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The sand ridge field of the South Yellow Sea: Origin by river–sea interaction

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ABSTRACT

The origin of a large field of sand ridges offshore from the north Jiangsu coast in the South Yellow Sea has been investigated on the basis of bathymetry, seabed samples, high-resolution seismic profiles and 31 to 71 m deep boreholes. Sediment composition including heavy minerals and clay minerals sampled from surface sediments shows that most of the sand was derived from the Changjiang (Yangtze) River, but in the northern part of the field particularly the clay came from the Huanghe (Yellow) River. Seismic profiles show late Pleistocene distributary channels of the ancient Changjiang River underlying much of the southern part of the sand ridge field. The Holocene transgression cut a widespread ravinement surface reworking abundant late Pleistocene sandy sediment. The available sand was reworked by tidal currents into large ridges. The location of the ridges is strongly influenced by relict channels in the southern part of the field and by tidal currents in the northern, and especially the northeastern part of the field, resulting in a radiating ridge pattern. These ridges provide an example of the evolution of a large scale geomorphic feature resulting from river–sea interaction, in which climatic and sea level changes played an important role.

1. Introduction

Sand ridge fields consist of large, elongate sand bodies and channels formed by tidal dynamics in shallow seas with abundant sediment. The ridges are linear-shaped deposits, aligned parallel to the direction of the tidal currents. They reach heights of several meters to several tens of meters, widths of several hundred meters to several kilometers, and lengths of several kilometers to tens of kilometers. Normally, the ridges are distributed in groups or fields in shallow seas. Such sand ridge fields occur widely in Chinese shelf seas (Fig. 1); for example, the radiating sand ridge field in the South Yellow Sea; the finger-shaped sandy ridges of Liaodong bank in the Bohai Strait (Fig. 1D); the parallel sandy ridges lying offshore of the Yalu River Estuary and the West Korean Bay (Fig. 1B); and the finger-shaped sandy ridges in the Qiongzhou Strait of the South China Sea (Fig. 1G). They have also been found on the continental shelf of the East China Sea (Fig. 1E) (Liu et al., 2000). The largest ridge complex along the Chinese coast is the field of radiating sand ridges off the north Jiangsu coast in the South Yellow Sea (Fig. 2) where the two largest Chinese rivers, the Changjiang River and the Yellow River, have supplied huge quantities of sediment since early Cenozoic times. These sand ridges fan out for 30–110 km, covering an area of 22,470 km^2, the water depth generally ranging from 0 to 25 m, but maximum depths can reach 50 m in certain parts of the tidal channels.

Sand ridges are in principle a result of tidal current action, but are also influenced by pre-existing morphology, river discharge (e.g., Giosan et al., 2005), and storm wave processes (Li and King, 2007). The deposits may preserve records of sea level and other environmental changes on the continental shelf and the flux of sediment from land to sea. As in other highly populated coastal areas of the world, land resources along the Jiangsu coast are very scarce. The radiating sand ridges are thus considered to be a potential land resource through reclamation. The deep tidal channels between the sand ridges are, furthermore, regarded as ideal locations for deep-water harbors in response to the demands of local economic development. The looming conflict between “economic development” and “conservation” thus calls for in-depth scientific studies in this area.

Sand ridges have been studied elsewhere since the 1960s. Good examples are those in the English Channel and the Celtic Sea between Ireland and France (Houbolt, 1968), in the south-eastern North Sea (Collins et al., 1995), and along the Atlantic coast of North American (Off, 1963). These regions have been continuously investigated over the last 40 years (e.g., Caston, 1972; Dyer and Hunltey, 1999; Kenyon, 1970; Swift, 1975). As far as is known, the largest sand ridge field is located along the shelf edge of the Celtic Sea southwest of England (Houbolt, 1968; Tessier et al., 2000). It is situated in water depths of 100–170 m, the parallel ridges being spaced 16 km apart and reaching 50 m in height, 5–7 km in width, and 40–120 km in length. These ridges formed

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during the last glacial maximum at 18 ka BP when sea level was about 120 m lower than at present. The relatively shallow water at that time and the large sediment supply, coupled with strong tidal currents, favored the formation of a large sand ridge complex reaching up to 50 m in thickness. The field has passed through several stages of development following changes in sea level, preserving coastal changes in the process. The fundamental factors controlling sand ridge development are thus the availability of large quantities of sediment that can be moved by strong tidal currents flowing at velocities of 0.25–2.5 $m s^{-1}$ (Off, 1963). The currents shape the sediments into sand bodies aligned in the direction of the tidal current to form erosive valleys and linear sand bodies or, in the presence of older valleys or depressions, these are further excavated, the eroded sediment being then deposited on adjacent sand ridges. The formation processes of ridges and troughs are related to a combination of horizontal and transverse currents developed in the troughs, which move sand from the troughs to the ridges. Due to a positive feedback, the development of the ridge and trough system is enhanced as it grows (Houbolt, 1968). Because the velocity of the tidal current is larger in the deep troughs than on the top of the ridges, the difference produces transverse water circulation, the bottom current in the trough diverging outwards, while converging inwards on top of the ridges. This helicoidal water circulation moves sediment eroded in the troughs to the crests of the ridges, thereby increasing their height. Caston (1972) and Stride (1974) showed that, in the southern North Sea, flood and ebb tidal currents were dominant on opposite sides of the ridges, respectively, the different velocities causing the ridges to slowly migrate laterally.

The radiating sand ridge field of the Yellow Sea was named as Five Sands on British Admiralty Charts of the 1930s. Hydrodynamical and geomorphological surveys have been undertaken in this region since the early 1960s by the Institute of Oceanology of the Chinese Academy of Sciences (Li and Li, 1981), and the Bureau of Marine Geological Surveys (Yang, 1985; Zhou and Sun, 1981). Major studies in marine hydrology, meteorology, geomorphology, geology, and biology were carried out along the Jiangsu coast in the period from 1980 to 1985. Offshore, the scientific focus was initially on the sand ridge field, but later included several tidal channels for the purpose of a harbor site selection. A systematic study of the sand ridge field was carried out from 1993 to 1996 by Nanjing University, jointly with Hohai University, Tongji University and the Institute of Oceanology of the Chinese Academy of Sciences (as a Key Study Project supported by the National Natural Science Foundation of China). The study involved the generation of a detailed bathymetric chart of the whole area, the acquisition of more than 600 km of seismic profile data, the retrieval of several hundred seabed samples, and the collection of hydrological data on tides, waves, currents and suspended sediment to improve the fundamental understanding of the sand ridge field (Wang et al., 1999). The results have been published in Chinese in a scientific volume under the title “Radiating sand ridge field of the South Yellow Sea” (Wang et al., 2002). The present study is primarily based on those results, but has been supplemented by new data collected during July–November of 2007 when 1050 km of additional seismic profile data and 9 long sediment cores were obtained in the field.

The purpose of this study is to comprehensively assess the sedimentary processes and the coastal geomorphological evolution in some key areas, especially the axial area and the northeastern part of the ridge field.

2. Geological and oceanographic setting

The radiating sand ridge field is located seaward of the large deltaic alluvial plain built by the Changjiang and Yellow rivers into the central Yellow Sea (Figs. 1 and 2). Its apex is located near Jianggang and Xiaoyangkou on the north Jiangsu coast where the trend of the modern coastline changes from NNW in the north to WNW in the south, being situated about 80 km north of the late Holocene path of the Changjiang River. Satellite imagery suggests that two former distributary channels of the Changjiang discharged near the apex of the radiating sand ridge field. The modern coastline is fringed by tidal flats typically 5–10 km wide. The coastline has prograded ~40 km over the last thousand years, most rapidly between 1128 and 1855 when the Yellow River mouth migrated from the Bohai Sea southwards to the north Jiangsu coast.

The semi-enclosed Yellow Sea is influenced by two types of tidal waves, a progressive tidal wave from the Pacific, which propagates from the southeast towards the North Yellow Sea, and a local reflected tidal wave formed by the obstruction of the Shandong Peninsula in the northwest. The two tidal waves converge along the Jiangsu coast in the western Yellow Sea, forming a “standing wave” (Zhang, 1998) that rotates clockwise about an amphidromic center 200 km north of Jianggang (Fig. 3A). In the radiating sand ridge field the semidiurnal rotary tidal currents are very strong, average spring tidal current velocities being ~2 $m s^{-1}$ and maximum tidal current velocities exceeding 2.5 $m s^{-1}$. Tidal ranges are normally 4–6 m, but can reach up to 9.28 m in the deepest channel of Huangshayang, which is the maximum tidal range recorded in the China Sea (Ren et al., 1986). Uehara et al. (2002) have modeled the tides of the middle and early Holocene at 6 ka and 10 ka BP (Fig. 3B and C). In the middle Holocene, tidal conditions were similar to the present, but when sea level was 45 m lower in the early Holocene, no amphidrome was developed.

Wave climate is controlled primarily by the Monsoon winds. Waves from a northerly and northeasterly direction prevail in winter, but waves from the southeastern quadrant prevail in summer. Wave energy progressively decreases while crossing the sand ridge field, to the extent that wave heights of 7–9 m in the open sea are reduced to 0.4 m, 2 m high waves occurring with a probability of only 5%. As a result, the outer parts of the sand ridge field suffer from wave-induced bottom erosion, to the extent that about 2.02×10^9 t of sediment has been transported into the sand ridge field from the offshore seabed (Zhu and Fu, 1986).

3. Methods

Sea floor bathymetry is based on published Chinese navigational charts. Altogether, 324 surface sediment samples were collected by means of short cores and single or double clam weight samplers during the first large-scale survey along the Jiangsu coast (1980–1984) carried out in the period when a key project was financed by the NSFC (1993–1996). This data set was complemented in the course of a second, more recent large-scale survey along the Jiangsu coast (2006–2010) when 125 more surface sediment samples were collected by mean of double clam weight samplers, and some 1650 km of seismic profiles were collected with penetrations up to 50 m into the sub-bottom sandy deposits. Of the total seismic profiles collected in the area, more than 600 km were acquired with a Geopulse seismic profiler (Ocean Research Equipment Inc.), which covered the whole radiating sand ridge field during the summer of 1994, and about 1050 km with a Boomer system (Applied Acoustic Engineering, UK) covering different sections along individual sand bodies or tidal channels in the summer and autumn of 2007. The boomer surveys were conducted at energy source levels of 300 or 400 J. To assist the interpretation of the sub-bottom seismic data, 2 long sediment cores were drilled in September 1992. The core that provided the most useful stratigraphic control penetrated 60.25 m into the supra-tidal flat just outside the protective coastal dike near the village of Sanming in Rudong County of Jiangsu Province (Fig. 2). Nine additional deep cores were drilled in shallow water in different parts of the radiating sand ridge field during 2007–2008 (Fig. 2). These penetrated to the sub-bottom depths of 30.8–70.9 m.

Grain-size analysis was carried out by sieving and a Mastersizer 2000 laser analyzer. Sediment classification is based on the triangular scheme of Shepard (1954). The 0.063–0.125 mm fraction was separated for mineral analysis. Heavy minerals were separated