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Original Research Paper

The Sedimentary Characteristics and Sediment Transport in the Tidal Depositional System of the Eastern Bohai Sea

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ABSTRACT

The Laotieshan Channel is one of the major channels in the north of the Bohai Strait, China. A tidal depositional system shaped by strong currents has developed in the eastern Bohai Sea, consisting of the Laotieshan Channel, the Liaodong Shoal and the Bozhong Shoal. Based on the grain-size characteristics, distribution of heavy minerals and numerical simulation results, the sediment distributions of different geomorphic units were analysed, and the trend of sediment transport is discussed. The results show that coarse-grained sediment is mainly distributed in the Laotieshan Channel, and the typical sediment type is muddy sandy gravel, whereas fine-grained sediment mainly covers the Liaodong Shoal and the Bozhong Shoal. Moreover, the sediments in sand ridges have a finer grain size than those in troughs. The sediment of the Bozhong Shoal mainly consists of muddy sand. The sediments of ridges, in contrast, are sand and silty sand; those of troughs are sandy silt and silty sand. The distribution of typical heavy minerals is similar to that of total heavy minerals and areas with relatively high content occur in the sand ridge area and the sand sheet area. The Laotieshan Channel is eroded and the sediment is transported to the Liaodong Shoal and the Bozhong Shoal. The sediment continues to be transported northwest in the Bozhong Shoal, while in the Liaodong Shoal it is transported approximately along the long axes of sand ridges. The sediment transport trends in the tidal depositional system are adapted to the hydrodynamic environment, and the tidal geomorphological system of the Liaodong Shoal will remain stable at the century scale.

INTRODUCTION

Tides are the most important and active marine dynamic factor in epeiric seas and on continental shelves. Tidal forces affect the development of submarine geomorphology and the processes of sedimentation. Tides construct longitudinal and transverse bedforms at different scales, transport eroded sand and silt, and generate large-scale tidal sand ridges and tidal sand sheets. The epeiric seas of China are broad and shallow, and the effects of tides are intense, and so various tidal sedimentary features and geomorphologies have been developed. The eastern Bohai Sea, which contains several different tidal geomorphic types, is a typical sea area in China. The tidal sand ridge system in the eastern Bohai Sea (Fig. 1a) consists of the erosion region of the Laotieshan Channel, the tidal sand ridge region of the Liaodong Shoal and the sand sheet region of the Bozhong Shoal (Liu et al. 1994).

The major tidal sedimentation of shallow seas is modern sedimentation, which is a process of sedimentation that occurs currently or has occurred recently and reflects the dynamic changes of the seafloor. Research on the tidal sedimentation in the eastern part of the Bohai Sea has great significance not only for understanding the hydrodynamic force conditions and the transportation of substances in the Bohai Sea, but also for the security of shipping, subaqueous military activities, fishery resources and exploitation of cultivation. In addition, these studies can provide a scientific basis for the engineering construction of submarine pipelines and cables in shoal regions.

Sand ridges are widely distributed in epeiric seas worldwide. The North Sea of Europe is an area in which tidal depositional geomorphologies have been developed intensively. Using the hydrodynamic conditions, submarine sand ridges can be divided into two types, tide-dominated and storm-dominated (Swift 1976). The submarine sand ridges of the Atlantic continental shelves all formed during the Holocene Epoch, but the layers exposed between the ridges formed during the Pleistocene Epoch. These sand ridges developed as the consequence of the adaptation of sediments of inner continental shelves to recent marine dynamic conditions (Swift et al. 1979). In the early 21st century, the study of shelf sand ridges remains an active research topic. Twichell et al. (2003) used bathymetric data, sidescan-sonar images,

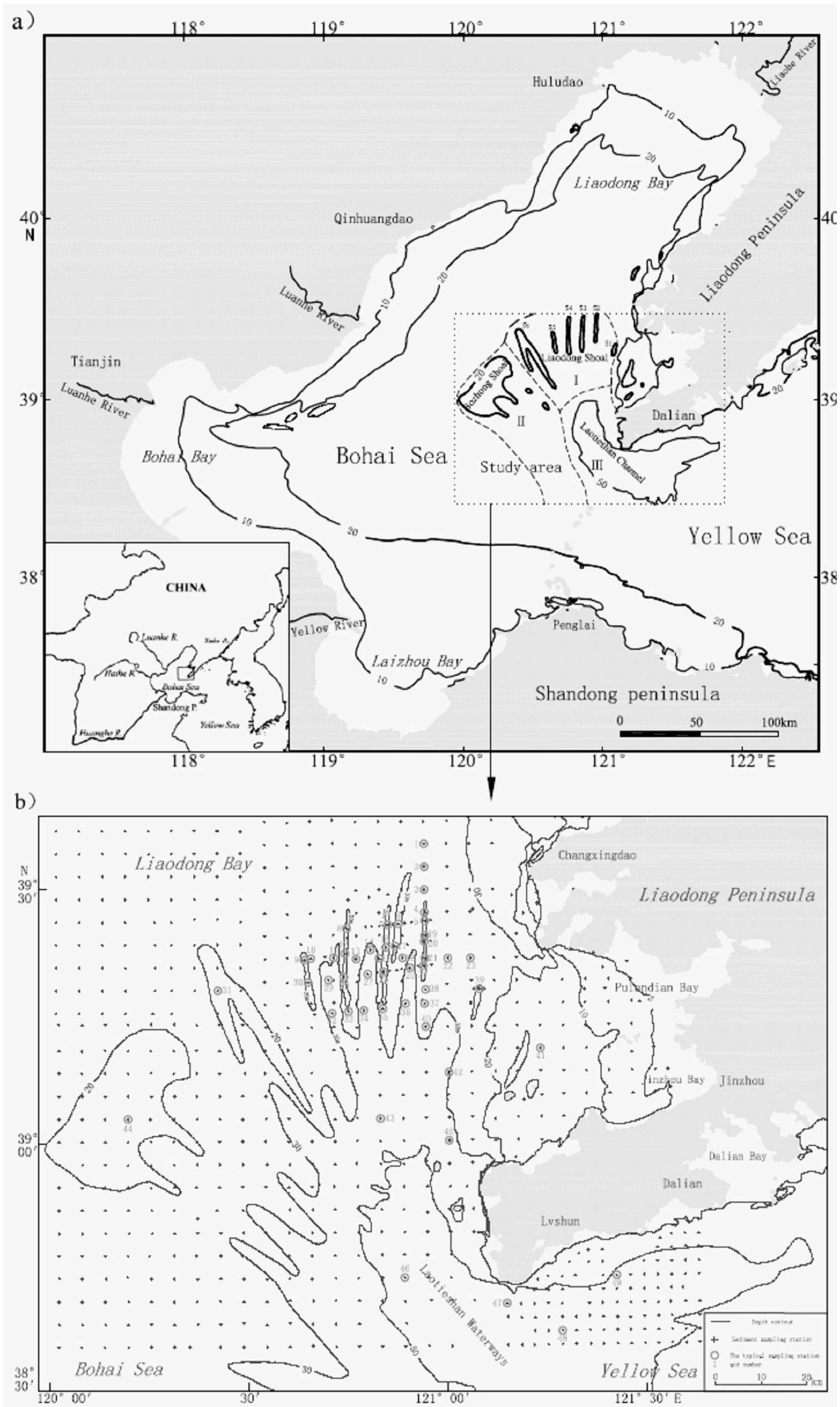

Fig. 1: Location of the study area (a) sampling stations (b) tidal depositional system in the eastern Bohai Sea (water depth in metres is on the basis of mean sea level). Note: I is the Liaodong Shoal; II is the Bozhong Shoal; III is the Laotieshan Channel, S1–S6 are the sand ridge numbers.

3.5-kHz sub-bottom profilers and surface sediment samples to perform research on sand ridges off Sarasota, Florida and reached the conclusion that along the southeastern sides of the ridges the facies boundary coincides with a stratigraphic discontinuity that separates Holocene from the older deposits while the transition along the northwestern sides of the ridges is within the Holocene deposit and is the result of sediment redistribution by modern processes. Michael & Edward (2007) characterized the surficial geology and morphology of offshore sand ridges on Sable Island Bank, Scotian Shelf using an integrated approach involving multibeam bathymetry surveys and demonstrated a relationship between storm processes and the development of sand ridges. Anthony et al. (2012) analysed the evolution of juxtaposed beach ridges of northeast Australia by considering the effects of wind and waves synthetically, and the result is a 'complex barrier' where a single ridge plain contains both foredunes developed through high frequency, low intensity events and beach ridges developed through high intensity, low frequency events associated with intense tropical cyclones.

Studies of offshore tidal sand ridges have been carried out in China since the 1960s. As the largest shelf sand ridge region of China, the radial sand ridge system in the South Yellow Sea has attracted extensive attention. Using measured hydrodynamic data, Xing et al. (2012) used a numerical simulation to study trends in sediment transportation in the radial sand ridge system in the southern Yellow Sea. Wang et al. (2012) synthetically analysed the heavy mineral characteristics of sediments and data from seismic sections and drill holes and explained the evolution of the radiating sand ridge field of the South Yellow Sea. In 1990s, several studies addressed the tidal sand ridges of Liaodong Shoal using information from sub-bottom profilers, sonar, depth soundings, bottom material and current surveying. The Liaodong Shoal and the Bozhong Shoal are the products of modern marine dynamic effects. With the thickest areas of the Holocene marine beds exceeding 20 m, the shoals were the thickest sediment traps in the Bohai Sea during the Holocene Epoch, except the Yellow River estuary, and they also had the highest rate of deposition (Liu et al. 1994). Zhu (2001) applied a two-dimensional tidal mathematical model to simulate the M_2 tidal constituent of the Bohai Sea, Yellow Sea and East China Sea. Research on sediment transport has shown that in the later part of the Pleistocene Epoch intense tides carried sediment from the Laotieshan Channel to the sea area of the western Liaodong peninsula, which generated the sand ridge of the Liaodong Shoal and the sand sheet of the Bozhong Shoal. However, without detailed measured data, the grain sizes of bottom material in the model are approximate grain sizes. From the stratigraphic analysis of lithology, biology and chronology in drill CD5, Liu et al. (2008) considered that the sandy sediments in the tidal sand sheet are the erosion productions of the Laotieshan Channel transported by strong tidal currents. Using Synthetic Aperture Radar (SAR) and Moderate Resolution Imaging Spectroradiometry to identify the ocean sand ridges in the eastern Bohai Sea, Shi et al. (2011) recognized 10 distinct sand ridges. However, there is no support for this conclusion from detailed depth-sounding and geological data. Chen et al. (2013) analysed the morphological characteristics and the effect factors of the tidal sand ridges in the sea area off the south coast of the Liaodong peninsula, finding that the sedimentary characteristics are dominated by tidal properties and eustatic sea level change.

Using detailed data on surface sediments in the research area, we analysed the distribution characteristics of sediments in each unit of the tidal depositional system. In addition, detailed analysis was performed on the grain-size characteristics of the Liaodong Shoal sediments. By combining the grain-size characteristics with the hydrodynamic condition, we discussed the connections between the sediment origin and the distribution of heavy minerals, and thus obtained the sediment transportation tendency in the tidal depositional system of the eastern Bohai Sea.

MATERIALS AND METHODS

Sea-floor bathymetry is based on published Chinese navigational charts. A total of 708 surface sediment samples were collected using single clam weight samplers in the study area during 2006-2012 (Fig. 1b). The sampling depth was 2 cm. Grain-size analysis was carried out by sieving and with a Mastersizer 2000 laser analyser. Sediment classification is based on the triangular scheme of Folk et al. (1970). The main grain size parameters were analysed using the matrix method of McManus (1988), including mean grain size, sorting, skewness and kurtosis. The 0.063-0.125 mm fraction was separated for mineral analysis. Heavy minerals were separated using tribromomethane (SG = 2.88) and were subsequently counted under a polarizing microscope.

The tidal hydrodynamics in the study area used the results of previous studies (Liu et al. 1994, Zhu 2001, Zhu 2010). The numerical model MIKE 3 was used to simulate the hydrodynamics in the eastern Bohai Sea (Zhu 2010). The current direction deviation is within a 10-cm range, and the current speed deviation is less than 10%. Thus, the simulation results can reflect the tidal hydrodynamics in the study area.

RESULTS

Grain-size characteristics of sediments: There are 10 main sediment types in the study area: muddy sandy gravel, gravelly sand, gravelly muddy sand, sand, silty sand, muddy sand, sandy silt, silt, mud and sandy mud. Fig. 2 shows the distribution of surface sediment types. The sediment type and grain-size parameters of different sedimentary geomorphic units are listed in Table 1.

***a. The Laotieshan channel region*:** The typical sediment types are muddy sandy gravel and gravelly muddy sand. The mean grain size varies from -0.9 to 2.7 φ. The sediments of station 47 (with a mean grain size of -0.9 φ) are located in the middle of the channel (Fig 1b, Table 1). The sediments become finer northward with decreasing gravel content, and the mean grain size is 0.7-6.3φ.

***b. The Bozhong shoal region*:** The sediment in this area is mainly composed of muddy sand; sand and silty sand occur in places. The mean grain size varies from 2.9 φ to 5.2 φ. The sediment of station 44 is located in the middle of the shoal (Fig 1b, Table 1) and the mean grain size is 3.8 φ.

***c. The Liaodong shoal region*:** Ridge S1: The sediment of the northern part of sand ridge S1 (station 39) is muddy sand and the mean grain size is 3.8 φ. The sediment of the southern part of sand ridge S1 mainly consists of sand.

Ridge S2: The sediment in the north (Stations 4 and 5) and centre (Stations 19, 20 and 21) of sand ridge S2 is sand, and the mean grain size ranges from 1.6 to 2.6 φ. In the southern part of the ridge (Station 24) the sediment is silty sand and the mean grain size is 2.9 φ.

Ridge S3: The sediment (Stations 7, 16 and 26), is mainly composed of sand and the mean grain size is 2.7-2.9 φ.

Ridge S4: The surface sediment (Stations 8, 12 and 28) is mainly composed of sand with a mean grain size of 2.8-3.1φ.

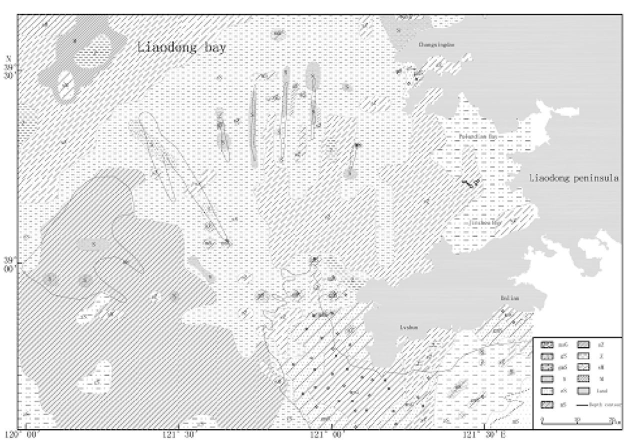

Fig. 2: Map of the study area showing distribution of sediment. Note: msG = muddy sandy gravel; gS = gravelly sand; gmS = gravelly muddy sand; S = sand; zS = silty sand; mS = muddy sand; sZ = sandy silt; Z = silt; sM = sandy mud; M = mud.

Ridge S5: The sediment of the northern part of ridge S5 (Station 9) is composed of muddy sand, and the sediment in the middle of ridge S5 mainly consists of sand with a mean grain size of 2.7 φ.

Ridge S6: The sediment in middle of ridge S6 mainly consists of sand; the mean grain size is 2.8 φ.

Trough area: The sediment in the trough area mainly consists of silty sand and sandy silt. The mean grain size ranges from 3.2 to 6.7 φ.

Sediment transport patterns: The cumulative probability curves of sediment grain size for the central area of the channel (Station 47) show that most of the sediment is bedload, with a content of more than 50%. But in the sand sheet area of the Bozhong Shoal (Station 44), it can be seen that the primary component is the siltation component, making up more than 90% of the content; there is a small suspension component and no bedload component. Different ridges in the tidal sand ridge area have different cumulative probability curves of sediment grain size, but their profiles look basically similar; thus, several typical curves are described. For sand ridge S2 (Station 20), the siltation component is the primary one, with a content of about 93%, as shown in the cumulative probability curves of sediment grain size for the central portion of the ridge. In this area, the suspension component is small, and the curves of siltation component and suspension component are both divided into two sections. According to the cumulative probability curves of sediment grain size for the central sand ridge in sand ridge S3 (Station 16), the primary component is the siltation component, the content of which exceeds 90%; a small bedload component and suspension component can also be observed. The cumulative probability curve of sediment grain size for the southern sand ridge (Station 26) also shows that the siltation component is dominant (more than 90%), a bedload component cannot be recognized, and a small suspension component is present. Sand ridge S4 (Station 12) has a similar cumulative probability curve of sediment grain size to that of Station 16. The primary component is the siltation component (content greater than 90%), with a small bedload component and suspension component.

Sediment mineralogy: There are 39 types of heavy mineral in the study area. The main minerals are hornblende, epidote, garnet, hematite, limonite, ilmenite and leucoxene, which together account for 81.90% of the total heavy minerals. The average content of heavy minerals is 2.50%, and the maximum is 13.80% (in the sand ridge area). Regions with relatively high heavy mineral content occur in the sand ridge area and the sand sheet area, while the relatively low-content regions are in the eastern offshore part of the study area, on the northwestern side of the sand ridge area, and near the

Table 1: Sediment type and grain-size parameters of different geomorphic units.

Station	Parameters				Sediment type
	Mean	Sorting	Skewness	Kurtosis	
Station 1	4.1	2.34	2.49	3.13	silty sand
Station 2	3.1	2.04	2.53	3.18	silty sand
Station 3	1.6	1.2	1.79	2.56	sand
Station 4	1.6	1.11	1.71	2.45	sand
Station 5	2	1.18	0.43	1.82	silty sand
Station 6	5.1	2.47	0.37	0.74	sandy silt
Station 7	2.9	0.35	0.27	0.93	sand
Station 8	3.1	0.91	0.32	3.58	sand
Station 9	3	1.38	0.67	4.19	muddy sand
Station 10	4.6	2.41	2.35	3.06	silty sand
Station 11	3.8	2.53	2.56	3.34	silty sand
Station 12	2.8	0.98	0.57	4.26	sand
Station 13	3.3	2.2	2.59	3.26	silty sand
Station 14	4.9	2.13	0.09	0.84	sandy silt
Station 15	3.9	2.45	2.5	3.25	silty sand
Station 16	2.9	0.32	0.19	0.78	sand
Station 17	5.7	2.37	0.19	0.78	sandy silt
Station 18	4.3	2.65	2.38	3.3	silty sand
Station 19	2.1	0.79	1.31	2.02	sand
Station 20	2.5	0.82	0.22	2.21	sand
Station 21	2.6	1.26	1.95	2.64	sand
Station 22	5.3	2.19	1.93	2.74	sandy silt
Station 23	4.9	2.54	1.98	3.02	sandy silt
Station 24	2.9	1.63	0.59	1.04	silty sand
Station 25	5.1	2	0.4	0.98	sandy silt
Station 26	2.7	0.32	-0.02	1.33	sand
Station 27	5.3	2.3	0.3	0.86	sandy silt
Station 28	2.8	0.85	0.52	5.24	sand
Station 29	3.6	2.27	0.6	0.93	silty sand
Station 30	2.7	0.35	0.09	1.42	sand
Station 31	2.8	0.99	1.71	2.38	sand
Station 32	3.2	2.19	0.73	1.32	silty sand
Station 33	1.7	0.7	0	1.21	sand
Station 34	4.8	2.15	0.34	1.22	sandy silt
Station 35	2.1	1.2	0.3	2.33	sand
Station 36	4.2	2.8	0.28	0.76	sandy silt
Station 37	4	2.43	2.52	3.19	silty sand
Station 38	4	2.25	2.45	3.07	silty sand
Station 39	2.7	1.31	0.65	6.26	muddy sand
Station 40	4.7	2.32	2.23	2.96	silty sand
Station 41	5.3	2.25	2.03	2.79	sandy silt
Station 42	6.4	2.19	-0.86	2.66	sandy silt
Station 43	6.7	1.89	1.24	2.3	silt
Station 44	3.8	2.16	2.56	3.15	muddy sand
Station 45	6.8	1.84	1.22	2.21	silt
Station 46	2	3.64	3.28	4.86	gravelly muddy sand
Station 47	-0.9	3.49	4.28	5.36	muddy sandy gravel
Station 48	2.2	3.74	0.12	1.21	gravelly muddy sand
Station 49	3.3	2.57	2.7	3.48	silty sand

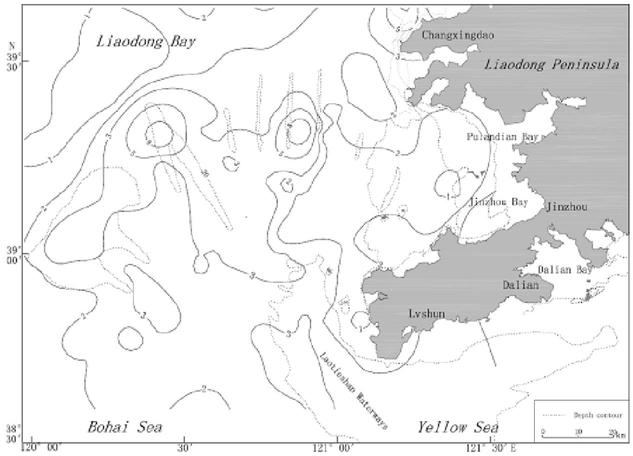

Fig. 3: Distribution of percentage content of heavy minerals.

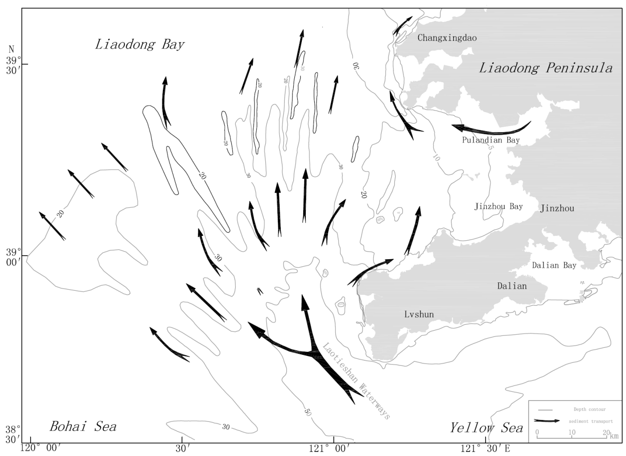

Fig. 4: Sediment transport trends in the study area.

Laotieshan Channel. The value increases from the offshore part of the bay in the study area to the northern Changxing Island area, and from the channel to the sand ridge and sand sheet area. Fig. 3 shows the distribution of heavy minerals in the study area.

The distribution of main heavy minerals is similar to the distribution of total heavy minerals. The relatively high-content areas are in the sand ridge area and the sand sheet area. The level of stable minerals in the sand ridge area is relatively high; the typical minerals are garnet and ilmenite, with average levels of 9.33% and 6.30%, respectively, and the relatively high-content areas are also in the sand ridge and sand sheet areas.

DISCUSSION

Analysis of Factors Influencing Sediment Distribution

Hydrodynamics: The part of the study area that has a water depth greater than 20 m has weak wave action and strong tidal currents. The tidal currents play a dominant role in the depositional system of the eastern Bohai Sea by shaping the pattern of sedimentary systems in this area. From the distribution of sediments (Fig. 2), the grain-size characteristics of sediments (Table 1) and the sediment transport pattern, tidal currents are considered to be the main factor controlling sediment transport in the study area. The sediments are transported primarily by siltation. The sediment in the high-energy environment of the Laotieshan Channel region is coarser than that of other units, and contains a higher amount of bedload.

The flow direction of the flood current is mainly northward while the ebb current is mainly southward, and the velocity measured in the Liaodong Shoal area shows that the velocity of flood current is greater than that of the ebb current, and that of the M_2 tidal current, the NNW-SSE long-axis direction of which is dominant in this area (Liu et al. 1994). In addition, the tidal currents in eastern Liaodong Shoal principally act as reciprocating flows, while in the west side the flows significantly rotate (Liu et al. 1998).

A simulation of the tidal current field shows the distribution of the bottom tidal current field in the study area (Zhu 2010). During low tide, the current flows southward from Liaodong Bay, while in the Laotieshan Channel it flows out of the Bohai Sea in a southeasterly direction. During high tide, the distribution of the tidal current is as same as at low tide, except that the flow direction is reversed and the current speed is greater. The current flows from east to west through the Laotieshan Channel, but shows a divergent distribution at the sand ridge in the Liaodong Shoal and the sand sheet in the Bozhong Shoal. The tidal currents in the eastern sand ridge of Liaodong Shoal flow northward, and the flow direction is northwest in the western Bozhong Shoal. The maximum flow rate in the western part of the Laotieshan Channel is about 1.5 m/s. The results indicate that the rate of flow in ridges is greater than that in troughs. The maximum flow rate at the bottom of ridges ranges from 0.53 to 0.68 m/s at low tide; the maximum velocity at the bottom of troughs varies from 0.47 to 0.58 m/s. In contrast, at high tide, the maximum flow rate at the bottom of ridges is 0.56 to 0.80 m/s and at the bottom of troughs is 0.54 to 0.65 m/s.

Sediment sources: Three large rivers, the Yellow River, the Liao River and the Luan River, flow into the Bohai Sea. The Yellow River has the most obvious influence on the sediment of the Bohai Sea. More than two-thirds of the sand and silt carried by the Yellow River accumulates in the estuary to form a delta, while the rest spreads to the coastal area and continental shelf. The quantity of sediment transported east of Liaodong Bay is very small (Li et al. 2005). The sand and silt carried by the Luan River is mostly deposited in the coastal area from the Luan River estuary to Caofeidiang. Moreover, the sediment from the Liao River just reaches the top of Liaodong Bay. On the whole, the sand and silt carried by rivers into the Bohai Sea is mainly deposited in estuarine deltas and therefore has little effect on sedimentation in the study area (Qiao et al. 2010). The coastal tide in the eastern part of the study area flows northeastward through Jinzhou Bay and Pulandian Bay and northward to the west of Changxing Island. Under the influence of the tide, near-shore sediment is transported to the north, and then to the northeast. Thus, the sand in the sedimentary system in the study area is mainly sourced from the bottom of the sea.

Sediment Transport

In the study area, the grain size of surface sediment decreases gradually from the Laotieshan Channel to the sand ridge and sand sheet areas. Conversely, the content of heavy minerals such as ilmenite and garnet in the Laotieshan Channel is smaller than in the sand ridge and sand sheet areas, because stable heavy minerals gather in the sand ridge and sand sheet areas. This indicates that sediment is transported from the Laotieshan Channel to the sand ridge and sand sheet areas.

The part of the study area in which the water depth is greater than 20 m (Fig. 1) has weak wave action and strong tidal currents. The tide controls the sedimentary system in the eastern Bohai Sea by shaping the sedimentary pattern of the area. During flood tide, the strong tide moves sand and silt into suspension as it flows through the Laotieshan Channel. After that, the tide runs through sand ridge and sand sheet areas. As the current speed increases, sand and silt are gradually deposited. At ebb tide, tidal flow and sediment transport reverse at a lower speed. Overall, the trend in sediment transport is from south to north and northwest (Fig. 4).

Of sandy sediments in the Bohai Sea shelf, sand ridges mainly form in the strong reciprocating tide area, while sand sheets mainly form in the rotating tide area (Zhu et al. 2001). In the sand ridges area, the reciprocating tidal current is strong and its direction is consistent with the long axes of the sand ridges. Under this influence, the transport direction of sediment in ridges and troughs is also consistent with the long axes of the sand ridges. Because of the differences in topography and current speed, the sand ridges and troughs contain sediment with different grain sizes, usually larger in sand ridges than in troughs. However, the sediment transport between sand ridges and troughs is not obvious. In the sand sheet area, the tide is weakly reciprocating and strongly rotating; thus it forms a flat sand sheet instead of radialized ridges. The sediment is mainly muddy sand, with a grain size smaller than that in the sand ridges. Under this comparatively weak tidal current action, sediment is transported towards the northwest (Fig. 4).

From analysis of sediment type, grain size, characteristics of heavy minerals and tide hydrodynamics, the total trend of sediment transport in study area can be summarized as follows. In the south of the study area, the sediments of the Laotieshan Channel are transported north and northwest; in the shoal in the north of the study area, the sediments of ridges S1 to S5 in the Liaodong Shoal are transported northwards, while for ridge S6 the direction is northeast, and the trend of sediment transport is consistent with the long axes of the sand ridges. However, in the Bozhong Shoal the sand sheet sediments are transported northwest. In addition, in the eastern offshore part of the study area the sediments are transported northeast and north, and the sediments of Jinzhou Bay and Pulandian Bay are transported northwest and then to the north of Changxing Island (Fig. 4).

CONCLUSION

1. There are 10 types of surface sediments in the study area. The sediments in Laotieshan Channel are characterized by coarse sediments, which mainly consist of muddy sandy gravel and gravely muddy sand, while the sediments of Bozhong Shoal are mainly composed of muddy sand. In the Liaodong Shoal the typical sediment types are sand and silty sand in the ridge area and sandy silt in the trough area. In addition, the sediments in the ridge area are coarser than those in the trough area.
2. The sediments of sand ridges (S1-S6) in Liaodong Shoal mainly consist of sand. However, silty sand, muddy sand and sandy silt can be found in some regions of the sand ridges.
3. Sediments are transported from the Laotieshan Channel to the Liaodong Shoal and the Bozhong Shoal. The direction of sediment transport is approximately consistent with the long axes of sand ridges. The sediments in the Bozhong Shoal are transported to the northwest. The sediments of the offshore area are transported northwards, thus the sediment supply from the offshore area to the sand ridge area is not obvious. The transportation of sediments makes the sand ridges degrade slightly to a certain extent; however, the Liaodong Shoal will remain stable at the century scale on the basis of the existing hydrodynamic environment.

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REFERENCES

Anthony, J.F., Jonathan, N., Mark, D.B. and Robin, J.B. 2012. Juxtaposed beach ridges and foredunes within a ridge plain-Wonga Beach, northeast Australia. Marine Geology, 307-310, 111-116.

Chen, X.H., Zhang, X.H., Li, R.H. and Lan, X.H. 2013. Characteristics of tidal sand ridges off the southeast Liaodong Peninsula and influence factors. Marine Geology & Quaternary Geology, 33(1): 11-17 (In Chinese with English abstract).

Folk, R.L., Andrews, P.B. and Lewis, D. W. 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. New Zealand Journal of Geology and Geophysics, 13: 937-968.

Jin, J.H. and Chough, S.K. 2002. Erosional shelf ridges in the mid-eastern Yellow Sea. Geo-Marine Letters, 21: 219-225.

Li, G.S., Wang, H.L. and Dong, C. 2005. Numerical simulations on transportation and deposition of SPM introduced from the Yellow River to the Bohai Sea. Acta Geographica Sinica, 60(5): 707-716 (In Chinese with English abstract).

Liu, S.F., Zhuang, Z.Y. and Long H.Y. 2008. Environmental evolution and sand sheet sedimentation in late Quaternary in the east Bohai Sea. Marine geology & Quaternary Geology, 28(1): 25-31 (In Chinese with English abstract).

Liu, Z.X., Xia, D.X., Berné, S., Wang, K.Y., Marsset, T., Tang, Y.X. and Bourillet, J.F. 1998. Tidal depositional systems of China's continental shelf, with special reference to the eastern Bohai Sea. Marine Geology, 145(3-4): 225-253.

Lin, Z.X., Xia, D.X., Tang, Y.X., Wang, K.Y., Berné, S., Marsset, T. and Bourillet, J.F. 1994. The Holocene tide sedimentary system in east of Bohai Sea. Science in China, 24(12): 1331-1338 (In Chinese).

Michael, Z.L. and Edward, L.K. 2007. Multibeam bathymetric investigations of the morphology of sand ridges and associated bedforms and their relation to storm processes, Sable Island Bank, Scotian Shelf. Marine Geology, 243: 200-228.

McManus, J. 1988. Grain-size determination and interpretation. Techniques in Sedimentology. Backwell, Oxford, pp. 63-85.

Qiao, S.Q., Shi, X.F., Wang, G.Q., Yang, G. and Hu, N.J. 2010. Discussion on grain-size characteristics of seafloor sediment and transport pattern in the Bohai Sea. Acta Oceanologica Sinica, 32(4): 139-147 (In Chinese with English abstract).

Swift, D.J.P. 1976. Continental shelf sedimentation. In: Marine Transport and Environmental Management, pp. 311-350.

Twichell, D., Brooks, G., Gelfenbaum, G., Paskevich, V. and Donahue, B., 2003. Sand ridges off Sarasota, Florida: A complex facies boundary on a low-energy inner shelf environment. Marine Geology, 200: 243-262.

Wang, Y., Zhang, Y.Z., Zou, X.Q., Zhu, D.K. and David, P. 2012. The sand ridge field of the South Yellow Sea: Origin by river-sea interaction. Marine Geology, 291: 132-146.

Xing, F., Wang, Y.P. and Harry, V.W. 2012. Tidal hydrodynamics and fine-grained sediment transport on the radial sand ridge system in the southern Yellow Sea. Marine Geology, 291: 192-210.

Zhu, L.H. 2010. Research on dynamic geomorphology of tidal deposition in Liaodong Shoal. Ocean University of China, Qingdao, pp. 61-75 (In Chinese).

Zhu, Y.R. 2001. The controlling role of tidal current regime in the distribution patterns of bottom sediments in the continental shelves of the Bohai Sea, Yellow Sea and East China Sea. Marine geology & Quaternary , 21(2): 7-13 (In Chinese with English abstract).