Sedimentary Geology 339 (2016) 68–82

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Morphologic and hydrodynamic controls on the occurrence of tidal bundles in an open-coast macrotidal environment, northern Gyeonggi Bay, west coast of Korea

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ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form 12 April 2016
Accepted 13 April 2016
Available online 22 April 2016

Editor: Dr. J. Knight

Keywords:
Dune
Tidal bundle
Time–velocity asymmetry
Tidal channel
Open-coast tidal flat
Velocity peak asymmetry

ABSTRACT

Tidal dunes with well-defined rhythmic tidal bundles are documented from the lower intertidal zone of an open-coast macrotidal environment in Gyeonggi Bay, Korea. Based on combined morphologic, sedimentologic and hydrodynamic datasets, this study aims to characterize the factors that govern the temporal and spatial variability of tidal bundles in a non-barred, unconfined macrotidal environment. The tidal dunes are flood-asymmetric and of longer wavelength (10–20 m) with small ebb caps on the upper bank, and symmetric to slightly ebb-asymmetric and of shorter wavelength (5–10 m) with larger ebb caps on the lower bank. The upper-bank dunes are characterized by more steeply dipping flood-directed planar cross-beds and thinner mud drapes than the lower-bank dunes. Each tidal bundle consists of a single mud drape that is stratified to cross-stratified, rich in silt and very fine sand. It overlies ebb-directed ripples and represents dynamic mud deposition during the ebb tidal phase. The presence of strong rotary currents (up to 0.25 m/s) and low suspended-sediment concentration of flood currents prevent deposition of mud drapes during the high-tide slack-water period. The distinct asymmetry in the water elevation at which the velocity peaks during the ebb and flood phases results in the preferential preservation of flood-directed cross-beds in the lower intertidal zone, where the ebb current – although stronger than the flood currents – is of shorter duration and hence unable to reverse the dune profile. The pronounced time–velocity asymmetry at the higher elevation combined with the distinct velocity peak asymmetry leads to a better preservation of hierarchical tidal cycles in the upper-bank dunes. The present study suggests that the persistent occurrence of single, stratified to cross-stratified mud drapes, which reflect dynamic mud deposition during the ebb phase, and the dominance of flood-directed cross-beds are diagnostic features of tidal bundles in the intertidal zone of unbarred, open-coast macrotidal environments. A proposed model for mud drape deposition provides a new perspective on the origin of tidal bundles together with useful criteria for reconstructing the paleo-depositional setting.

1. Introduction

A tidal bundle is defined as the increment of either dune cross-stratified beds (e.g., Boersma, 1969; Nio and Yang, 1991) or vertically stratified tidal beds (e.g., Dalrymple et al., 1991; Dalrymple, 2010), which is in each case deposited during a single dominant tidal phase, i.e., either during the flood tide *or* the ebb tide. Tidal bundle successions provide geologists with a plethora of information on the tidal flows that generated them, including how fast currents were flowing and the degree of local ebb-flood asymmetry (Martinius and Van den Berg, 2011), whether the tides were semi-diurnal or (less commonly) diurnal, and other phenomena such as diurnal inequality, neap–spring cyclicity, and fortnightly inequality. Neap–spring tidal cyclicities, fortnightly inequalities and tidal cycles of longer duration associated with differences in the Earth's rotational and lunar orbital periodicities, are well documented from ancient tidal deposits (e.g., Yang and Nio, 1985; Kvale and Archer, 1991; Williams, 1991; Tirsgaard, 1993; Eriksson and Simpson, 2000; Tape et al., 2003; Longhitano, 2011; Longhitano et al., 2012; Legler et al., 2013; Reynaud et al., 2013; Abouessa et al., 2014). By contrast, although tidal bundles are a common feature in modern tidal environments (e.g., Dalrymple, 1984; Fenies and Tastet, 1998; Fenies et al., 1999; Flemming, 2012), neap–spring cycles and fortnightly inequalities in maximum tidal elevations have rarely been documented in cross-section (Visser, 1980; Boersma and Terwindt, 1981; Van den Berg et al., 2007).

The internal structure of tidal bundles is known to reflect both the asymmetry and the strength of tidal currents (De Mowbray and Visser, 1984; Nio and Yang, 1991). Variation of the strength of the subordinate current leads to a wide spectrum of structures, from entirely unidirectional cross-stratification to complex, bidirectional cross-stratification replete with reactivation surfaces (Boersma and Terwindt, 1981; De

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http://dx.doi.org/10.1016/j.sedgeo.2016.04.008

Mowbray and Visser, 1984; Van den Berg et al., 2007; Martinius and Van den Berg, 2011). Because tidal asymmetry varies with water depth in tidal channels, tidal bundles also provide information regarding tidal elevation (e.g., Martinius and Van den Berg, 2011). In particular, the nature of mud drapes with pause planes bracketing tidal bundles is commonly taken as a faithful indicator of subtidal versus intertidal deposition. Conventionally, if double mud-drapes bracket tidal bundles, subtidal deposition is assumed because the subtidal zone can experience both high- and low-tide slack-water periods, whereas if single mud drapes bracket tidal bundles, intertidal deposition is assumed because the intertidal zone only experience one slack-water period (high-tide slack water) per tidal cycle (Visser, 1980). However, there seem to be exceptions to this. Thus, Fenies et al. (1999), for example, documented double mud drapes in the intertidal zone that formed by the trapping of highly turbid water in dune troughs during falling tides. Also, in subtidal settings where tidal asymmetry is small, the subordinate current may erode the underlying mud drape, resulting in the generation of a single mud drape per tidal cycle (De Mowbray and Visser, 1984; Nio and Yang, 1991). Caution is therefore advised when inferring elevation within the tidal frame based on mud drapes alone. Although the internal structures of tidal bundles and associated hydrodynamic processes are described in detail by many authors (e.g., Boersma and Terwindt, 1981; Martinius and Van den Berg, 2011), existing case studies have mainly documented tidal bundles from channelized backbarrier mesotidal settings where tidal currents are generally rectilinear (Boersma and Terwindt, 1981).

The present study documents tidal dunes in the lower intertidal zone of an open-coast macrotidal environment in Gyeonggi Bay, Korea. The internal structures of the dunes reveal hierarchical tidal cycles preserved as tidal bundles—the first documented example of such features from an unbarred, macrotidal setting. The morphodynamics and hydrodynamics of the dunes are analyzed to elucidate the factors that controlled the temporal and spatial variability of the tidal bundle structures. A model for mud-drape deposition is proposed to help differentiate deposition in unconfined open-coast tidal settings (this study) from deposition in confined channelized tidal settings.

2. Study area

Gyeonggi Bay is a wide-mouthed, macrotidal embayment along the west coast of Korea (Fig. 1A). The outer part of the bay is occupied by large, NE–SW elongated tidal bars (100 km long and 30 km wide). In the inner part, the Han River splits into four delta distributary channels around bedrock islands before debouching into Gyeonggi Bay (Cummings et al., 2016). Wide, gently sloping open-coast tidal flats fringe the rocky coastlines of the islands and mainland near the mouth of the Han River. The Yeochari tidal flat is located on the southwestern side of Ganghwa Island in the northern Gyeonggi Bay (Fig. 1A, B). Bounded by two distributary channels of the Han River, the Jangbong and Sukmo channels, it stretches southwestward, reaching a maximum width of 6 km during spring low tides. The tidal flat has three distinct morphologic zones, an upper-intertidal zone, which has a convex-up profile; a middle-intertidal zone, which has a concave-to-convex profile intersected by small tidal creeks; and a lower-intertidal zone, where large tidal channels are present. The area of investigation is located in the lower intertidal zone (Fig. 1C). Tidal channels are narrow and highly sinuous in the middle intertidal zone, and become wider and straighter toward the lower intertidal zone. Flood-oriented and ebb-oriented dunes are present on the channel banks of the lower intertidal zone. Most of the dunes are asymmetric and lack smaller, superimposed dunes. Large compound dunes are locally found on the lower channel bank near the Jangbong Channel.

Tides are semidiurnal and have a distinct diurnal and fortnightly inequality of up to 1 m (Fig. 2). Tidal ranges are 9 m during spring tides and 6 m during neap tides. Tidal currents range from 0.8 m/s during neap tides to over 1.5 m/s during spring tides. They are flood-dominated on the tidal flats and ebb-dominated in the channel (Choi and Jo, 2015). Suspended-sediment concentrations reach up to 2.5 g/l (Lee et al., 2013) and are greater during the ebb than during the flood (Choi and Jo, 2015). Significant wave heights reach 1.2 m during winter storms when winds blow from the northwest and during summer typhoons when south and southeast winds blow, but are lower than 0.3 m during fairweather conditions (Choi and Jo, 2015). Precipitation is seasonal with highest rainfalls during the summer season (July to September), accounting for about two-thirds of the mean annual precipitation of 1300 mm (KMA, 2013).

3. Materials and methods

High-precision morphologic profiles were acquired seven times from October 2014 to August 2015 along three transects (AB, CD, and EF) on foot at low tide with RTK-GPS positioning with a 10 mm horizontal and 20 mm vertical accuracy (Figs. 1, 2). Transects AB and CD run parallel to the channel and are 120 and 140 m long, respectively. They cross the dunes on the upper and the lower bank, respectively. Transect EF is oriented perpendicular to the channel and is 150 m long. Transects were repeatedly measured at one-day intervals to calculate dune migration rates. GPS positions were recorded at 3–5 m intervals along the transects. Elevations were corrected relative to the mean sea level (Incheon Datum). Current profiles and directions were measured at two locations representing the upper (A1 in Fig. 1C) and the lower bank (A2 in Fig. 1C) using Nortek AQUADOPP current profilers (2 MHz) equipped with optical back-scatter (OBS) sensors. Current profilers were moored from 8 to 25 January in 2015. The elevations of the AQUADOPP sensors were −2.2 m for A1 and −3.6 m for A2, which is approximately 0.8 m above the tidal flat surface. The blanking distance was 0.2 m for both AQUADOPPs. Current data were sampled every 5 min in burst mode for 3 min with a ping rate of 1 s. Suspended-sediment concentrations (SSCs) were measured by the OBSs attached to the AQUADOPP profilers using a sampling rate of 30 s. A series of water samples was taken during the late ebb stage and the early flood phase. These were subsequently filtered through 0.45 μm Millipore membranes, with the residues being dried for 3 h at 90 °C in an oven and then weighed to calculate SSCs. The SSCs of the water samples were used to convert nephelometric turbidity units (NTUs) measured by the OBSs to sediment concentrations (g/l).

A total of 15 trenches were excavated in the tidal dune field of the western bank of the main channel. The trenches range from 5 to 16 m in length and 0.3 to 0.8 m in depth and, in each case, cover the distance of one dune wavelength. The exposed tidal bundles along two trench sections (T1 and T2 in Fig. 1D) were documented and described in detail. The thicknesses of the tidal bundles (measured normal to cross-stratification) were extracted from photographs. A fast Fourier transform (FFT) program was used to calculate a periodogram of the tidal bundle thickness data from T1. Undisturbed core slabs were taken from the trenches using two types of stainless steel can corer (60 cm × 10 cm × 2 cm, 80 cm × 10 cm × 2 cm). Relief peels were made from the core slabs using epoxy and cheese cloth to preserve sedimentary structures for detailed analysis. Grain-size analysis was conducted using conventional sieve and pipette methods. Orientations and dip angles of dunes and bedding surfaces were measured by means of a compass fitted with a clinometer (Suunto Tandem 360PC).

4. Results

4.1. Dune occurrence and morphology

Dunes are present in the lower intertidal zone on the western bank of the main channel (Figs. 3, 4). This channel is 300 m wide and 5 m deep along transect EF (Fig. 3B), and is bordered by muddy tidal flats (Choi and Jo, 2015). During spring high tides, when the entire tidal flat becomes submerged, the water depth above the channel thalweg