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Marine sedimentology

Classifications, sedimentary features and facies associations of tidal flats

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Abstract Significant progress has been achieved in the research of tide-dominated environments in the past two decades. These studies highlight both the importance and diversity of tidal flats in modern coastal environments. Based on their developing settings, tidal flats are subdivided into nine types, which are in turn grouped into sheltered or exposed spectrums according to the magnitude of exposure to waves. The ternary coastal classification model is revised with an embedded triangle to highlight non-open coast tidal flats as major second-order morphological elements to the first-order coastal environments including deltas, estuaries and lagoons. A new continuous spectrum of open coast depositional settings is proposed from muddy tidal flats of tide dominance with wave influence, through sandy tidal flats of mixed energy (tide-dominated), and tidal beaches of mixed energy (wave-dominated), to beaches of wave-dominance with tide influence. It is worth noting that no open coast setting is absolutely exempt from wave or tide influence. Three diagnostic criteria for the intertidal-flat deposits are proposed. Upon an upward-fining succession, (1) regular changes vertically from flaser bedding, through wavy bedding and to lenticular bedding are diagnostic of most of intertidal flats; (2) cyclical tidal rhythmites point to sheltered intertidal flats typically at the inner part of macrotidal estuaries; (3) rhythmic alternations of storm and tidal deposition are diagnostic of exposed intertidal flats, especially the open coast types. Intertidal-flat deposits are generally topped by saltmarsh deposits, but underlain by different subtidal successions, like thick subtidal channel-fills, sand-bar complexes (sheltered coastal settings), and upwards coarsening successions of subtidal flats or thick subtidal sand ridge/bar complexes (exposed coastal environments).

Key words coastal classification, tidal flat, tidal deposit, open coast, facies association

1 Introduction

Tidal flats lie between the land and the sea, characteristic of regular alternations of exposure and flooding by tides. They are valuable for coastal-wetland biodiversity conservation, and buffer zone to accommodate rising sea level, and more and stronger rough seas due to global change. However, these lands are under increasing pressure from coastal erosion and land reclamation, with the latter the primary way that our ancestors conquered the sea for hundreds to thousands of years. Scientific research on the nature of tidal flats and tidal deposits did not start earlier than the early 20th century. Research interest has been further fostered in the second half of the 20th century by the need to provide a comparative facies model for the interpretation of fossil tidal facies, because coarse tidal deposits are potentially important petroleum reservoirs, and fine-grain tidal facies can be caprock or coal-bearing rock.

The first systematic geologic study of tidal flats was carried out by Rudolf Richter, a German paleontologist,

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along the German North Sea coast in the early 1920s. These studies were not only well carried on by his successors at the Senckenberg Institute, but also rapidly spread out to the Netherlands, UK and North America after the World War II (Ginsburg, 1975; Middleton, 1991; Klein, 1998). China has the most widespread tidal flats in the world, and Chinese scientists have conducted comprehensive research on tidal flats since the early 1960s, but these studies were not widely noticed until the past two decades (Dalrymple, 2010; Davis and Dalrymple, 2011). In the recent decades, the research focus has spread out from tidal flats to various tidal environments, including tide-dominated estuaries/deltas, shelf tidal-current sand ridges and sand sheets, and even deep-ocean internal tidal deposits. The new book "Principles of Tidal Sedimentology", gave a state-of-the-art review of these progresses on the full spectrum of tidal depositional environments (Davis and Dalrymple, 2011).

Increased interests in fossil tidal deposits ignited comparative studies, and provided diagnostic criteria for tidal deposits make effort of numerous textbooks on the sedimentology. A spectrum of heterolithic bedding or laminations known to be present in intertidal evironments include lenticular, wavy and flaser bedding (Reineck and Singh, 1980), although they were later recognized to occur in other environments. Nio and Yang (1989, 1991) gave a state-of-the-art review of diagnostic features of clastic tidal deposits in subtidal environments, including single and additional criteria. The single criteria, considered as unique features of tidal processes, include mud couplets, rhythmic tidal-bundle successions with tidal signatures of diurnal inequality and/or neap-spring cycles, and (uni- and bidirectional) reactivation surfaces. Additional criteria that may be produced by, but are not unique to tidal processes, include sigmoidal bedding, flaser and lenticular bedding, herringbone cross-bedding (Nio and Yang, 1989, 1991). Complete neap-spring successions of tidal bundles or tidal rhythmites are absolutely diagnostic of tidal deposition, while tidal-bundle sequences and tidal rhythmites are rarely complete (Dalrymple, 2010). "Therefore, a tidal origin must be based on less than definitive evidence in many cases" (Dalrymple, 2010). The similar conclusions have also been reiterated by Fan and his colleagues (Fan and Li, 2002; Fan *et al.*, 2004; Fan, 2011). Especially on the open coast tidal flats, their deposition bears significant signatures of wave/storm processes, including typical storm-generated hummocky cross-stratification (HCS), and storm deposition can take predominance over the tidal deposition in terms of layer thickness along the vertical tidal-flat successions (Fan *et al.*, 2004; Yang *et al.*, 2005; Fan, 2011). Overstress on the pure tide-depositional criteria to facies interpretation will therefore undoubtedly lead to misidentification of the open coast tidal-flat deposition into wave-dominated environments (Fan, 2011).

Open coast tidal flats remained less studied until the current century, although they are much more widely distributed than sheltered tidal flats along the world′s coasts and their importance for both modern and ancient tidal sedimentology has been highlighted since the mid-1970s (Klein, 1975; Wang, 1983; Ren, 1985; Wells *et al.*, 1990; Fan *et al.*, 2004; Yang *et al.*, 2005; Dalyrmple, 2010; Fan, 2011). There has been a rapid increase in publications related to open coast tidal flats since the beginning of this century. The topics cover all fields including hydrodynamics, sediment- and morpho- dynamics, sedimentology and stratigraphy, especially those in China and Korea (Li *et al.*, 2000, 2005; Chang and Choi, 2001; Fan, 2001; Fan and Li, 2002; Fan *et al.*, 2002, 2004, 2006; Kim, 2003; Yang *et al.*, 2005, 2006, 2008; Gao, 2009; Wang *et al.*, 2009). In these studies, open coast tidal flats have been highlighted as the major coastal setting, significantly different from the well-known sheltered tidal flats and tidal beaches.

Tidal flats are generally important topics of numerous textbooks on sedimentology, sedimentary environments or facies. Incomplete lists of important textbooks include "Depositional Sedimentary Environments (2nd edition) edited by Reineck and Singh (1980), "Coastal Sedimentary Environments (2nd edition)" by Davis (1985), "Sedimentary Environments: Processes, Facies, and Stratigraphy" by Reading (1996). These textbooks usually neglect the importance of open coast tidal flats or even deny their potential of wide distribution. We carefully examined the widely-used and regularly-revised textbook "Principles of Sedimentology and Stratigraphy", and found little that addressed the increasing knowledge of tidal-flat deposition, although five editions have been published since the first edition was available in 1987, and the newest edition is coming out in 2012 (Boggs, 1987, 2012). Here we try to give a brief review of the research progresses on tidal flats, especially open coast classification, and highlight is put on the varied features of different types of tidal flats, and the association of intertidal flats with other depositional elements in the entire depositional systems. The ternary process-based coastal classification model of Boyd *et al.* (1992) will be revised to accommodate the newly coming-up knowledge on the tidal-flat deposition.

2 Classifications of tidal flats and coastal environments

2.1 Classifications of tidal flats

Tidal flats are low-relief environments typically flanking the coast of a broad shelf with marked tidal rhythms. Macrotidal conditions undoubtedly favor the development of extensive tidal flats, but they are also common in mesotidal to microtidal coasts (Eisma *et al.*, 1998). Different from wave processes quickly dissipated on the shore, tides can penetrate into lagoons, estuaries and deltaic distributaries for tens to hundreds of kilometers landward from the shore. Tidal magnitude can be greatly amplified when entering a funnel-shaped estuary or distributary before decreasing upstream and vanishing. Therefore, tidal flats can be developed in numerous environments, including chenier plains, lagoons, estuaries, deltas (Figs. 1, 2).

Morphology and sedimentology of tidal flats are majorly controlled by sediment types and flux, and interactions of tides and waves. According to the magnitude of exposure to waves, tidal flats can be classified into three major types in terms of their depositional environments: (1) back-barrier settings, (2) tide-dominated estuaries, and (3) deltas and adjacent chenier plains, with increasing wave exposure from low to high (Fig. 3).

Back-barrier tidal flats are referred to those occupying the landward side of barrier islands, spits and bars, where waves are typically low or absent. Tides penetrate into the systems through tidal inlets and decrease landward quickly. The back-barrier area can be partly occupied by tidal flats like those in lagoons and wave-dominated estuaries (Fig. 2a), or entirely filled with the tidal channel and flat system like the Wadden Sea (Fig. 2b). All of them receive limited sediment input from land. Back-barrier tidal flats are typically well-developed along the North Sea coast, and the Atlantic coast of Europe and North America, which are both trailing edge coast receiving limited fluvial sediment input. They can also develop along the leading edge coasts like the Pacific US coast (*e.g.*, Alaska and northern California) where they receive abundant sediments.

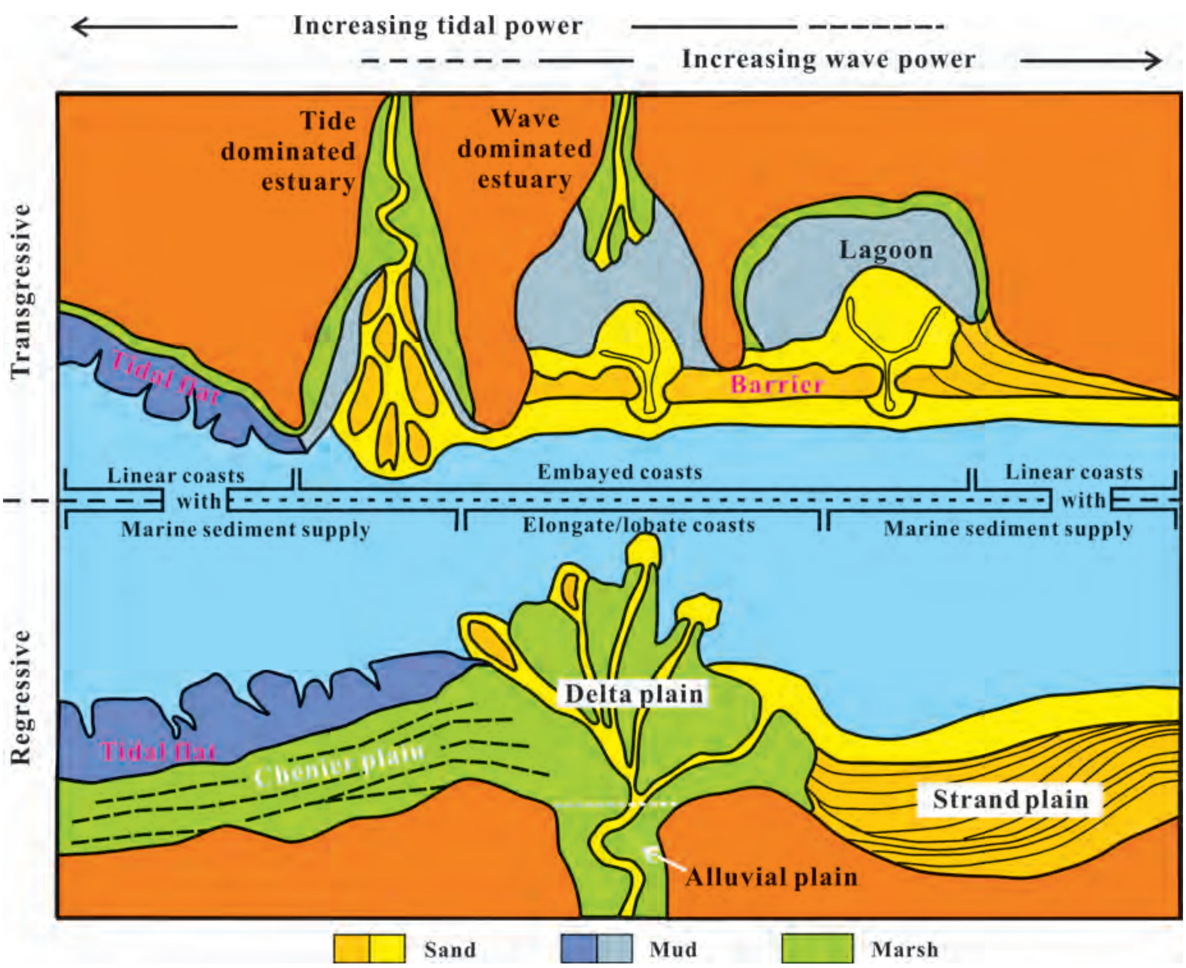

Fig. 1 The distribution of major coastal depositional features (after Boyd *et al.*, 1992).

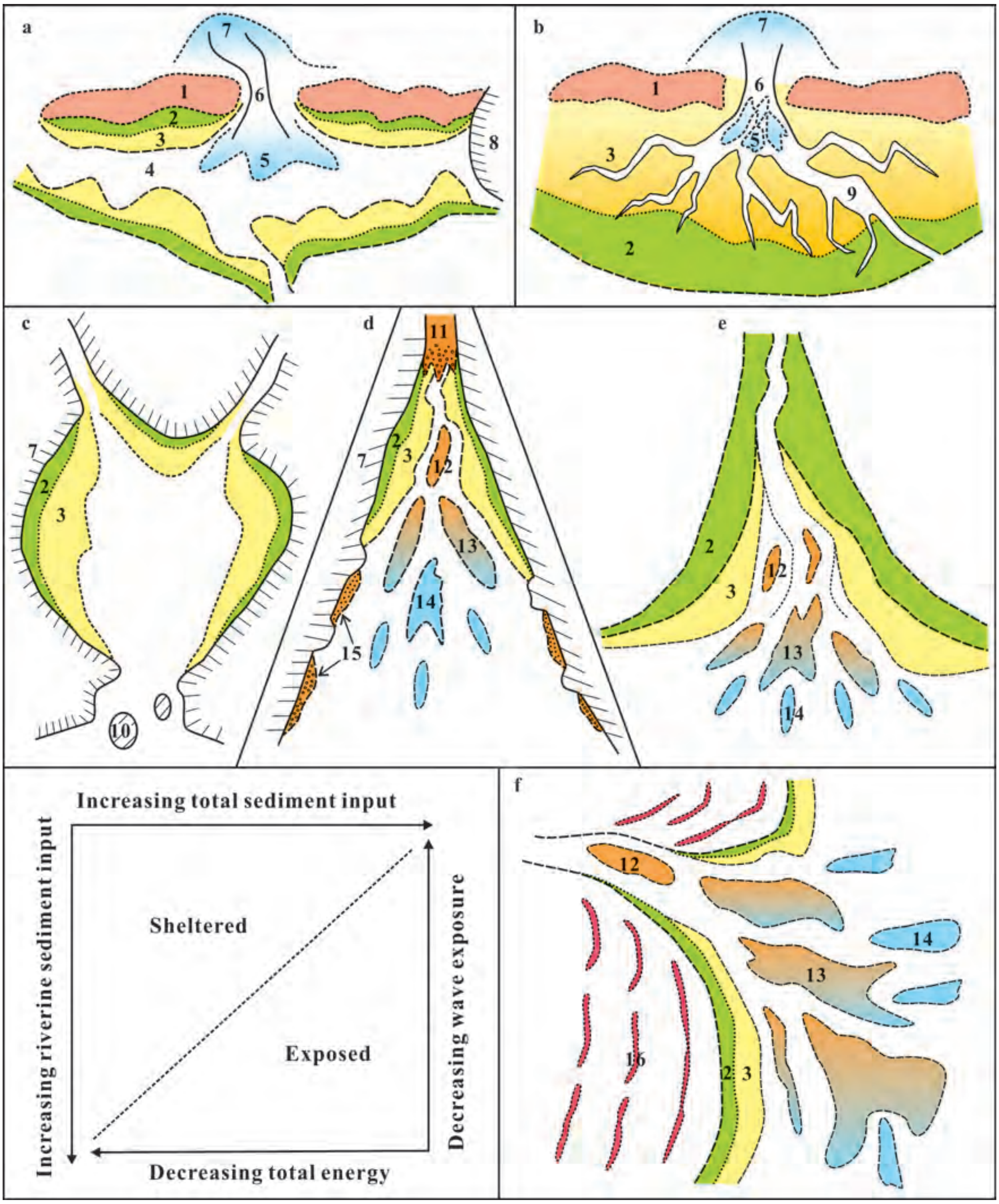

Fig. 2 Schematic plots of tidal flats in the different coastal environments with varying sediment input and wave exposure. a−Barrier-lagoon to wave-dominated-estuary system; b−Barrier-flat system (*e.g.*, Wadden Sea); c−Poorly filled gourd-shaped estuary; d−Partly filled open-mouth estuary; e−Highly filled open-mouth estuary; f−Tide-dominated delta and adjacent chenier plain. 1−Barrier island, 2−Saltmarsh, 3−Bare intertidal flat, 4−Lagoon, 5−Flood tidal delta, 6−Tidal inlet, 7−Ebb tidal delta, 8−Rocky coast, 9−Tidal channel/creek, 10−Rocky island, 11−Bay-head delta, 12~13−Tidal sand bar/island, 14−Subtidal sand bar/ridge, 15−Gravel/sand beach, 16−Chenier ridge.

Tidal flats fringing the tide-dominated estuaries/deltas have varied magnitudes of wave exposure. Those are generally exempted from wave influence in the gourd-shaped estuaries or the inner most part of the estuarine/deltaic system (Fig. 2c). The outer part of the open-mouth estuaries and deltas are subject to wave impacts, especially during storm seasons (Figs. 2d−2f). In general, small river estuaries of tide domination usually foster sandy tidal flats because of limited fine sediments input from the rivers, like those along the west-central South Korea coast, and

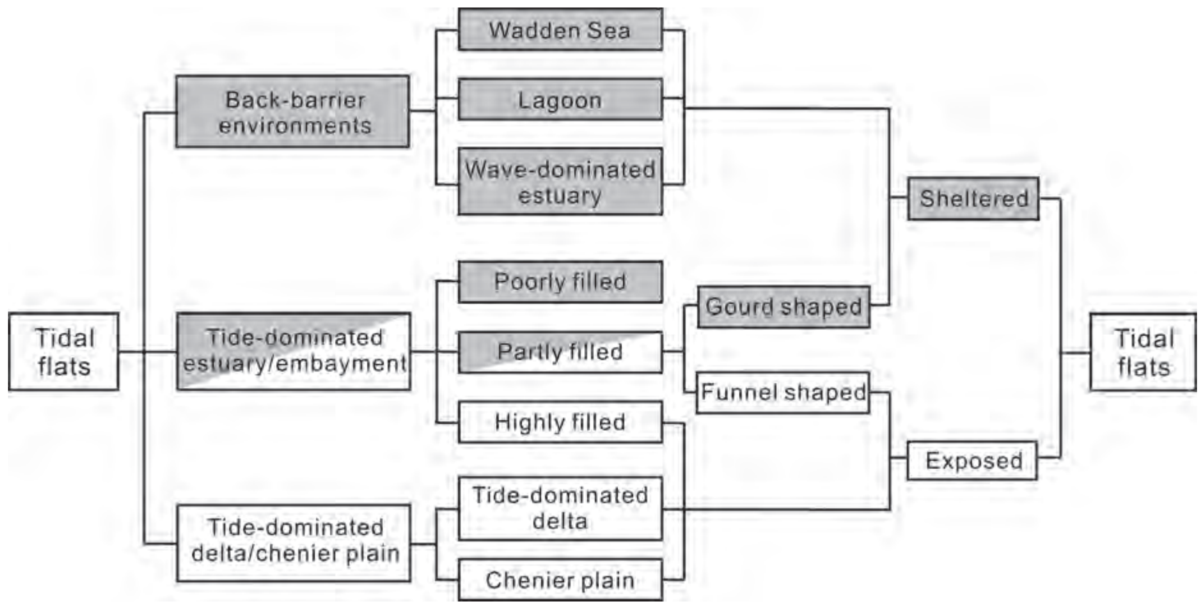

Fig. 3 Classifications of tidal flats and their relationship.

the west-central coast of Taiwan. However, some small river estuaries along the downstream coast of mega-river deltas can be filled with fine-grained sediments, which are transported by longshore currents down from the deltas. For example, several estuaries along the Zhejiang and Fujian coast are filled with fine sediments sourced from the Changjiang Delta.

Tidal flats flanking chenier plains are directly open to the sea. They belong to the first-order coastal depositional setting according to Boyd′s model, equivalent to beaches margining strandplains (Boyd *et al.*, 1992; Fig. 1). The chenier plain tidal flats are therefore named as open coast tidal flats to differ from others in lagoons, estuaries and deltas (Fan, 2011). Long-term alternations of deposition and erosion of open coast tidal flats are conceived to develop extensive chenier plains abutting the deltas in the Holocene, linked to the secular fluctuation of wave climates, river sediment discharge or shifting of the main river channel. Larger river deltas tend to foster wider and longer chenier plains with extensive muddy tidal flats at the margin. The two longest stretches of muddy open coast tidal flats are linked to the river deltas of the Changjiang and the Amazon, extending over 600 km along the Jiangsu coast and 1600 km along the Guiana coast, respectively (Fan, 2011). Sandy open coast tidal flats are generally related to small river estuaries or deltas, bordering the Holocene chenier plains of relative smaller areal scales (Reineck and Cheng, 1978; Semeniuk, 1981), the erosional Late Quaternary deposits or the rocky cliff (Thompson, 1968; Semeniuk, 1981; Yang *et al.*, 2005).

Therefore, tidal flats are classified into 9 types in terms of their developing coastal environments (Fig. 3). They are in turn grouped into sheltered or exposed tidal flats according to the magnitude of wave exposure. The nomenclature of open coast tidal flats used here is conservative for the chenier plain tidal flats instead of the wide usage by Fan (2011) to include moderately to highly exposed estuarine/deltaic tidal flats.

2.2 Revising classification model of clastic coastal depositional settings to accommodate non-open coast tidal flats

Great efforts have been put on the structuring of coastal classifications since the early 20th century. Various approaches have been employed to categorize coastal environments. For example, Curray (1964) classified the coasts into transgression and regression based on the relationship of sediment supply and relative sea level change. Because of universal presence of tides on the coasts, a simple approach on the basis of tidal ranges, proposed by Davies (1964, 1980), has been widely used to classify shorelines into microtidal (<2 m), mesotidal (2−4 m), and macrotidal (>4 m). Hayes (1979) further subdivided Davies′s tidal classification into 5 categories: microtidal (0−1 m), low mesotidal (1−2 m), high mesotidal (2−3.5 m), low macrotidal (3.5−5 m), high macrotidal (>5 m). Levoy *et al.* (2000) created a new term "megatidal" typically for the larger spring tidal range over 8 m. However, the coasts with microtidal ranges are not necessary to be wave-dominated, and macrotidal ranges are not equivalent to tide dominance. The relative effects of waves and tides were considered of extreme importance for coastal genetic morphologies by Hayes (1979) and Davis and Hayes (1984), who proposed a graphic model on the basis of mean wave height and mean tidal range to display the spectrum of wave-to tide-dominated coasts. In this model, the middle ground between two coastal end members is highlighted, including mixed energy (wave-dominated), mixed energy (tide-dominated) and tide-dominated (low). These mixed wave-tide-dominated coasts were estimated to constitute a considerable proportion of the world′s shorelines. Their fundamental processes differ from extremely wave- or tide-dominated coasts due to the interactions of waves and tides through mutual muting, modulation, or amplification, resulting in distinct process signatures, sediment transport patterns and coastal morphologies (Anthony and Orford, 2002).

Fluvial process is another critical factor to classify coasts in addition to marine processes. A ternary classification model based on wave, tide and river processes was firstly proposed by Golloway (1975) to categorize deltas, which has been extensively used because of its simple but effective nature. Boyd *et al.* (1992) developed a more comprehensive ternary coastal classification model, aiming to include all major clastic depositional coastal settings including deltas, estuaries, beaches (strand plains), tidal flats (chenier plains), and lagoons (Fig. 4a). The upper triangle of the model is equivalent to Galloway′s delta classification model, denoting progradational coasts characteristic of predominant river sediment source and elongate/lobate shorelines (Fig. 1). The middle trapezoid provides a framework for the process classification of estuaries and lagoons with an embayed shoreline and a mixed river and marine sediment source. The basal part is conceptually similar to Hayes′ bivariate (wave/tide) classification of coasts away from rivers, with a linear or irregular shoreline receiving marine source sediment by onshore or longshore transport, the latter usually originating from the river deltas (Boyd *et al.*, 1992). Progradation of beaches and tidal flats tends to build up varied width of strand plains and chenier plains in the Holocene, respectively (Fig. 1).

Based on updated knowledge of tidal beaches and open coast tidal flats, Yang *et al.* (2005) revised the Boyd model by appending an inverse trapezoid to denote in more detail the coastal classification spectrum from tide-dominated tidal flats, through open coast tidal flats and tidal beaches, to wave-dominated beaches (Fig. 4a). However, sheltered tidal flats were incorrectly assigned as the end member of tide-dominated tidal flats that should develop along the open coasts according to the original connotations of Boyd *et al.* (1992). Sheltered tidal flats are actually the second-order coastal morphologic settings, important elements of the first-order coastal environments including deltas, estuaries and lagoons. They are not yet included in the coastal classification model of Boyd *et al.* (1992; Figs. 1, 4a). Intertidal flats and subtidal flats/channels become more and more important in our understanding of coastal depositional systems and the related facies models, especially for tide-dominated estuaries and deltas. These units have been treated as separate elements from the delta front in depositional facies models of deltas (*e.g.*, Roberts and Sydow, 2003; Bhattachary, 2006). Therefore, Boyd′s ternary model was here revised again through using an embedded triangle to denote the importance of these second-order depositional settings to the first-order coastal environments (Fig. 4b). The asymmetrical triangle indicates the universal existence of tides in coastal settings but higher abundance of tidal flats to the tide-dominated deltas and estuaries than wave-dominated counterparts

Along the open coasts, muddy tidal flats should be treated as extremely tide-dominated coastal environments, equivalent to wave-dominated beaches. Waves can be greatly damped over the extensive muddy tidal flats, especially at the presence of fluid mud which has been frequently observed (Fan, 2011). As wave energy increases, deposits of tidal flats coarsen toward the middle ground between extremely tide- and wave-dominated environments. Baeksu tidal flat is a typical sandy open coast tidal flat with distinct seasonal alternation of depositional settings from summer muddy flat to winter sandy shoreface. The prevalence of storm deposits over tidal deposits in terms of layer thickness, and extensive distribution of wave-generated structures including HCS make it difficult to differentiate from tidal beaches (Yang *et al.*, 2005). Therefore, a new spectrum of open coast depositional settings is proposed to change from muddy tidal flats of tide dominance with wave influence, through sandy tidal flats of mixed energy (tide-dominated), and tidal beaches of mixed energy (wave-dominated), to beaches of wave-dominance with tide influence (Fig. 4b).

3 Morphology and sedimentary features of tidal flats

3.1 Morphology of tidal flats

Tidal flats have been generally used with different annotations: (1) bare intertidal flats, (2) intertidal zone in-

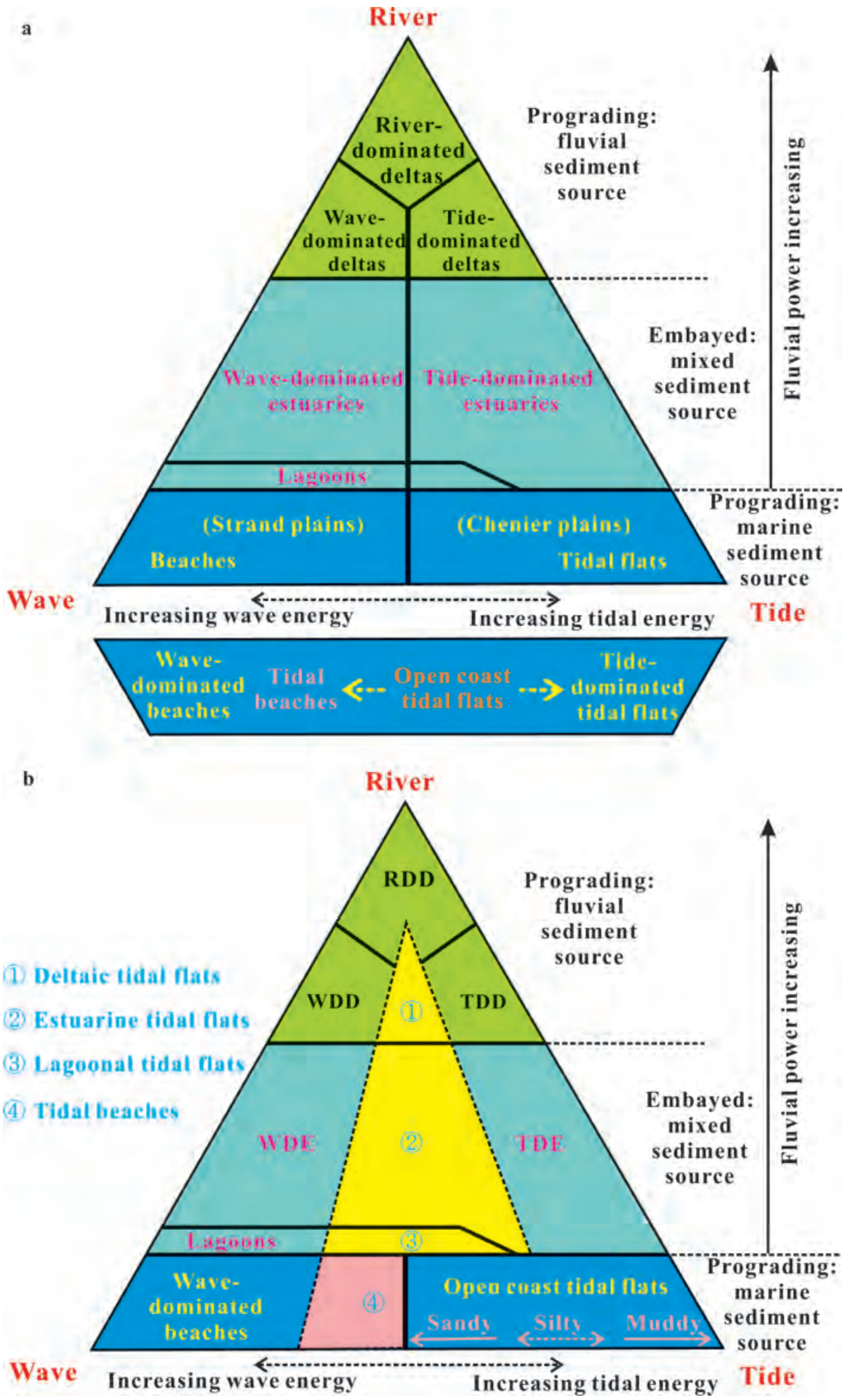

Fig. 4 Ternary process-based clastic coastal classification. a–Modified after Boyd *et al.* (1992) and Yang *et al.* (2005); b–Revised to recognize non-open coast tidal flats as the most important second-order depositional units to coastal classification, and reorganize open coast depositional settings on the basis of updated understanding of relative tide energy versus wave energy from right to left.

cluding bare flats and saltmarshes, (3) extensive low-relief platform extending from supratidal to subtidal zone. In this context a loose definition (the third) of tidal flats has been used. Intertidal flats have been the most extensively studied among the three subdivisions. The intertidal flats can be further divided into upper, middle and lower subzones (Fig. 5). However, the zonation boundary is quite varied among the different criteria of grain size, vegetation and tidal level, and a worldwide zonation can only be distinguished by tidal levels (Amos, 1995; Eisma, 1998). Here we describe the zonation of tidal flats in a synthetical way instead of using single criteria.

The supratidal and the upper part of intertidal flats are usually covered with vegetation, characterized by extraordinarily gentle relief, fine-grained deposits principally consisting of clay and fine silt, and higher concentration of organic matter. The canopies change from mangroves in the tropical zone to saltmarsh plants in the temperate zone. In some dry regions, the higher part of tidal flats supports only scant vegetation where salt pans can be well developed with sediment having higher concentration of evaporate minerals. Vegetated flats are usually dissected by delicate tidal creek systems. Landward side of vegetated flats lies on varied width of deltaic/chenier plains, ranging from hundreds of meters to over tens of kilometers determined by the sediment supply.

The vegetated intertidal flats may transit smoothly to the bare intertidal flats without a discernable topographical relief especially for the prograding tidal flats during the low-wave accretionary periods. However, the boundary is generally demarcated by an erosional escarpment of several centimeters to decimeters on the receding tidal flats. Erosional escarpments were also found to be present on some prograding flats, typically after episodic erosion by large waves (Fan, 2011). In general, there is a fining (coarsening) landward trend of surficial sediment on the progradational (recessional) intertidal flats (Fan *et al.*, 2004; Yang *et al.*, 2005), tending to have a convex-up (concave-up) profile, respectively (Kirby, 2000). Tidal channel networks are generally not much developed or event absent on the exposed intertidal flats in comparison with their delicate development on sheltered tidal flats. The most obvious relief over the exposed intertidal flats is the presence of single or more than two swash sand sheets/bars with higher concentration of shell debris, which may fully develop into chenier ridges if erosion continues for a longer term.

The intertidal flats usually grade smoothly into the subtidal flats without a discernible relief in an exposed coastal environment, and surficial sediment on the subtidal flats becomes finer seaward from the lower waterline, reversing the seaward-coarsening trend of the intertidal flats. However, in a sheltered coastal environment the intertidal flats are generally bordered by estuarine/ distributary channels, which are usually occupied by tidal sand shoals/bars (Fig. 5).

3.2 For the intertidal flats, there are no unique bedding types restricted to these environments

Diagnostic criteria of tidal deposits have been well discussed and summarized by Nio and Yang (1989, 1991), including mud couplets, rhythmic tidal-bundle successions bearing diurnal-inequality and/or neap-spring tidal signatures, and (uni- and bidirectional) reactivation surfaces. These sedimentary features are mainly produced by lateral migration of large bedforms, especially in the subtidal environments, although mud couplets were also reported on the intertidal environments (Fenies *et al.*, 1999; Fan *et al.*, 2012). For the intertidal flats, there are no unique bedding types restricted to these environments (Reineck and Singh, 1980). Tide-genesis interpretation should be based on the balance of probabilities for any bedding types present in

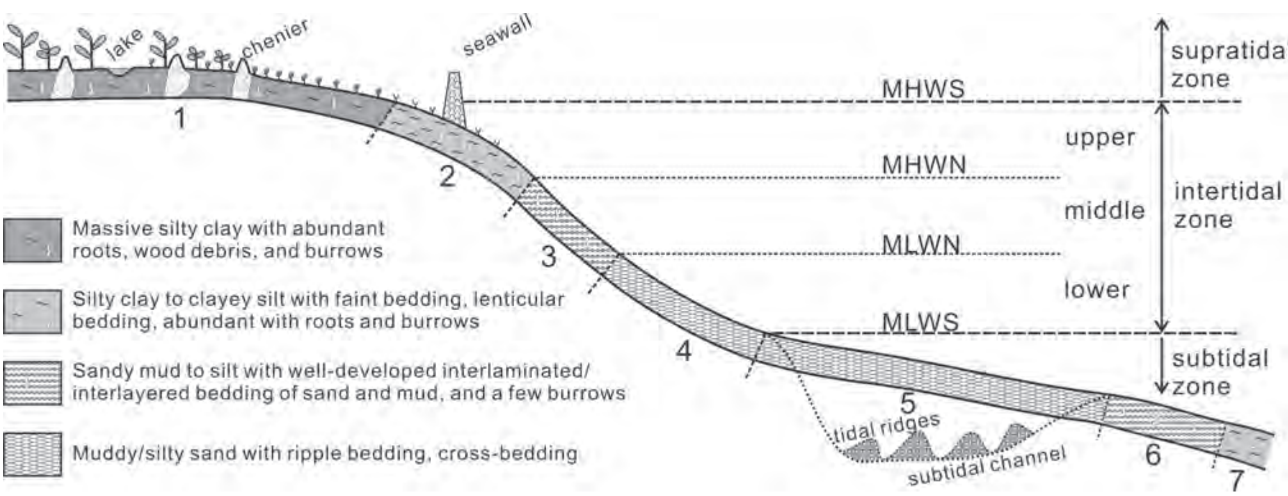

Fig. 5 Schematic map showing the cross profile variations in morphology and sedimentology of tidal flats from the supratidal to the subtidal zones.

tidal settings and other environments (Dalrymple, 2010) and/or regular arrangement of a group of structures instead of a single bedding.

3.2.1 *Regular changes of flaser, wavy and lenticular bedding in an upward-fining succession*

Flaser, wavy and lenticular bedding is a gradational spectrum of heterolithic deposits with alternating beds/laminae of sand and mud. They may also be produced by episodic flooding on the alluvial plains, or weak storms in the offshore environments, but their primary occurrence is in tidal settings where the regular presence of slack tides favors mud deposition (Reineck and Singh, 1980; Dalrymple, 2010). Field observations by using tiles on the modern tidal flats showed the formation and preservation potential of tidal bedding (Fig. 6), which has been extensively discussed by Fan *et al.* (2004) and Fan (2011). Tidal bedding can be non-tidal origin or formed in a subtidal setting, but regular changes of tidal bedding from flaser bedding, through wavy bedding, and to lenticular bedding in an upward-fining succession should be ascribed to intertidal-flat deposition. There is a general seaward-coarsening trend of surface sediment on the accretional intertidal flats, so a prograding intertidal flat will build up an upward-fining succession, with coarse sediment at the base predominated by flaser bedding, and fine sediment at the top dominated by lenticular bedding.

3.2.2 *Cyclical tidal rhythmites in an upward-fining succession*

Cyclical tidal rhythmites refer to horizontal laminations or beddings bearing neap-spring cyclicity in terms of regular variations in (sandy) bed/lamina thickness. They are the tidal-flat depositional equivalent of cyclic tidal-bundle sequences in the subtidal channel settings. Although cyclical tidal rhythmites are diagnostic of tidal-flat deposition, they are not common in both modern and ancient tidal-flat environments. Their development requires certain circumstances including wave protection, high sediment supply and enough accommodation space availability over a short term. The margins of estuarine channels have a high potential to deposit neap-spring cyclic sequences, especially in megatidal estuaries where tidal bores may occur. A few modern cyclical tidal rhythmites have been reported in such environments, like the Cobequid Bay-Salmon River estuary in Bay of Fundy (Dalrymple *et al.*, 1991), the Turagain Arm in Cook Inlet (Greb *et al.*, 2011), and the Qiantang Estuary in Hangzhou Bay (Fan *et al.*, 2012). Groupings of thick sandy beds/laminae are referred to deposition of spring tides, while those of thin sandy layers are products of neap tides, and their regular alternations consist of spring-neap cycles (Fig. 7). It is worthy noting that these sections with cyclic tidal rhythmites are not thicker than ~1.0 m when compared to interpret ancient tidal rhythmites.

3.2.3 *Rhythmic alternations of storm and tidal deposition in an upward-fining succession*

Exposed tidal flats are subject to wave or even storm impacts. Interactions of tides and waves are critical factor in shaping morphology and sedimentation on exposed tidal flats. During low wave conditions, tides take a lead-

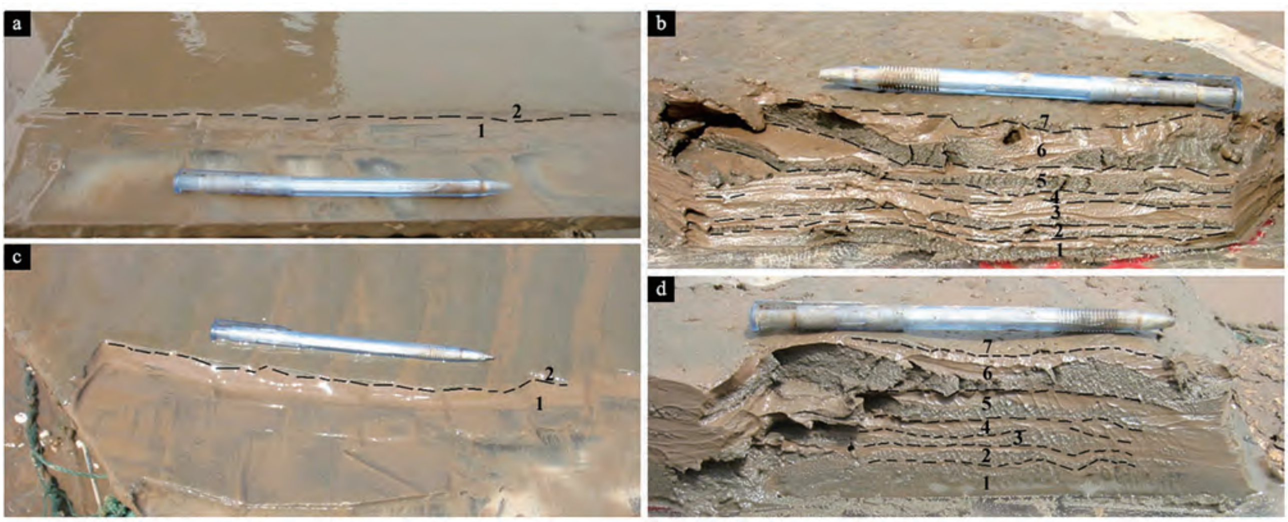

Fig. 6 Deposits accumulated on the observation tiles which were deployed on the surface of the middle intertidal flats: a−One semidiurnal tide; b−One day (two semidiurnal) tides; c−15 days (29 semidiurnal) tides; d−A month (60 semidiurnal) tides.

Fig. 7 Series of photos of short cores collected from Jianshan tidal-flats along the north bank of the Qiantang Estuary showing cross-shore change in cyclic tidal rhythmites at the higher intertidal flats to massive tidal-bore deposits at the lower intertidal flats (N: neap tide, S: spring tide).

ing role in deposition, producing thin alternations of sand and mud laminae (Fig. 6). During the storm conditions, tidal flats are lowered and sediment becomes sandier, and an upward-fining succession are deposited at and after a storm waning phase (Fig. 8a). Therefore, a grouping pair of sand-dominated layers (SDLs) and mud-dominated layers (MDLs) is the product of seasonal alternations of wave climates on the muddy exposed tidal flats (Fan *et al.*, 2004). On the sandy exposed tidal flats, grouping of sand-dominated layers may contain hummocky cross-stratification, making it similar to tidal beaches (Fig. 8b). However, the HCS on sandy open coast tidal flats has a smaller wave length, usually less than 2 m, than that with <2 m on beaches and shelves (Yang *et al.*, 2005). A specific

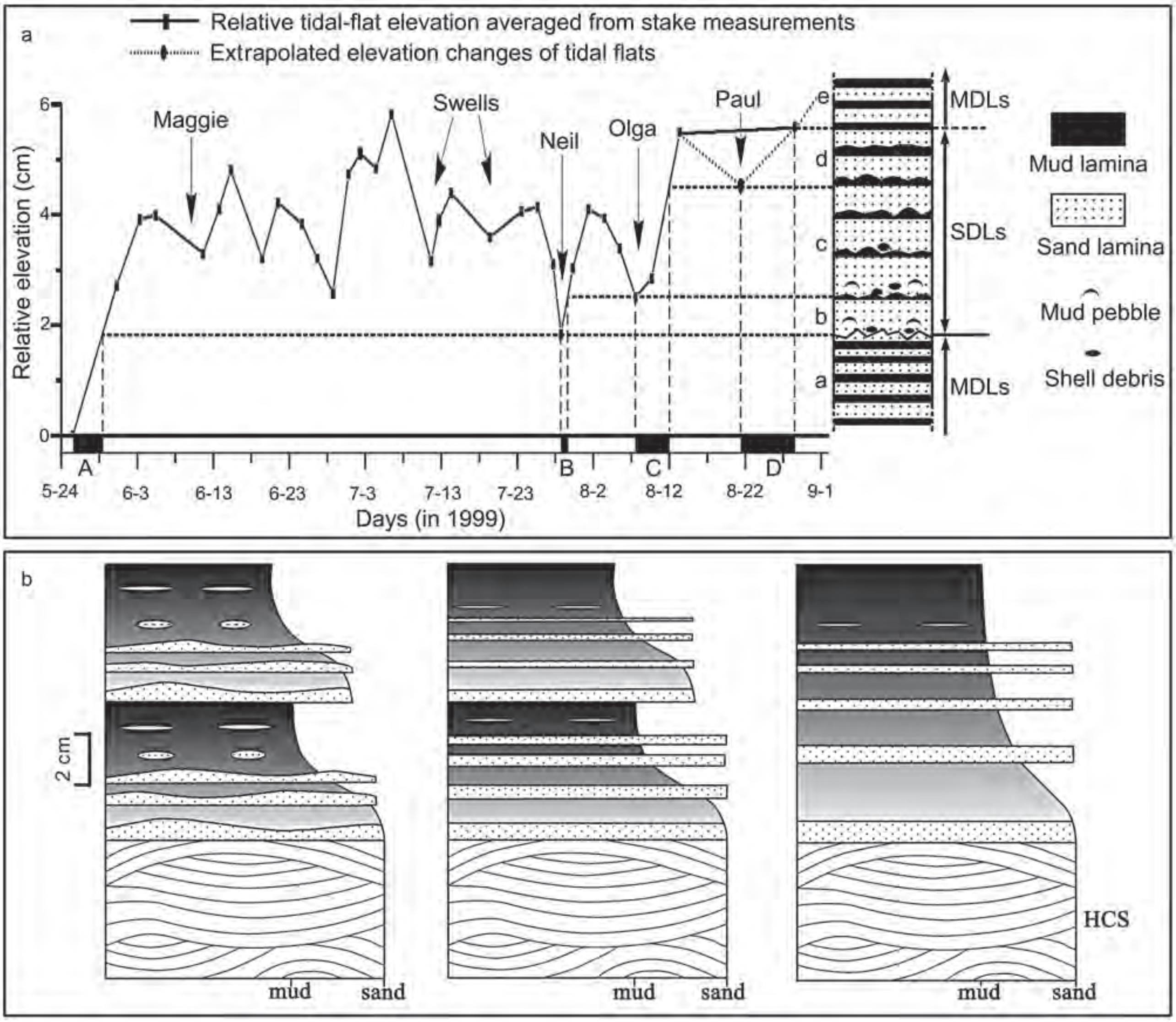

Fig. 8 A pair of groupings of sand-dominated layers (SDLs) and mud-dominated layers (MDLs) is the product of seasonal alternations of wave climates. a−A genesis interpretation model was developed upon the long term elevation monitoring data at an exposed tidal flat of the Changjiang Delta (Fan *et al.*, 2004); b−The SDLs package consisting of hummocky cross-stratification (HCS) was formed in winter during the waning stage of the bigger storms, overlain by summer MDLs packages with different structures (Yang *et al.*, 2005).

structure, wave-generated tidal bundles, has been recently reported as a good indicator of wave-dominated tidal flats, produced by the interaction of waves and reversing tidal currents over a single tidal cycle (Yang *et al.*, 2008).

4 Facies associations of intertidal flats

Three major sub-environments of tide-dominated settings include tidal flats, tidal channels and tidal sand bars or tidal-current sand ridges in shelf settings, and their relationships have been elaborately discussed by Dalrymple (2010). Tidal flats may develop in all coastal settings except the wave-dominated beaches (Fig. 2), which can be categorized into sheltered and exposed groupings according to their wave exposure magnitude (Fig. 3). There is not a bedding type definitely ascribed to intertidal flats, which should therefore be studied using a depositional system approach instead of individual separate elements, especially for the interpretation of ancient tidal facies.

Intertidal flats generally transit landward into saltmarshes or mangroves without much difference between sheltered and exposed tidal flats. Because of the availability of coarse sediment and landward decreasing of the total hydrodynamic energy, surface sediment usually fines landward from the lower intertidal flat to the supratidal flat except for a few transgressive tidal flats. Therefore, a prograding intertidal flat will build up an upward-fining succession with well developed flaser bedding at the base, wavy bedding at the middle, and lenticular bedding at the top, overlapped by saltmarsh deposits (Fig. 9). The major difference is that sheltered tidal flats may contain more channel-filled deposits and thick sand-flat deposits than exposed tidal flats. Whereas, exposed tidal-flat successions are characterized by abundance of combined-flow and wave-induced structures and bedding, which may predominate over tidal deposition in the vertical sequence in terms of layer thickness, especially for sandy open coast tidal flats.

Great diversity occurs at the subtidal zone annexing the intertidal flats. Exposed intertidal flats usually transit into subtidal flats without a discernible relief. The subtidal flats tend to have very gentle slope and a fining-seaward trend of surface sediment because of the availability of coarse sediment and decreasing total hydrodynamic energy seaward with increasing water depth. Therefore, a regressive exposed tidal flats consists of two parts, with the lower half coarsening upward from lower to upper subtidal flats, and the upper half fining upward from lower to upper intertidal flats (Fig. 9b; Li *et al.*, 1992). Some exposed tidal flats may prograde over the subtidal sand-ridge systems like those on the central North Jiangsu coast (Ren, 1985) and the estuarine or deltaic-distributary mouth bars, where thick sand ridge/bar deposits are expected (Fig. 9c; Dalrymple *et al.*, 2003). However, the intertidal flats are generally bordered by estuarine/distributary channels in a sheltered coastal environment, which are usually occupied by tidal sand shoals/bars. The prograding channel-flat system will produce a fining-upward sequence, with thick sand deposition successions at the base including subtidal channel-filling facies, subtidal shoal/bar complex and intertidal shoal deposits, topped by intertidal muddy deposits and marsh deposits (Fig. 9a; Dalrymple, 1992).

5 Conclusions

Increasing research interest in tidal flats has been re-

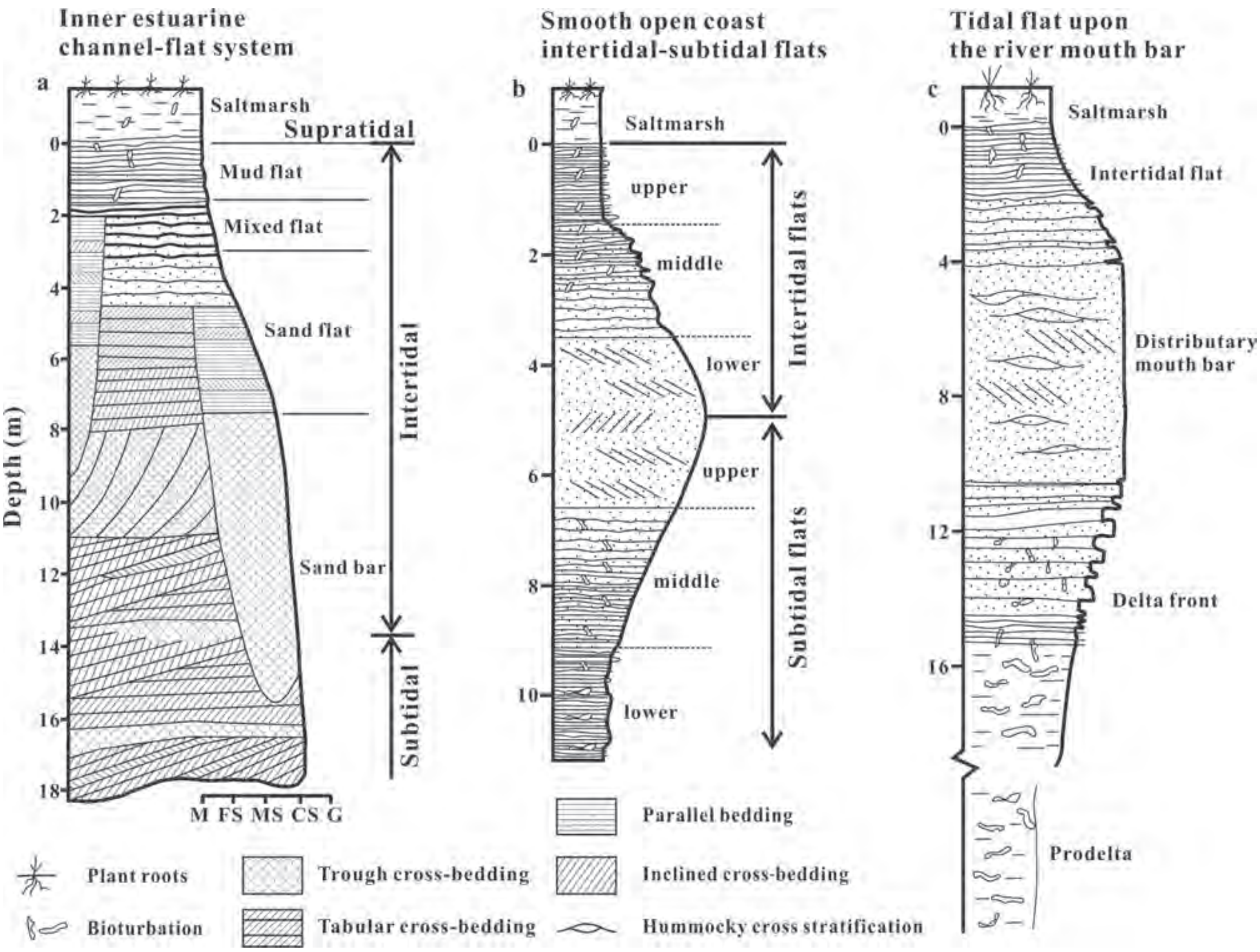

Fig. 9 Schematic models showing the three most common progradational tidal-flat successions in the sheltered, open coast and deltaic environments (after Li and Li, 1982; Dalrymple, 1992; Li *et al.*, 1992; Dalrymple *et al.*, 2003; Fan, 2011).

cently stimulated by their important roles in the conservation of coastal wetland biodiversity and buffering coastal erosion and flooding by rising sea levels and intensifying storms, also by the need of comparative study for fossil tidal facies interpretation, in that coarse tidal deposits have the potential to be important petroleum reservoirs and fine-grained tidal facies can be caprock or coal-bearing rock. Updated knowledge is massive from the studies of tide-dominated deltas or estuaries, and open coast tidal flats. The latter is extraordinarily critical in renovation of our previous pseudo conception that the open coast settings are unfavorable to develop extensive tidal flats due to significant wave influence or even dominance by waves.

Recent research highlights both the importance and diversity of tidal flats in modern coastal environments. Tidal flats have been classified on the basis of their depositional settings into nine types, which are in turn grouped into sheltered or exposed spectrums. The ternary coastal classification model of Boyd *et al.* (1992) is therefore revised to mirror non-open coast tidal flats as major morphological a greater elements to the first-order coastal environments, including deltas, estuaries and lagoons. The embedded triangle denotes the universal existence of tides and their important role in shaping coastal morphology, and its asymmetry indicates a greater abundance of tidal flats in tide-dominated deltas/estuaries than wave-dominated counterparts. The spectrum of open coast depositional settings is also revised to change from muddy tidal flats of tide dominance with wave influence, through sandy tidal flats of mixed energy (tide-dominated) and tidal beaches of mixed energy (wave-dominated), to beaches of wave-dominance with tide influence. It is worth noting that no open coastal setting is absolutely exempt from wave or tide influence.

There are no unique bedding types restricted only to tidal flats. Intertidal-flat setting interpretations should be based on the grouping of structures instead of any single bedding type. Three diagnostic criteria for intertidal-flat deposits are proposed. Within an upward-fining succession, (1) regular changes vertically from flaser bedding, through wavy bedding and to lenticular bedding are diagnostic of most intertidal flats; (2) cyclical tidal rhythmites are absolutely of tide origin, typically pointing to intertidal flats at the inner part of macrotidal estuaries; (3) rhythmic alternations of storm and tidal deposition are diagnostic of exposed intertidal flats, especially the open coast types.

Facies interpretation of intertidal flats and their diversity can be further strengthened if examined in terms of depositional system and facies association methodology. A regressive succession of sheltered intertidal flats usually contains abundant channel-fill deposits, underlain by thick subtidal channel-fills, and sand-bar complexes without significant changes in grain size. In comparison, a regressive succession of exposed intertidal flats contain scant channel-fill deposits, underlain by an upward-coarsening succession of subtidal flats, inversely mirroring the intertidal upward-fining succession. It is worth noting that some exposed tidal flats may develop upon subtidal sand ridges, estuarine or deltaic-distributary mouth bars, where thick sand ridge/bar deposits are expected.

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