 3. Identification values of neritic sediment and fluvial deposit.

Coastal river	Core	*Y*
Yellow River	Z13	–32.1887
	Z1	–22.7472
	Z6	–35.1430
Guangli River	Z4	–12.7609
	Z5	–11.0840
Xiaoqing River	Z8	–18.4398
Mihe River	Z9	–12.8650
Bailang River	Z10	–3.5441
Y=–5.3167 (average value of neritic sediment)		
Y=–10.4418 (average value of fluvial deposit)		

geological tool (Passega R, 1964), which can reflect the relationship between the maximum size and the median size (Fig. 5). The grain size distributions are used for the analysis of sedimentary dynamics which is used for studying hydrodynamic conditions during sedimentary processes although the result is unambiguous, while the picture in Fig. 5 is open to interpretation. Among these, *C* is the particle size corresponding to 1% content on the accumulation curve, representing the maximum energy (Initial Energy) when the hydrodynamic starts to transport sediments. *M* is the particle size corresponding to 50% content on the cumulative curve, representing the average energy (Average Energy) of hydrodynamic forces. The results showed that the value of *M* remained unchanged whereas *C* changed significantly, indicating the average energy source was relatively stable under the initial energy changing in lateral of the modern Yellow River estuary. It could be explained that the northern tidal of the Guangli estuary had homogenous suspension characteristics by *C*, *M* relatively concentrated, and initial and average energy stable. The values of *C* and *M* in the southern Laizhou Bay were roughly equivalent and had both the characteristics of the homogenous and graded suspension. *C* and *M* in the central shallow sea area changed greatly, indicating that the initial and average water energy changed significantly.

5. Discussion

5.1. Sediment model

Grain characteristics and accumulation curves are usually used to distinguish and classify the sedimentary environment. The sedimentary records are constructed by the frequent oscillations of diversion channels, sedimentary, and erosion interaction characteristics in this study. The sedimentary distribution patterns were reconstructed to identify the sedimentary evolution characteristics in the western Laizhou Bay (Fig. 6).

In the northern section (“Z4-Z6-Z1-Z13 ”), sediment changed from silty sand and silt to clayey silt. The distribution of clay silt was relatively concentrated in the weak sedimentary dynamic area (lateral delta). This suggested the subaqueous delta overlapped during five diversions of the Yellow River (1897–1904, 1929–1934, 1938–1947, 1947–1953, 1976–1996) and the sedimentary environment change (north tidal flat-abandoned subaqueous delta-lateral delta-delta front).

In the southern section (“Z5-Z8-Z9-Z10 ”), sediments changed from the interphase of silty sand and clayey silt to the upper coarse and lower fine (in the upper segment), and gradually coarse (the lower segment, from clayey silt to silty sand). The southern sediments came from different multi-source rivers under the influence of the Xiaoqing River, the Mihe River, and other coastal rivers.

Clays’ content increased from Xiaoqing estuary to central of Laizhou Bay (“Z8-Z7-Z2-Z12 ”), but the sand content increased at 80–150 cm depth. The frequency curve had 2–3

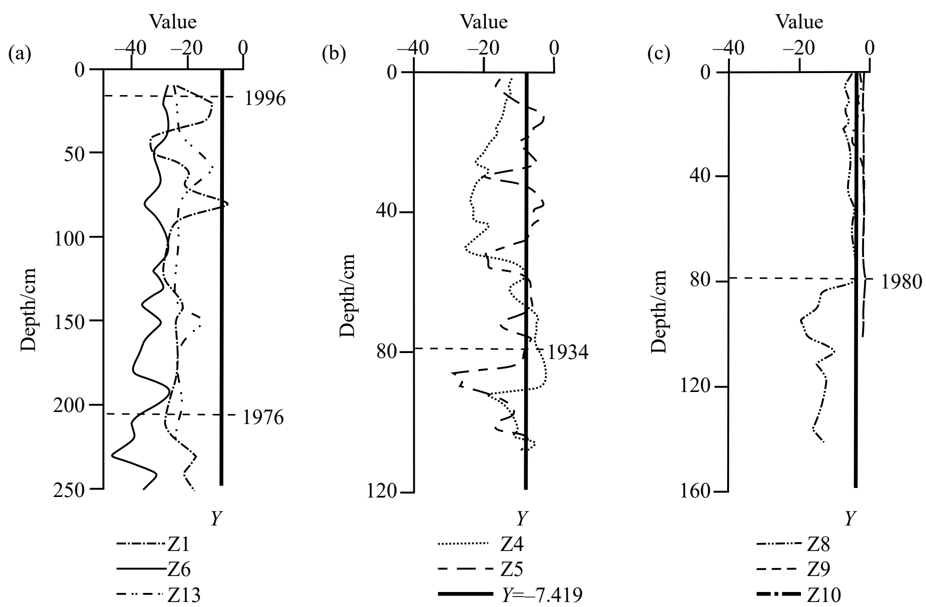

Fig. 4. Vertical distribution of the parameter discriminant value in eight cores.

peaks with a sharp negative skewness showing sedimentary source diversity. The probabilistic accumulation curve mostly consisted of three phases (“Z7-Z2-Z12 ”), with transitions from shift to suspension, reflecting a complex and varied sedimentary dynamics environment in the central shallow sea (Fig. 7).

5.2. Sediment environment evolution

The Yellow River entered the Bohai Sea from the northern tidal area at the Guangli estuary in 1897–1904 and 1929–1934 (Fig. 8a). At that time, the river’s location was south of the modern Yellow River, and the Guangli River had not yet developed. Bounded by the Guangli River, deposited sediment characteristics in the north were mainly affected by the Yellow River, and the south by the Xiaoqing River, Mihe River, and other coastal rivers.

After 1934, the Yellow River was diverted to the north in three strands (1934–1938 and 1947–1953), and the Guangli River became a separate distributary that reconstructed the sedimentary environment (Fig. 8b). The sediment in the western Laizhou Bay was shown as follows: The northern area was directly affected by the Yellow River, the central part was transformed by the Guangli River, and the southern part was affected by the Xiaoqing and Mihe rivers.

From 1976 to 1996, the Yellow River changed its course to flow into the sea from the Qingshui Ditch, and the sediment diffused from the north to south spread (Fig. 8c).

Artificial diversions of the Yellow River to the north-northeast followed in 1996 (Zhou LY et al., 2016). The range of influence of the rivers was further expanded in the west Laizhou Bay, represented by the Guangli River and Zimai Ditch. However, the influence of coastal rivers such as the Guangli River, Yongfeng River, and Xiaodao River on the sedimentary environment was limited to coastal areas only.

Bounded by the Guangli estuary, the northern sediment was affected by water and sand flowing from the Yellow River during different periods. The formed subaqueous deltas overlapped and changed the sedimentary environment. The southern sediments came from different multi-source rivers under the influence of the Xiaoqing River, Mihe River, and other coastal rivers.

So the dating (1976 and 1996) in Z1, Z6, and Z13 (Fig. 4a), dating (1934) in Z4 and Z5 (Fig. 4b), and dating (1980) in Z1, Z6, and Z13 (Fig. 4c) was clearly recorded by the diversion channel combined with the characteristics of grain size, accumulation curve, erosion, and regression. The dating (1953, 1976, and 1996) in the core (Z7, Z2, and Z12) was recorded by the diversion channel combined with sediment accumulation rates from the delta front to the prodelta (Fig. 7;

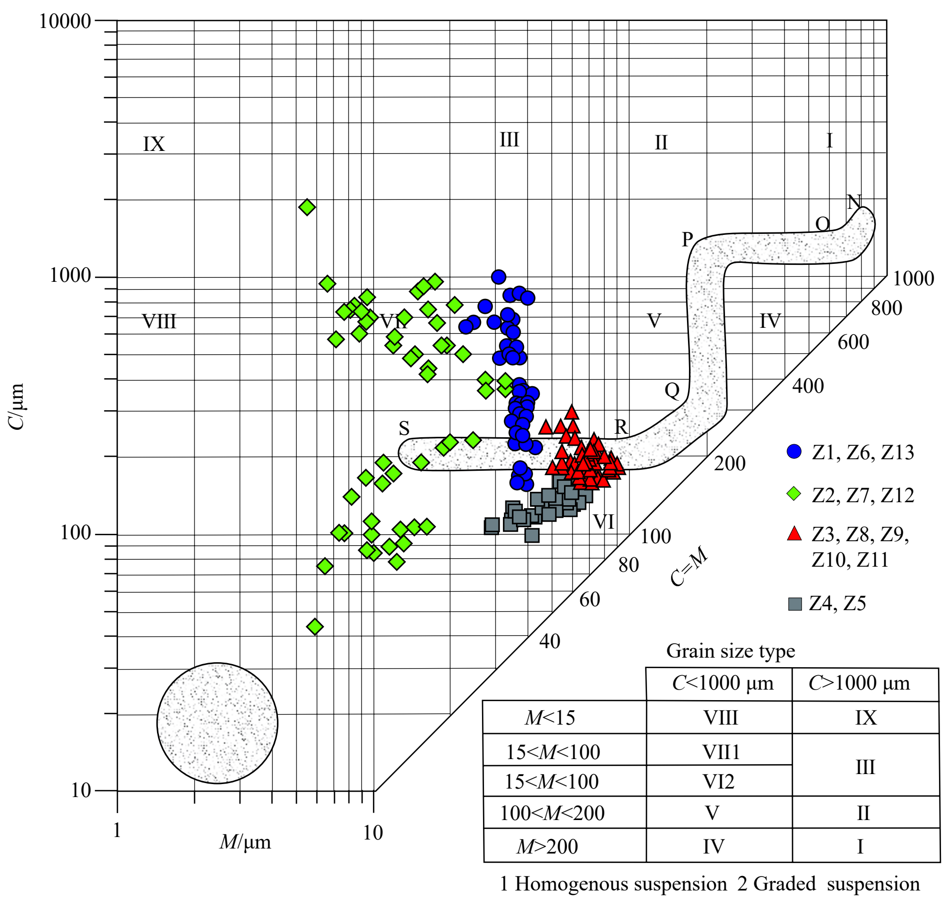

Fig. 5. The *C-M* diagrams of sedimentary column sampling in western Laizhou Bay. Eight sedimentary segments (Ⅰ–Ⅷ) and five sedimentary graph sections (NO, OP, PQ, QR and RS) by *C* and *M*. RS–homogenous suspension; QR–graded suspension; PQ–dominated by suspended deposition; OP–mainly rolling transportion mixed with suspension; NO–rolling transportion.

Li J et al., 2002). The deposited sedimentary characteristics in the western Laizhou Bay kept a dynamic balance due to the superimposed effect of multiple rivers along the coast.

The sedimentary evolution in the west of Laizhou Bay was restricted by the sediment condition of the Yellow River, the interaction between the small and medium rivers, and the ocean hydrodynamics. On the other hand, human activities play an important role in the evolution of the sedimentary environment in west Laizhou Bay.

Since 2002, the Water and Sediment Regulation of the Yellow River has accelerated the change of the sedimentary environment in the south of the modern estuary. At present, the north tidal flat of the Guangli River estuary in this research area is basically balanced, the salinity of tidal flat is effectively controlled, and the reclamation area is expanded, forming a sedimentary environment conducive to local

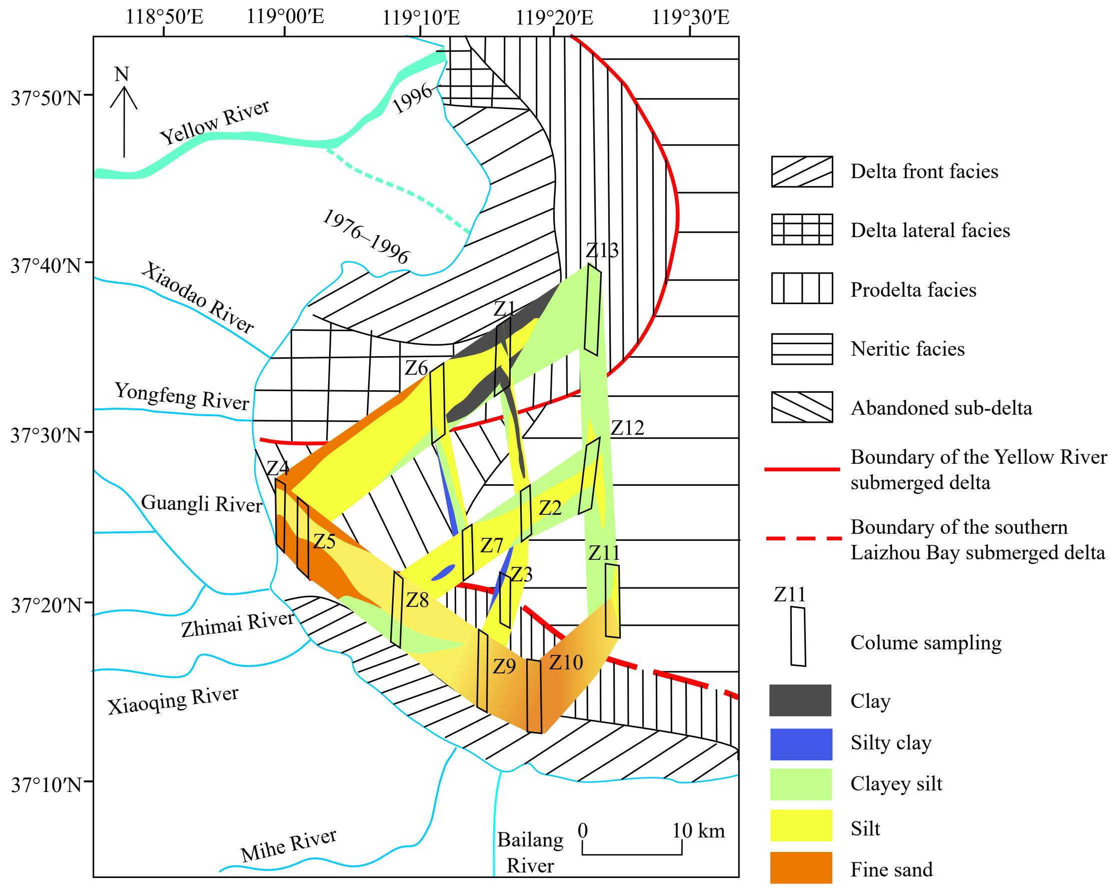

Fig. 6. The fence diagrams and sedimentary facies model in Western Laizhou Bay, China (Modified from Cheng GD and Xue CT, 1997; Xue CT and Ding D, 2008).

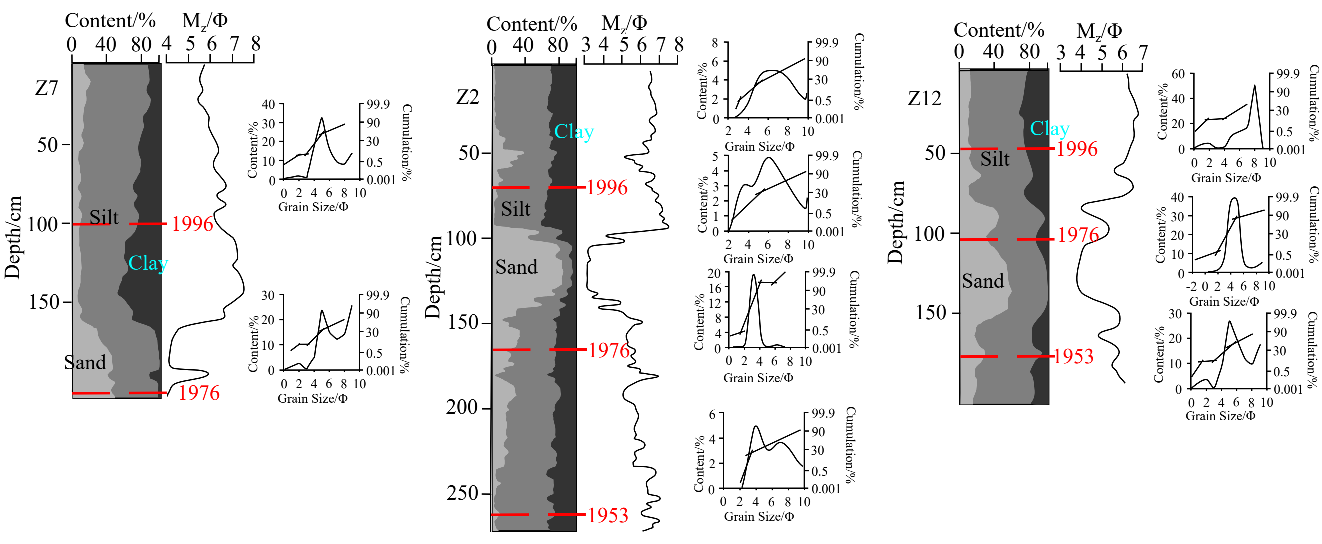

Fig. 7. Vertical distribution of the grain size and cumulative relative curve in the shallow sea.

aquaculture and sea rice cultivation. Since 2013, the team of Academician Long-ping Yuan has carried out the research and development of new varieties of sea rice in the reclamation area of Dongying in Shandong Province by using the tidal flat with medium salinity, and established 1000 acre planting demonstration base, which has become an important growth point of the local economy (Pan JQ, 2018; Fig. 9). In 2020, the planting area of super hybrid rice will be expanded to over 10000 acres in saline-alkali soil of Shandong Province (http://m.mnr.gov.cn/dt/hy/202003/t20200313_2501409.html).

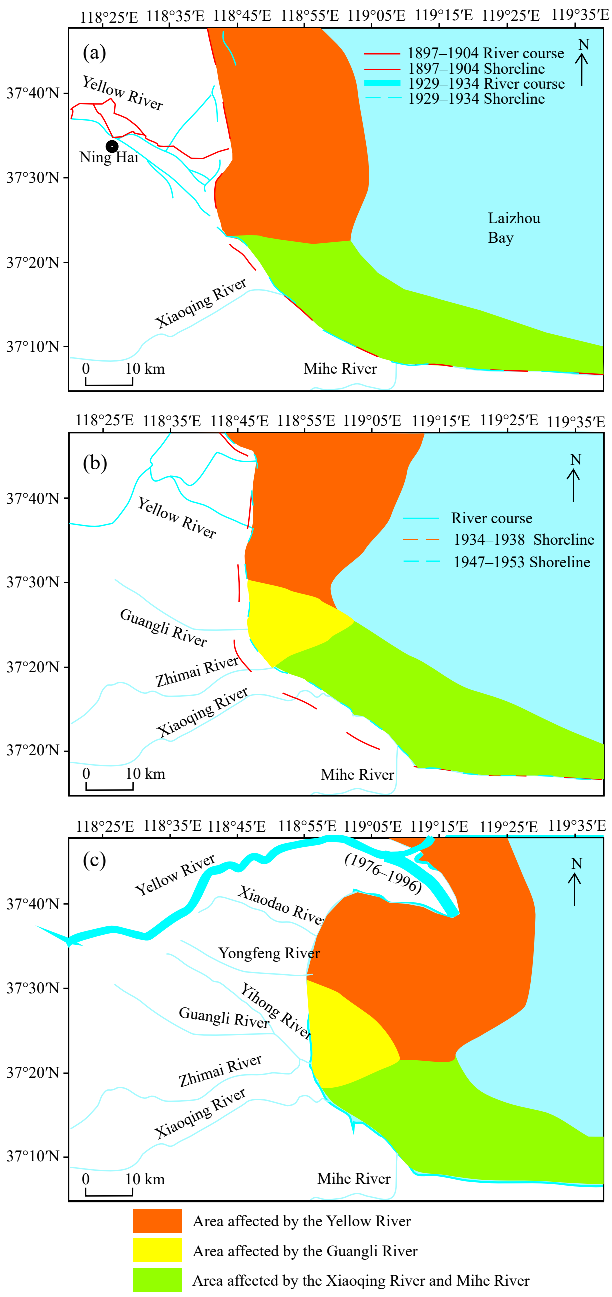

Fig. 8. Diversions of the Yellow River and sedimentary area of coastal rivers within 100 years. a–the Yellow River diversion at Guangli estuary (1897–1904 and 1929–1934); b–the Yellow River diverted to north in three strands (1934–1938 and 1947–1953), and a new sediment area forming (Guangli River as a separate distributary); c–the Yellow River flowed to Qingshui Ditch, and the sediment area spread (1976–1996).

Fig. 9. Sea rice of saline-alkali soil in Shandong coastal (after Pan JQ, 2018).

At the same time, the scale and production of characteristic aquacultures, such as Yellow River estuary hairy crabs, which are adapted to the local sedimentary environment, continue to increase.

6. Conclusion

The sediment of the western Laizhou Bay mainly originates from the modern Yellow River, multi-source coastal rivers, and other coastal erosion. Mainly the Yellow River substance, and other coastal rivers merely play a sedimentary reconstruction role in the western Laizhou Bay.

Deposited sediments mainly include the lateral margin of the modern Yellow River estuary, the north tidal area of the Guangli River estuary, the southern area of Laizhou Bay, and the central shallow sea area. There are sediment environment evolutions, however, that can be revealed only by studying their branched diversions of the Yellow River and coastal multi-rivers. And the sedimentary records of the past one hundred years have been reconstructed.

Dating of the northern estuary sediment is determined by a clear historical record of the branched channel oscillation (the Yellow River) combined with the characteristics of river diversion, erosion, and regression.

CRediT authorship contribution statement

Mao-sheng Gao and Guo-hua Hou conceived of the presented idea. Mao-sheng Gao and Xue-yong Huang developed the environment evolution theory and performed the computations. Xue-yong Huang and Xian-zhang Dang verified the grain size analytical methods. Mao-sheng Gao encouraged Guo-hua Hou and Xue-yong Huang to investigate sedimentary distribution characteristic and supervised the findings of this work. All authors discussed the results and commented on the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

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