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Erosional shelf ridges in the mid-eastern Yellow Sea

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Abstract In the mid-eastern Yellow Sea, closely spaced high-resolution seismic profiles and a 44-m-long sediment core (YSDP-104) were analyzed to reveal the internal structures and stratigraphy of the shelf ridges currently shaped by tidal currents. Three depositional sequences (sequences I, II and III in descending order) can be recognized. Sequence III, the substratum of the ridges, consists of coarse-grained sediments in the lower part (non-marine deposits) and tide-influenced muddy sediments in the upper part (probable transgressive to highstand systems tract). Sequence II represents internal ridge sediments, similar in character to sequence III, but is demarcated by an undulatory ridge topography. According to radiocarbon dating of marine muds, these sequences range in age from 47,000 to 28,000 years B.P., representing two cycles of short-term sea-level fluctuations during oxygen isotope stage 3. Sequence I consists mostly of late-Holocene transgressive sand veneer on the ridge surface. It also includes minor amounts of early-Holocene muddy sediments occasionally underlying the sand. Most of the ridges are presently undergoing erosion by tidal currents, forming widespread sand dunes on the entire surface.

Introduction

Sand ridges, large-scale elongate shelf sand bodies, are a dominant geomorphic element in a wide range of ancient and modern shelves which are either tide-, wave- or storm-dominated (Houbolt 1968; McBride and Moslow 1991; Johnson and Baldwin 1996; van de Meene et al. 1996). Sand ridges form where flow deceleration occurs across the ridge crest, resulting in downstream accretion of sands (e.g., Huthnance 1982; Gaynor and Swift 1988; Trowbridge 1995; Hulscher 1996). Most shelf ridges are constructional under strong hydrodynamic influence, sufficient sand supply and an initial seabed irregularity (Snedden and Dalrymple 2000), although some are erosional in origin (e.g., Berne et al. 1994, 1998). Based on airgun and Chirp profiles as well as short sediment cores in the mid-eastern part of the Yellow Sea, Jung et al. (1998) have reported a large-scale pseudo-tidal sand ridge formed by tidal erosion of pre-deposited muddy sediments. Recently, closely spaced seismic profiles and a deep drill core (44 m long) were obtained from a ridge in the mid-eastern Yellow Sea in order to establish the stratigraphy and to interpret depositional processes (KIGAM 1996). Detailed assessments of the seismic profiles and new drill core data help reveal the evolution of the ridges in a sequence stratigraphic perspective.

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Geological setting

The mid-eastern part of the Yellow Sea, up to 80 m deep (Fig. 1A), is under macro-tidal regime with peak tidal currents exceeding 2 knots in many coastal and offshore regions (Korea Hydrographic Office 1990). Tidal ellipses of M_2 component show that tidal currents generally flow NE-SW (Lee and Jung 1999). The seafloor is relatively flat and monotonous in the nearshore area, whereas it is undulatory in the offshore area with topographic relief a few tens of meters high, forming ridges and swales which trend NE-SW (Fig. 1A). These ridges and swales are largely covered with sands which originated from active reworking of sediments during the Holocene transgression (Fig. 1B; Lee et al. 1988). The ridge and swale topography disappears northwards, to form a flat seabed in contact with large-scale lobes in the northernmost part (Fig. 1A).

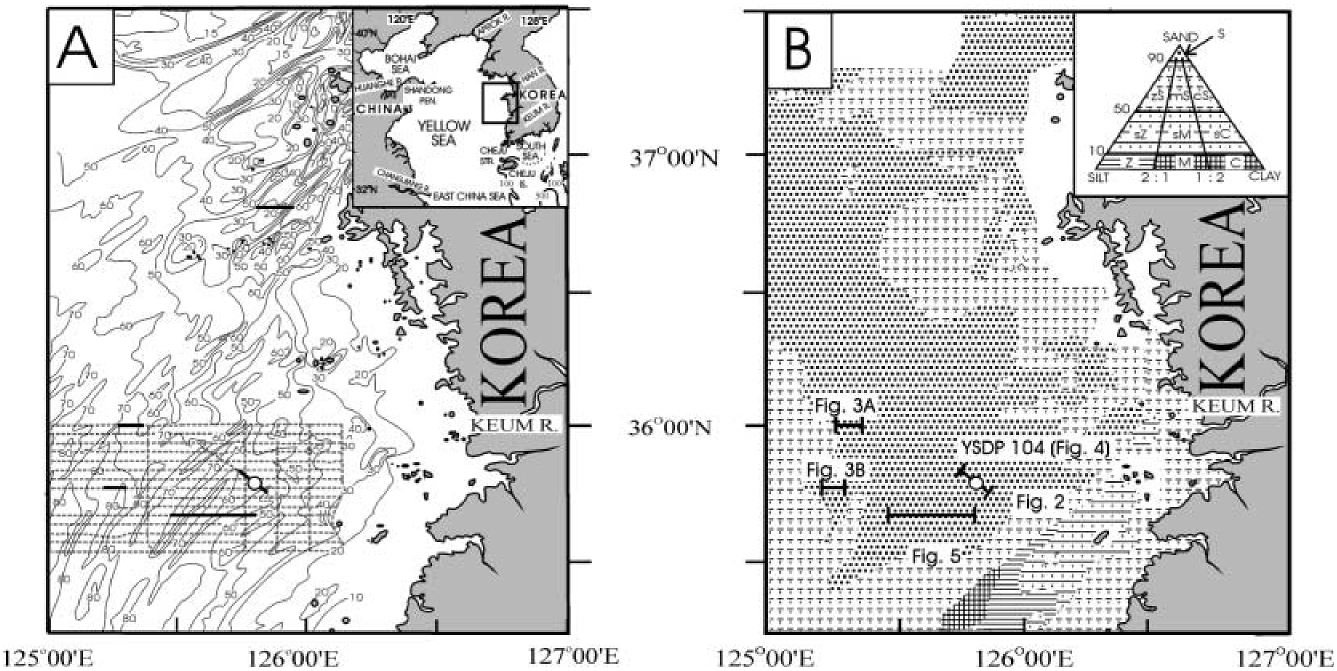

Fig. 1 Geographic location, bathymetry **A** and surface sediment distribution **B** in the mid-eastern part of the Yellow Sea (contours in meters). **A** The seafloor ranges in water depth from 20 to 80 m and displays a ridge-and-swale topography, especially in the area between 35°30′ and 36°00′N. Note seismic-survey track lines and the drill hole position (YSDP-104). The track line in the northernmost part (south of 37°N) is that of Jung et al. (1998). **B** Muddy sediments are present in the nearshore and westernmost offshore areas, whereas sand predominates over the remaining area. *Bold track lines* indicate seismic profiles cited in the text

Two large Chinese rivers, the Huanghe and Changjiang rivers (Fig. 1A, inset), are the major source of sediments for the Yellow Sea, emptying 1,080×10^{6} and 478×10^{6} t/year, respectively (Milliman and Meade 1983; Lee 1991). Much of the sediment builds extensive deltas off the river mouths (Xue 1993; Chen and Stanley 1993), and the rest is transported offshore (Milliman et al. 1985a, 1985b; Lee and Chough 1989). In the eastern part of the Yellow Sea, relatively small amounts of terrestrial sediments are derived from small Korean rivers such as the Han, Keum and Youngsan rivers (Lee 1991). The Keum River empties 5.6×10^{6} t/year of sediment directly into the mid-eastern part of the Yellow Sea. Fine-grained fractions of the sediment are transported by coast-parallel currents, resulting in mud accumulation with rates of 0.3–1 cm/year in the nearshore area (Chough and Kim 1981; Lee and Chough 1989; Alexander et al. 1991; Jin and Chough 1998; Lee and Chu 2001; Fig. 1B). Offshore sands are not covered with mud, forming a sand veneer on ridges and swales (Jung et al. 1998).

Materials and methods

Closely spaced (~2-mile intervals) high-resolution seismic profiles were obtained from the mid-eastern Yellow Sea (Fig. 1; KIGAM 1993). A deep drill core (YSDP-104, 44 m long, 35°45.663′N, 125°49.813′E, 45-m water depth) was raised from a hole on the crest of a ridge (Figs. 1A and 2; KIGAM 1996). The core was analyzed for texture, sedimentary structures and faunal fossils. Radiocarbon dating of foraminiferal tests and organic material was conducted by means of an accelerator mass spectrometry (AMS) at the Institute of Geological and Nuclear Sciences, New Zealand.

Results

Seismic and lithofacies characteristics

High-resolution seismic profiles from the mid-eastern Yellow Sea reveal five seismo-stratigraphic units, designated here units 1–5 in descending order (Figs. 2 and 3). The drilled ridge displays these units in the upper stratigraphic sections which are sharply truncated at the flanks. Based on seismic and core data, the ridge can be divided into three sections: (1) ridge substratum, (2) ridge proper, and (3) ridge surface layer (Fig. 4).

Ridge substratum

Two distinct seismic units are visible beneath the ridge (units 4 and 5). The lower one (unit 5) is seismically chaotic and laterally discontinuous, and displays an erosional base (Fig. 2). It comprises laminated muddy sand and disorganized muddy sandy gravel completely devoid of marine fossils (Fig. 4). The upper unit (unit 4) is acoustically stratified and laterally persistent, and displays small-scale variations in thickness caused by irregular erosional scars on the surface. This unit largely

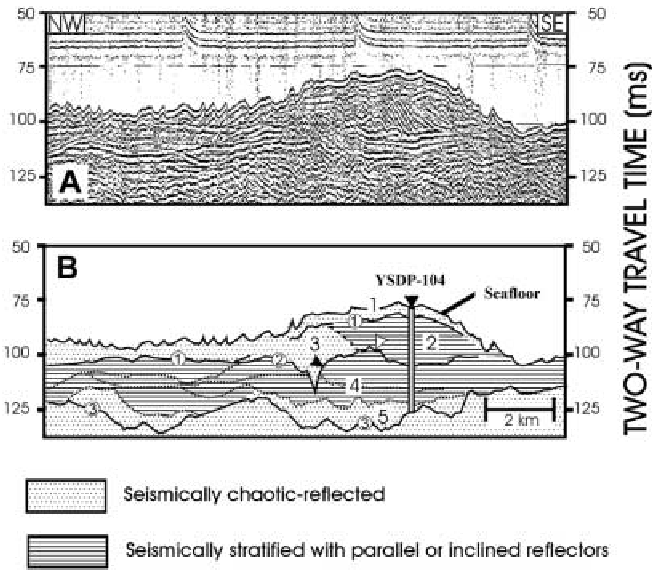

Fig. 2 Seismic profile **A** and interpretation **B** in the area of the drill hole YSDP 104 (for location, see Fig. 1). Five distinct seismic units are shown (units 1–5). Unit 3 displays chaotic internal structures over an irregular base with occasional incised topography (*filled arrowhead*). Unit 2 (stratified) also has an erosional base and occasionally forms large-scale hollows (*open arrowhead*). *Circled numbers* represent lithologic boundaries identified in the drill hole

comprises muddy sediments 40,000~50,000 years old (Fig. 4). The muddy sediments are characterized by rhythmic interlaminations of silt and clay with some bimodal and cyclic variations in layer thickness. Occasionally low-angle truncation surfaces and abundant foraminiferal tests are observed. Thin sand beds with a sharp erosional base are intercalated between the muddy sediments (Fig. 4).

The absence of marine fossils in unit 5 is suggestive of a non-marine origin, whereas sedimentary features such as rhythmic interlamination of silt and clay, occasional low-angle truncation surfaces, and abundant foraminiferal tests in unit 4 are indicative of mud deposition in a tide-dominated shallow-marine environment (e.g., Lanier et al. 1993; Archer et al. 1994; Greb and Archer 1995). The sandy intercalations between mud layers most likely indicate episodic high-energy events such as storms (e.g., Aigner 1985; Leithold 1989).

Ridge proper

The ridge is represented by two seismic units (units 2 and 3) which are truncated laterally by an erosional surface (Fig. 2). The lower unit (unit 3) is seismically chaotic and has an irregular base. This unit pinches out near the drill hole where it is bounded by a large hollow (Fig. 2). The hollow is filled with sediment of unit 2 displaying inclined high-amplitude reflectors. The reflectors are sharply truncated at the ridge surface.

The drill core raised from unit 2 displays alternating sand, muddy sand, sandy mud and mud of variable thickness (Fig. 4). Sandy muds are prevalent in the core

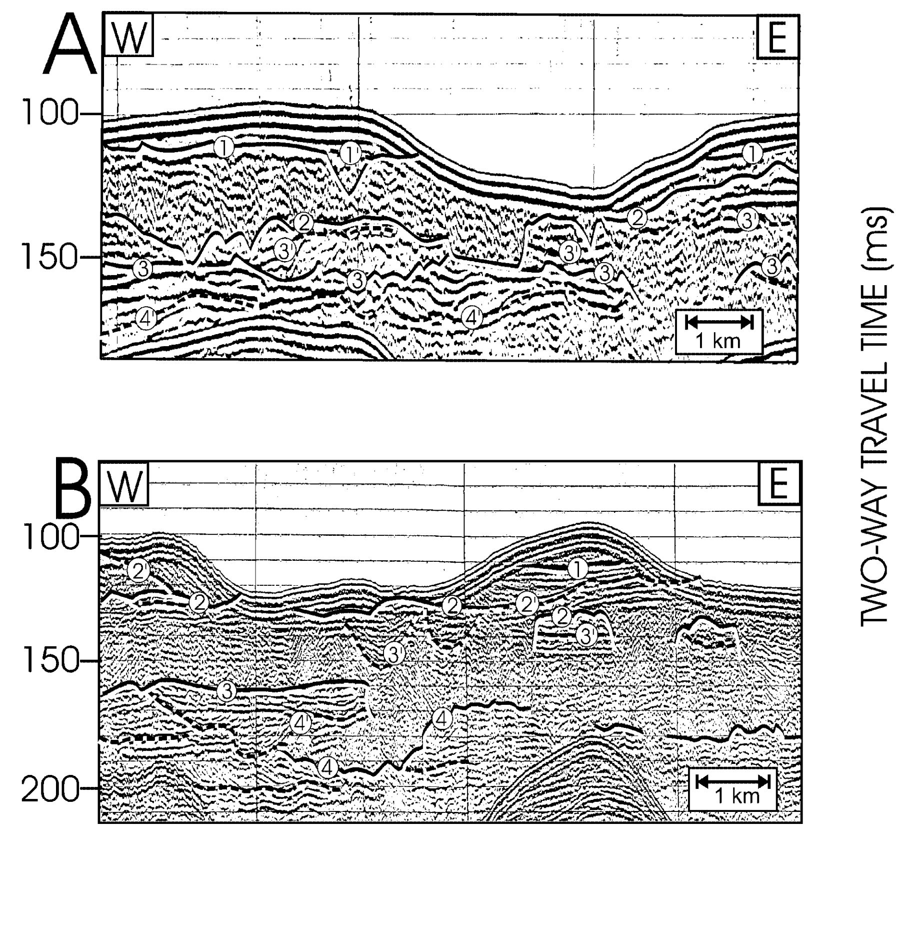

Fig. 3 Interpreted high-resolution seismic profiles in the mid-eastern Yellow Sea. The profiles display an alternation of two contrasting seismic units which are either seismically chaotic or stratified, and generally well correlated across the shelf area (for location, see Fig. 1). The stratified units are characterized by internal high-amplitude reflectors and wedge- or lens-like external forms. Based on drill core data, the chaotic units comprise clast-rich sediments, probably of non-marine origin, their base representing the sequence boundary (*circled numbers without prime*). The stratified units consist of fine-grained tidal sediments and the base represents an early transgressive tidal ravinement surface (*circled numbers with prime*)

YSDP-104

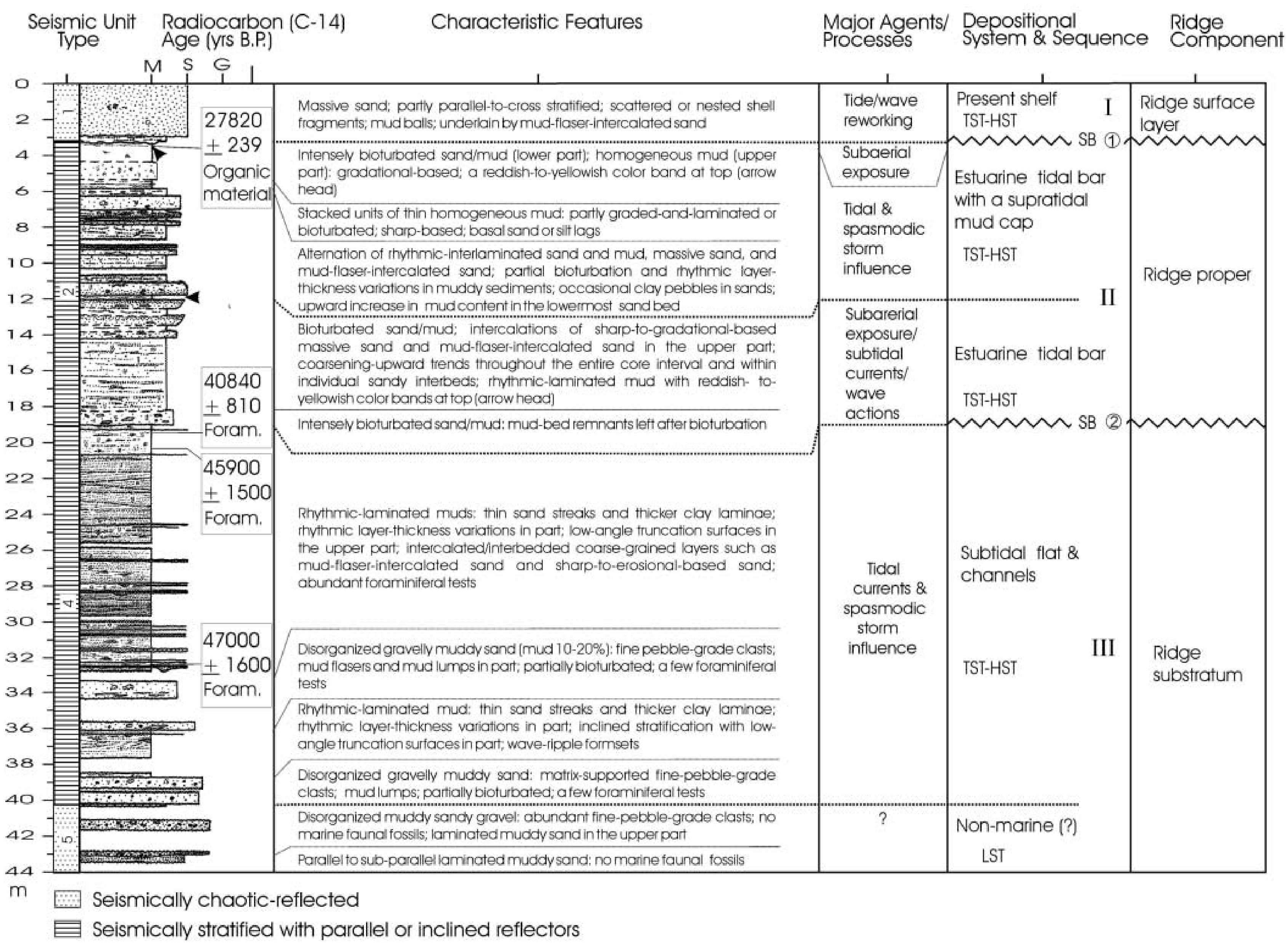
Seismic Unit Type
Radiocarbon (C-14) Age (yrs B.P.)
Characteristic Features
Major Agents/ Processes
Depositional System & Sequence
Ridge Component
M S G
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 m
1
2
4
5
27820 ± 239 Organic material
40840 ± 810 Foram.
45900 ± 1500 Foram.
47000 ± 1600 Foram.
Massive sand; partly parallel-to-cross stratified; scattered or nested shell fragments; mud balls; underlain by mud-flaser-intercalated sand
Intensely bioturbated sand/mud (lower part); homogeneous mud (upper part); gradational-based; a reddish-to-yellowish color band at top (arrow head)
Stacked units of thin homogeneous mud; partly graded-and-laminated or bioturbated; sharp-based; basal sand or silt lags
Alternation of rhythmic-interlaminated sand and mud, massive sand, and mud-flaser-intercalated sand; partial bioturbation and rhythmic layer-thickness variations in muddy sediments; occasional clay pebbles in sands; upward increase in mud content in the lowermost sand bed
Bioturbated sand/mud; intercalations of sharp-to-gradational-based massive sand and mud-flaser-intercalated sand in the upper part; coarsening-upward trends throughout the entire core interval and within individual sandy interbeds; rhythmic-laminated mud with reddish- to-yellowish color bands at top (arrow head)
Intensely bioturbated sand/mud: mud-bed remnants left after bioturbation
Rhythmic-laminated muds: thin sand streaks and thicker clay laminae; rhythmic layer-thickness variations in part; low-angle truncation surfaces in the upper part; intercalated/interbedded coarse-grained layers such as mud-flaser-intercalated sand and sharp-to-erosional-based sand; abundant foraminiferal tests
Disorganized gravelly muddy sand (mud 10-20%): fine pebble-grade clasts; mud flasers and mud lumps in part; partially bioturbated; a few foraminiferal tests
Rhythmic-laminated mud: thin sand streaks and thicker clay laminae; rhythmic layer-thickness variations in part; inclined stratification with low-angle truncation surfaces in part; wave-ripple formsets
Disorganized gravelly muddy sand: matrix-supported fine-pebble-grade clasts; mud lumps; partially bioturbated; a few foraminiferal tests
Disorganized muddy sandy gravel: abundant fine-pebble-grade clasts; no marine faunal fossils; laminated muddy sand in the upper part
Parallel to sub-parallel laminated muddy sand: no marine faunal fossils
Tide/wave reworking
Subaerial exposure
Tidal & spasmodic storm influence
Subareial exposure/ subtidal currents/ wave actions
Tidal currents & spasmodic storm influence
?
Present shelf
TST-HST
I
SB ①
Estuarine tidal bar with a supratidal mud cap
TST-HST
II
Estuarine tidal bar
TST-HST
SB ②
Subtidal flat & channels
III
TST-HST
Non-marine (?)
LST
Ridge surface layer
Ridge proper
Ridge substratum
Seismically chaotic-reflected
Seismically stratified with parallel or inclined reflectors

Fig. 4 Analytical results of deep drill hole YSDP 104, including texture, sedimentary structures, radiocarbon ages, interpretation of possible depositional processes, environments, sequences and sequence boundaries (*SB*)

and are characterized by rhythmic interlamination of sand and clay (occasionally bioturbated) and abundant foraminiferal tests. Sandy muds occasionally grade into mud. Subordinate sands and muddy sands are generally massive and show either sharp or gradational contacts with the underlying muddy sediments. Mud flasers and chips are common. In the uppermost part, a thick (~90 cm), stiff, non-fossiliferous and homogeneous mud layer is present, which has reddish to yellowish bands in the uppermost part (0–5 cm). Immediately below the color bands, the mud has been dated at 27,820 years B.P. (Fig. 4).

Rhythmic interlamination of sand and clay, intense to moderate bioturbation, and abundant foraminiferal tests in the muddy sediments (mud and sandy mud) are common characteristics of tide-influenced shallow-marineenvironments (e.g., Archer et al. 1994). The intercalating muddy sands and sands with mud chips and mud flasers are most likely indicative of sandy bedforms developed in a tide-influenced muddy environment, similar to those of estuarine tidal-bar sequences (Fenies and Testet 1998). The reddish-to-yellowish banded mud in the uppermost part is likely indicative of oxidation on the subaerially exposed surface of supratidal zones (Park et al. 1998).

Ridge surface layer

The entire ridge is covered with a sediment veneer (~3 m thick) which is seismically chaotic and has a wavy surface (Fig. 2). The sediment veneer comprises sands into which mud flasers are intercalated in the lower part, passing upwards into well-sorted sand (Fig. 4).

The sand veneer probably originated from the Holocene transgressive sand sheet which is widespread in the eastern part of the Yellow Sea (e.g., Lee et al. 1988). The wavy surface indicates the presence of subaqueous sand dunes which most likely formed in response to tidal currents. In this area, peak tidal currents in the surface layer of the water mass are strong (>2 knots) and flow approximately parallel to the ridges (Lee and Jung 1999).

Depositional processes and sequence stratigraphic interpretation

The lowermost unit (unit 5) most likely represents lowstand non-marine sediments whose chaotic character is also indicative of laterally discontinuous clast-rich subaerial deposits (e.g., Evans et al. 1995). The overlying unit (unit 4) experienced marine flooding, as suggested by the abundance of foraminiferal tests and records of tidal rhythms. Radiocarbon ages indicate that the unit is representative of isotope stage 3 which is characterized by small-scale and short-term sea-level fluctuations (Pinter and Gardner 1989; Chappell et al. 1996; Hernandez-Molina et al. 2000). The ridge substratum (units 4 and 5) thus represents a depositional sequence (sequence III) reflecting one cycle of sea-level fluctuations (Fig. 4).

The V-shaped erosional surface at the base of the ridge (Fig. 2), i.e., the lower boundary of unit 3, is most likely indicative of lowstand fluvial incision. Chaotic internal reflections also suggest the presence of discontinuous clast-rich beds of non-marine origin (e.g., Evans et al. 1995). By contrast, the large-scale hollow at the base of unit 2 (Fig. 2) most likely represents an early transgressive tidal ravinement surface filled with fine-grained tidal sediments (unit 2; e.g., Allen and Posamentier 1993). During the transgression, the seafloor was partially subaerially exposed for some periods, as suggested by the presence of supratidal mud with reddish color banding at the top (Fig. 4). The internal ridge sediments (units 2 and 3) hence represent a depositional sequence (sequence II) reflecting one complete cycle of short-term sea-level fluctuations. According to the radiocarbon age (27,000 years B.P.) at the top of unit 2, the sea-level cycle also corresponds to isotope stage 3 but is probably different from that of sequence III.

A Holocene transgressive sand sheet directly overlies the ridge deposits which mostly formed prior to the last glacial maximum (LGM: ~18,000 years B.P.) and are sharply truncated along the ridge flanks. The stratigraphic context further suggests that sedimentation was punctuated during events of large-scale sea-level fall. The Holocene transgressive sand sheet hence solely represents a depositional sequence (sequence I), its base corresponding to a type-1 sequence boundary in the sense of Posamentier and James (1993). Such near-surface unconformities are a common feature of the mid-eastern Yellow Sea ridges.

Considering ridge sediments at a shelf-wide scale, one more fragmentary unit is occasionally observed within some of undrilled ridges, being situated between the Holocene sand cover and the lower sequence II. It has thus been interpreted to be part of sequence I (Fig. 5). This unit is either seismically transparent or parallel stratified, and it is truncated at the ridge surface in similar manner to the lower sequence II. Based on its relationship to the overlying Holocene transgressive sand sheet, the deposit can be interpreted as a muddy transgressive systems tract formed at an earlier stage of the transgression. The lowstand systems tract of sequence II, i.e., unit 3 in the drilled ridge, progressively thins southwards and ultimately terminates in the southernmost part (cf. Figs. 2 and 5). Thus, ridges in the southernmost part comprise muddy transgressive highstand systems tracts of sequences I, II and III which merge up-section (Fig. 5).

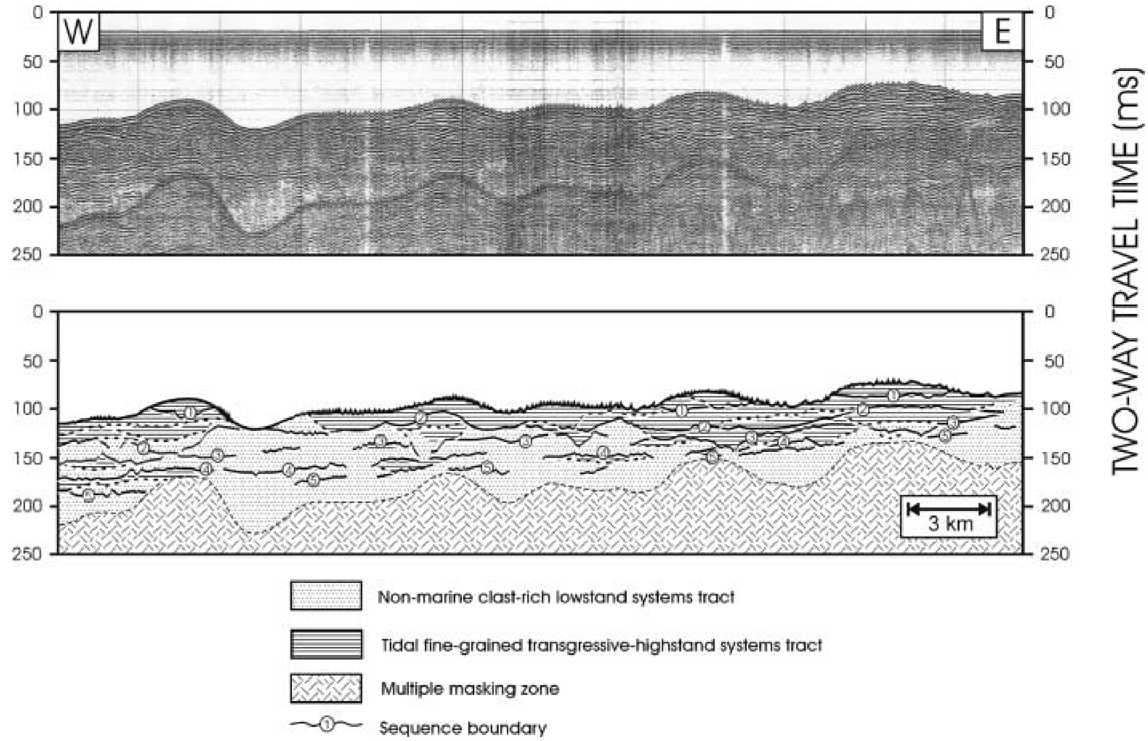

Fig. 5 Seismic profile and interpretation. The seafloor displays a ridge-and-swale topography, and the subsurface strata comprise chaotic or stratified seismic units (for location, see Fig. 1). Immediately below the ridges, non-chaotic seismic units are stacked vertically, representing merged transgressive highstand systems tracts bounded by sequence boundaries. Note that the lower boundary of sequence I is occasionally present within the ridges, underlying a stratified unit which corresponds to an early transgressive muddy deposit of sequence I. The strata below the third sequence boundary are not discussed in this study

Discussion

The mid-eastern Yellow Sea ridges are generally 10–20 m high, a few kilometers wide, and tens of kilometers long (Fig. 1), being similar to constructional sand ridges on other wave-, storm- or tide-dominated shelves (e.g., Houbolt 1968; McBride and Moslow 1991; Johnson and Baldwin 1996; van de Meene et al. 1996; Snedden and Dalrymple 2000). Despite the marked similarity in shape, the ridges in the mid-eastern Yellow Sea are, however, erosional in origin, as revealed by internal strata truncated on either side of the ridges. Based on airgun and Chirp profiles and short sediment cores, Jung et al. (1998) have also suggested that a large-scale ridge, about 60 km north of the present study area (Fig. 1A), is erosional in origin, forming a pseudo-tidal sand ridge of early-Holocene muddy deposits.

Erosional shelf ridges have also been reported from other shelf areas exposed to different hydrodynamic conditions (Berne et al. 1994, 1998). Some ridges correspond to 'juvenile ridges', i.e., precursory seabed irregularities which promote construction of 'real' sand ridges and ultimately disappear in the course of ridge migration (Snedden and Darlymple 2000). Others may simply be an expression of moribund or degraded sand ridges related to an earlier transgressional phase (Johnson and Baldwin 1996). However, we note that the ridges in the deep mid-shelf area comprise older mud-rich sediments, and that the Holocene sand cover widely displays superimposed sand dunes covering both ridges and troughs (Fig. 5). This feature suggests that the ridges neither migrate in a preferred direction to evolve into 'real' sand ridges nor are they simply degradational after initial up-building. Instead, the sand dunes indicate a strong hydrodynamic influence on the entire ridge surface, regardless of water depth between ridge crests and troughs. It would thus appear that all the ridges have undergone the same erosional shaping of their form, and are still being eroded in their original position by strong tidal currents.

Conclusions

An analysis of high-resolution seismic profiles and a deep drill core on a ridge in the eastern part of the Yellow Sea suggests that the ridges are undergoing erosion. Mud-rich sediments were largely deposited prior to the last glacial maximum and are presently being eroded on either side of the ridges. These erosional ridges are covered with a late-Holocene transgressive sand sheet displaying widespread sand dunes on the surface, indicating significant influence of strong tidal currents.

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