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Invited review

Tidal depositional systems in the rock record: A review and new insights

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ABSTRACT

Some of the principles of tidal-wave theory and examples of mega-, macro-, meso- and microtidal coasts are reviewed, as well as sedimentary successions showing general tidal signals (tidalites) and thinly-laminated, cyclically stacked tidal strata (tidal rhythmites). Although tidalites are well known for their muddy stratification, some of the most spectacular tidal deposits are the sand-rich, cross stratified successions that accumulated as tidal dunes, compound dunes and tidal bars in deltas, estuaries, shelves and straits. Recent progress has been made on modelling of ancient tidal strata, (1) in relation to sea-level rise and fall, (2) in recognition of the systematic changes occurring within the important fluvial–marine transition zone, (3) in the prediction of ancient tidally influenced deposits using shoreline morphology, shelf width and accommodation to supply ratios, and in (4) generation of palaeo-ocean models and the computation of tidal dynamics in ancient seas and seaways. Recent key insights into ancient tidal strata include the recognition of fluid-mud deposits, the realization of the significance of tidal bars versus tidal dunes, the use of palaeogeographic data for prediction of tidal sediments and the recognition of ancient tidal-strait deposits.

1. Introduction

Tides are capable of generating currents that erode, transport and accumulate sediments. These processes, widely documented in modern environments, were both significant and widespread throughout much of Earth history. The importance of understanding the tidal mechanism and its influence as a sedimentary process has long attracted the attention of many scientists. From the 17th century, many theories were proposed to explain the observations and the prediction of local tidal behaviour. Quantitative models have increased in accuracy and complexity in more recent times, and have brought new insights on the nature of tidal dynamics and tidal processes.

These models, directly applied by geologists working to reconstruct tidal cyclicity in ancient successions, have required new methodological approaches through time. The observations of bedforms (ripples and dunes) created by tidal currents on a time scale of hours have suggested the existence of depositional environments and systems that are subject to a tidal influence or dominance during the time of their development. Such systems, known as "tidal depositional systems" are possibly best developed in coastal areas where the tidal range is significant and where currents are sufficiently strong to impact the environment or drive local marine circulation. In adjacent shoreline sectors tides may be subordinate to waves or along-shore currents.

Detailed oceanographic and stratigraphic analyses have demonstrated, however, that also in microtidal seas, tidal range and tidal current speeds can be significantly amplified, particularly where the incoming tidal wave becomes constricted. In this paper, we briefly discuss the key tidal bedforms and facies, new ideas on large and smaller scale modelling of tidal systems, as well as some of the new insights on the questions of tidal dunes versus bars and on tidal straits.

2. The "equilibrium tidal theory"

The foundation for all studies about tides, tidal systems and tidal signatures in the rock record is the so-called "equilibrium tidal theory" (Open University Course Team, 1999; Duxbury et al., 2002). The equilibrium tidal theory was originally postulated by Isaac Newton ("Philosophiae Naturalis Principia Mathematica", 1687), and simply assumed that since the Earth is covered by a quasi-uniform depth of water, it must be impacted by astronomical forcing and ocean tide responses. This model, recently reviewed by Kvale (2006) and Coughenour et al. (2009), explains how the combined gravitational attractions of the Moon and Sun, associated with the rotation of the Earth around an Earth–Moon centre of mass, generate oceanic bulges on opposite sides of the Earth. The spin of the Earth through each of these bulges over a period of 24 h and 50 min (the "tidal day"), produces two high tides and two low tides (the semi-diurnal tide). Semi-diurnal, diurnal, semi-monthly, monthly, semi-annual, and longer tidal cyclicities also can be associated with the various changes of the Moon and the Earth orbits (Fig. 1A) (Defant, 1958; MacMillan, 1966).

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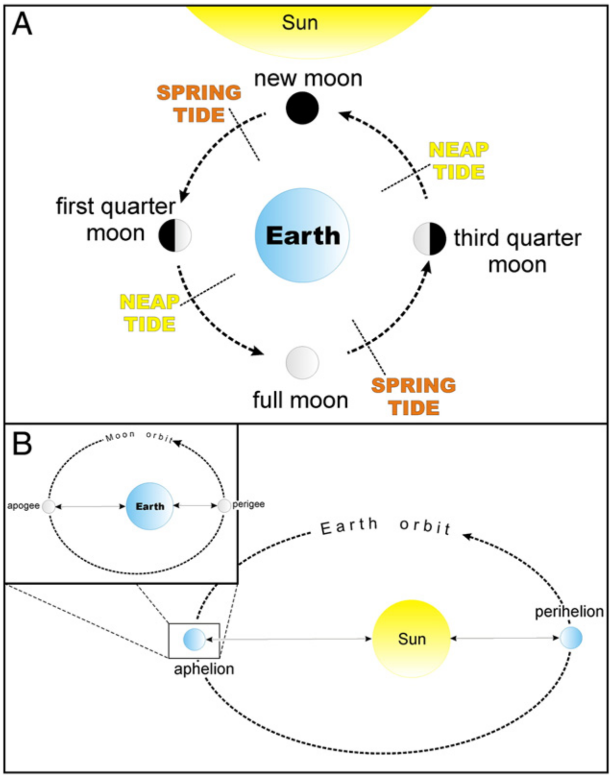

Fig. 1. (A) Relative position of the Earth and Moon system around the Sun with Spring and Neap periods. (B) Also *apogee* and *perigee* Moon positions, as well as *aphelion* and *perihelion* Earth positions, generate decreases and increases of tides.

In most marginal marine environments, the largest tidal constituent is the "principal lunar semi-diurnal" tide, also known as the M2 tidal constituent. Its period is about 12 h and 25.2 min, exactly half of a tidal lunar day. The semi-diurnal tidal range varies over a two-week cycle (spring-neap period). Around the new and full moon when the Sun, Moon and Earth are aligned (syzygy), the tidal range is at its maximum (spring tide). When the Sun and Moon are at 90° in their orbit (first and third quarters), the tidal range tends to be minimum (neap tide) (Fig. 1A).

Spring tides result in stronger than average tidal currents, whereas neap tides result in weaker than average tidal-current velocities. Other tidal cycles reflect the changing distance that separates the Earth and the Moon, producing perigee and apogee tides (Fig. 1B). Also perihelion and aphelion Earth's orbital positions generate increases and decreases of the tidal range, respectively (Fig. 1B). These cycles are semi-annual in duration (equinoctial cycles). Other longer tidal cycles include the 8.8-year lunar apside cycles and the 18.6-year nodal cycles (Pugh, 1987; Archer et al., 1991). 1800-year oceanic tidal cycles are also considered as a possible cause of rapid climate change (Keeling and Whorf, 2000).

The Equilibrium Tidal Theory was misleadingly applied in the past to some geological models and reconstructions. Due to the positions of the continents, the two bulges postulated by the tidal theory consist of points of rotational oceanic water movement around specific areas or amphidromic points (Fig. 2), rather than pure momentary sea level rises (e.g., Komar, 1998). Therefore, this theory fails to explain a series of 'anomalistic' tidal movements, including the occurrence of low-latitude diurnal or mid-latitude semi-diurnal tides (Kvale, 2006).

It is well known today that all of these discrepancies from an ideal global equilibrium in the world's tides depend upon local conditions that regulate different segments of the coastlines along continents. These sectors are subject to tidal regimes, marine circulations and sediment accumulations that can be included in a wide spectrum of depositional systems that, if primarily influenced or dominated by tides, are defined as "tidal depositional systems".

3. Tidal depositional systems

The sedimentary geology literature abounds with studies of sedimentary deposits and facies where windows into the dynamics of ancient tides have been interpreted with reference to present-day tides (e.g., see the dedicated volumes by Flemming and Bartholomä, 1995; Alexander et

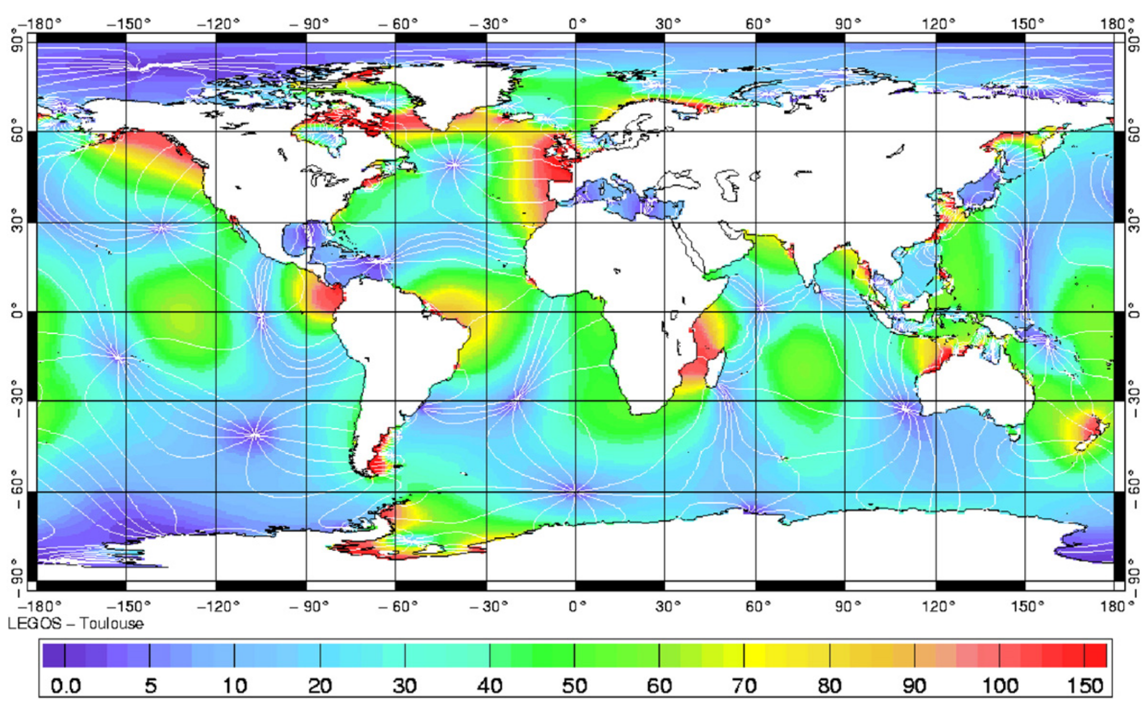

Fig. 2. Amplitude of M2 and K1 tidal constituents (in centimetres) derived from the FES99 model. Cotidal lines indicating phase every 30° originate at amphidromic points where the tidal range is zero (L.G.O.S. image).

al., 1998). In ancient settings, these sediments have been studied mainly in marginal marine successions that have been referred to as tidal depositional systems, i.e., a complex of sedimentary environments, which were dominated or influenced by the effects of tidal processes. Tidal environments can be classed according to tidal range, as macro-, meso- and microtidal (Hayes, 1979) (Fig. 3), though we also know that within a single estuary or bay the tidal range can vary from mouth to head due to the funnelling effect on the tide. Nearly one-third of the world's coastlines are macrotidal (with a tidal range 4–8 m; Davies, 1964), and several coastal areas, many of which have estuarine settings, are considered megatidal, with tidal ranges that are greater than 8 m (Masselink and Turner, 1999; Levoy et al., 2001; Anthony et al., 2004; Dashtgard et al., 2009).

Other marginal marine settings are also subject to tidal influence of lesser amplitude, where waves or currents are locally mitigated by specific coastal morphologies. However, in all these different tidal systems, the occurrence of *supratidal*, *intertidal* and *subtidal* zones is common (Bridge and Demicco, 2008). (i) The supratidal zone occupies that part of a coastal area above the mean high-tide level. This zone corresponds with the uppermost parts of beach ridges (backshore and aeolian dunes) and is inundated by the sea only during the highest tides and storms. The supratidal zone comprises various environments, including salt marshes, mangrove swamps and washover fans. (ii) The intertidal zone is a coastal area between the mean low tide and mean high tide levels, and includes environments such as proximal tidal channels and intertidal flats of estuaries and deltas, as well as the foreshore of open coasts. (iii) The subtidal zone occurs below the mean low-tide level, where tidal currents and wave currents dominate. Tidal environments typical of this zone include distal tidal channels of estuaries and deltas, wave- and tide-influenced delta fronts, and tide-influenced shorefaces (Fig. 3).

The aerial extent of the tidal zones varies greatly among different coastal areas depending on the tidal range and the type of coastline (Allen, 1970; Hayes, 1979; Dalrymple, 1992; Reinson, 1992; Davis and Fitzgerald, 2004).

3.1. Mega- and macrotidal systems

Tidal currents are dominant in mega- (tidal range > 8 m) and macrotidal (tidal range > 4 m) settings where wave currents are normally subordinate, i.e., especially in estuaries and tide-dominated deltas (Prandle, 2009). Estuaries are the most common macrotidal depositional systems and modern examples include the Bristol Channel and Severn River, England (Parker and Kirby, 1982; Harris and Collins, 1985; Allen and Rae, 1988), the Mont Saint-Michel Bay, France (Larsonneur, 1975, 1988; Tessier, 1993; Tessier et al., 2012–this issue), the Cook Inlet, Alaska (Bartsch-Winklse and Ovenshine, 1984; Bartsch-Winkler, 1988), the South Alligator River, Australia (Woodroffe et al., 1985a,b, 1989) the Avon River, Cumberland Basin and Cobequid Bay-Salmon River, Bay of Fundy (Fig. 4) (Lambiase, 1977, 1980; Amos and Long, 1980; Dalrymple et al., 1982; Amos and Zaitlin, 1985), and many others.

In such areas sediments are not only brought into the estuary by river currents, but they are also transported in large volumes from the sea landwards to accumulate in shallow subtidal and intertidal settings at the head of the embayments. Sediments are commonly organized to form large complexes of sandy bars in the shallowest environments and compound dune fields in the deeper zones. The existing facies models that summarise the main sedimentological features of these type of deposits for macrotidal environments are those proposed from Knight and Dalrymple (1975), Coleman and Wright (1975), Galloway and Hobday (1983), Harris (1988), Terwindt (1988).

3.2. Mesotidal systems

Tidal currents are also locally important in mesotidal coastal areas (tidal range 2–4 m), where wave currents are also significant. Barrier beach coasts, tidal deltas and estuaries are commonly found in mesotidal depositional settings (Hayes, 1979; Boothroyd et al., 1985; Ashley and Zeff, 1988; Nichols, 1989; Oertel et al., 1989). Modern examples of mesotidal systems include the Frisian barrier islands,

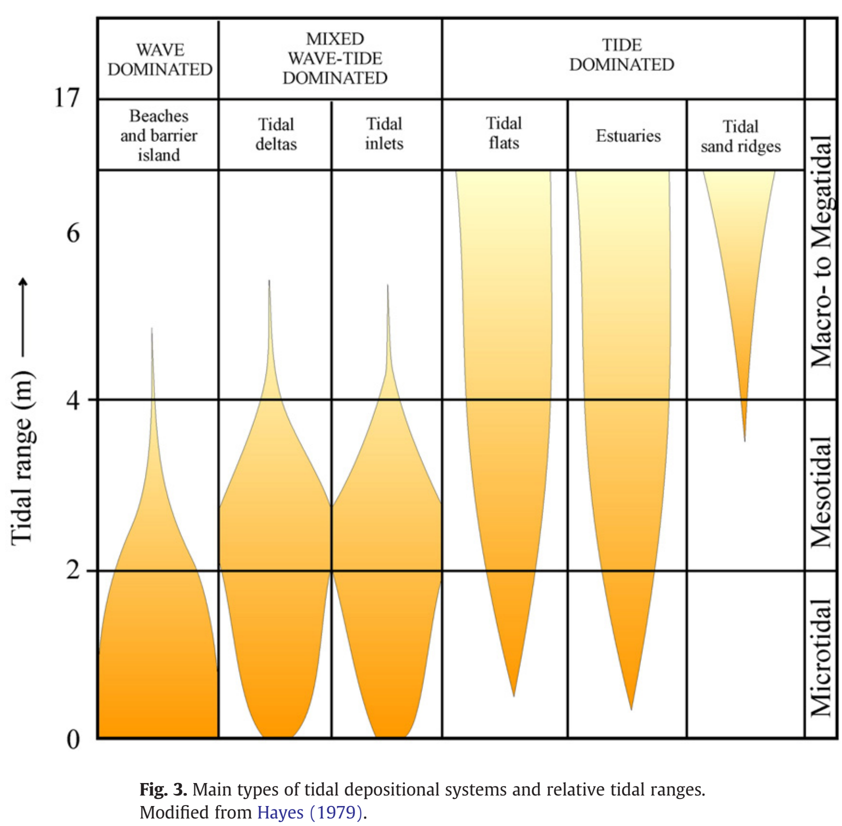

Fig. 3. Main types of tidal depositional systems and relative tidal ranges. Modified from Hayes (1979).

Fig. 4. (A) High and (B) low tide as occurs every six hours per day in the Cobequid Bay.

northern Germany (FitzGerald et al., 1984; Hoekstra et al., 2009) the tidal inlet in the Gulf of Maine, eastern USA (Lynch and Naimie, 1993), the Willapa (Fig. 5) and the Skagit bays, southwest Washington, USA (Smith et al., 1999), and the Georgia Bight estuary, Georgia, USA (Frey and Howard, 1986).

Where sandy barriers are intersected by inlets, flow expansion, deceleration, and sediment deposition through these openings occur. These deposits form flood-tidal deltas if they form on the landward side, and ebb-tidal deltas if on the seaward side of tidal inlets (Fig. 6). Tidal deltas may be hundreds of metres to kilometres long and wide, and many tens of metres thick (Hayes, 1979; Boothroyd et al., 1985; Davis and Fitzgerald, 2004).

Tidal sand bars, usually adjacent to, or within, channels are important components of both estuaries (especially tide-dominated ones) and tide-dominated deltas in mesotidal settings. Tidal sand ridges, sand sheets and compound dunes, as well as limited areas of exposed sea bed with sand ribbons, often occur in tide-dominated shallow seaways and shelves.

Mesotidal systems are thus frequently characterized by complex associations of depositional environments in which the tidal effects variously interplay with other hydrodynamic processes. Consequently, in corresponding ancient analogues the tidal signal is not always easy to detect, because sediments tend to record the youngest superimposed influences.

3.3. Microtidal systems

Microtidal depositional systems (tidal range <2 m) are generally considered wave dominated, because tides are subordinate to other processes (Dean and Dalrymple, 2004). The tidal signal is rarely preserved in the sedimentary record of ancient microtidal systems, except for

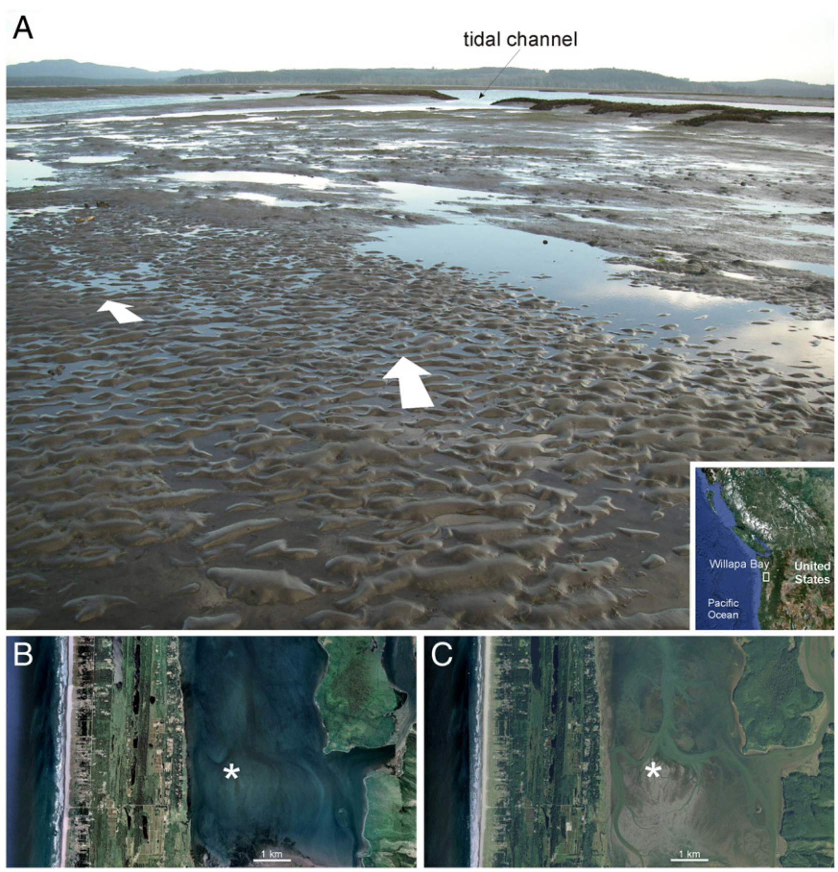

Fig. 5. (A) The Willapa Bay mesotidal flat during low tide. Note the bedforms resulted from the maximum current speed during the ebb period (arrows indicate the ebb current directions). (B) Inner tidal flat of the Willapa Bay during high and (C) low tide (the asterisk indicates the point where the picture in (A) was taken).

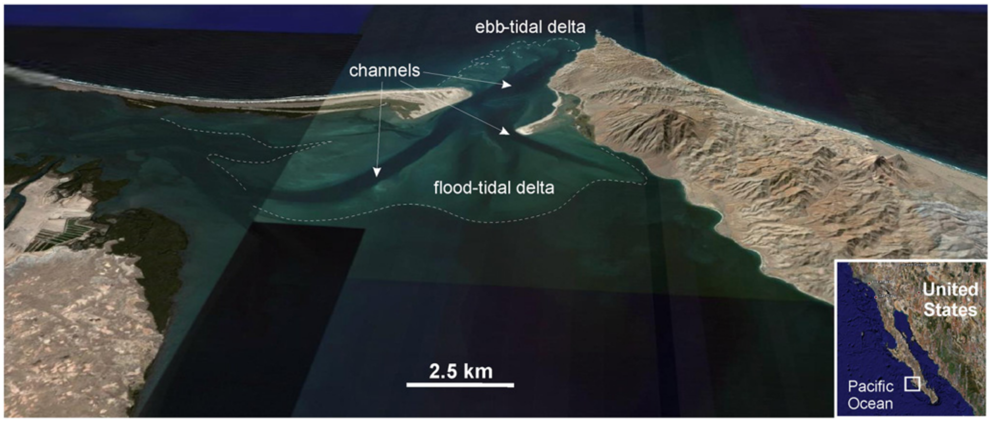

Fig. 6. Along the western coast of the California, between Bahia Santa Marina and Bahia Almejas, a complex system of ebb- and flood-tidal deltas develops, due to the effect of tidal currents amplified by flow through a coastal inlet.

specific coastal settings, such as narrow gulfs, embayments or straits (see discussion in Longhitano and Nemec, 2005; Longhitano, 2011). In these microtidal environments, a tidal wave can be subject to hydraulic amplification by entering into resonance with the length of the bay or because of a reduction of the hydraulic cross section along shallow coastal shelves (Pugh, 1987; Sztanò and De Boer, 1995). Moreover, a number of present-day settings demonstrate that out-of-phase tidal currents can be generated along narrow straits or passageways, related to the semi-diurnal tidal inversion, where continuous exchanges of marine waters occur between two adjacent basins (Keller and Richards, 1967; Selli et al., 1978). A modern example of a microtidal coast where the tidal effects are locally amplified is the Messina Strait, in the central Mediterranean (Fig. 7), where a 3 km wide passageway between Sicily and Calabria links the Tyrrhenian Sea to the Ionian Sea. In this tectonically-formed marine passageway, powerful tidal currents flow axially every six hours per day (Fig. 7) (Vercelli, 1925; Blanc, 1954) producing sandy to gravelly dunes up to 6 m high in deep subtidal environments (Barrier, 1987; Mercier et al., 1987).

Another present-day example is the northern Adriatic Sea, the northernmost sector of which consists of a very shallow shelf, diurnally subjected to the amplification of the landwards directed tidal wave of up to 2 m (Defant, 1961; Trincardi et al., 2007; Storms et al., 2008), although the Mediterranean Sea has a general tidal range of only ~30 cm (Wells et al., 2005).

In general for microtidal depositional environments, tidal cyclicity can be masked in the sediments by “random” or non-tidal events such as periodic erosion due to waves, storms, river floods, or wind-driven currents (Kvale et al., 1995). The tidal effects in the sediments can be locally observed near low-gradient wide inshore profiles of sandy shorelines, under the form of broad sandy shoals or spits attached to the shoreline (Fig. 8).

4. Tidal signals in the rock record

Sediments subjected to tidal hydrodynamics are distributed and organized into specific sedimentary facies. The preservation of these tidal facies records strong tidal constituents that influence a given coastal area, with minor signals being lost or unrecognizable (Allen, 1980, 1984a,b; Dalrymple, 1984; Dalrymple and Makino, 1989; Archer et al., 1991; Kvale and Archer, 1991; Nio and Yang, 1991; Shi, 1991; Archer, 1995, 1998; Tessier, 1998). Tidal cycles are modulated at temporal scales ranging from daily to millennial (Pugh, 1987; Archer et al., 1991). The recognition of a tidal regime exhibiting one of more tidal periodicities then depends upon factors such as the latitude of a given marine area, its geomorphic coastal features, the shape of the sea bottom and many other local influences (Coughenour et al., 2009).

Sedimentary successions that exhibit a tidal signature are sometimes known generally as ‘tidalites’ (Klein, 1998); these are both mud-rich and sand-rich and vary from thin, muddy heterolithic strata (lenticular, wavy or mud-flasered bedding) to sand-rich unidirectional, bi-directional (herring-bone) or ‘bundled’ cross-stratification (Fig. 9A and B) (see reviews by Klein, 1998; Coughenour et al., 2009; Steel et al., 2012). One

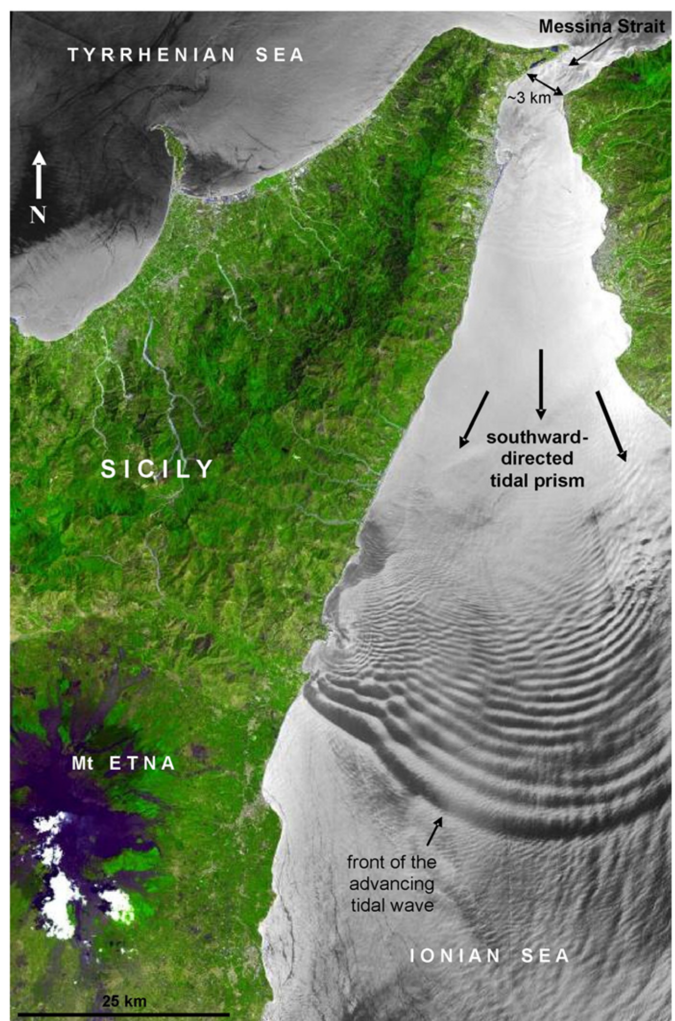

Fig. 7. Satellite image of the Messina Strait descendant semi-diurnal tidal prism. Image from NASA/SFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team.

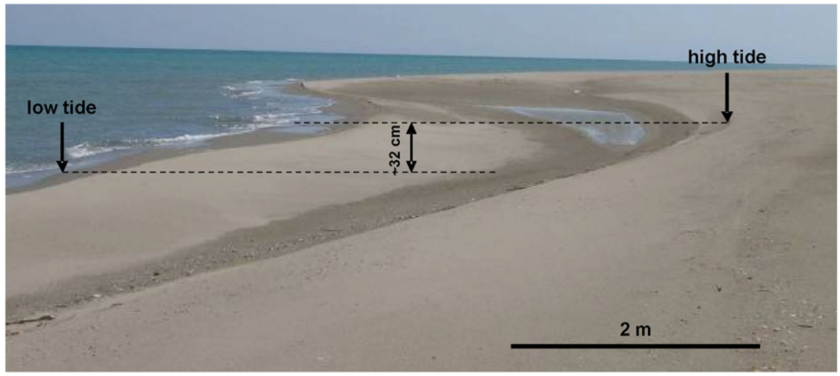

Fig. 8. The effect of a microtidal, semidiurnal excursion (arrows) into low-gradient, sandy beaches may result in the formation of sandy spits attached to the high-tide beach profile (Ionian coast of Basilicata, south Italy).

of the best-documented examples of tidalites comes from the Carboniferous of the mid-western USA (e.g. Brown et al., 1990; Kuecher et al., 1990; Archer, 1991; Kvale and Archer, 1991). The Carboniferous tidalites exhibit tidally controlled periodicities in laminae or bed thickness that range from semidiurnal through yearly. Another ancient case is represented by the Pennsylvanian deltaic succession of the Hazel Pach Sandstone (eastern Kentucky coal field) (Fig. 10A), where a near complete record of daily, semi-monthly and monthly tidal periodicities has been recognized (Adkins and Eriksson, 1998) (Fig. 10B).

Tidalites have been described also in mixed silici–bioclastic deposits from the Plio-Pleistocene of southern Italy (Longhitano et al., 2010; Longhitano, 2011). Tide-generated ripples and dunes form cycles with alternating couplets of terrigenous extra-basinal siliciclastics and intra-basinal bioclastics. Heterolithic cycles of segregated clastics indicate tidal periodicities of short duration (from semi-diurnal to monthly) in bay-fill successions, whereas longer tidal cycles (up to annual) occur in strait-fill successions (Longhitano et al. 2012–this issue). Segregation of silici-bioclastic particles reflects changes in the tidal current competence. Thus, the occurrence of bioclastic-rich horizons in such mixed systems may indicate slack water periods, analogous to the muddy drapes in siliciclastic tidal systems (Longhitano, 2009; 2011).

4.1. Tidal rhythmites in the rock record

Repetitive tidal signals developed as very thin strata in a wide range of tide-dominated systems are known as tidal 'rhythmites' (Greb and Archer, 1995; Archer, 1995). Rhythmites consist of cyclical stacking of sand and mud-lamina couplets whose thickness varies rhythmically (Reineck and Singh, 1973; Kvale et al., 1989; Kvale and Archer, 1990; Archer, 1991; Dalrymple et al., 1991; Dalrymple, 1992; Archer, 1996). The term "rhythmites" was designed to indicate vertically accreted tidal facies, that commonly originate in inter-tidal to sub-tidal environments from alternating flood and ebb tidal currents and consequently related sandy/muddy deposition (Fig. 11) (Williams, 1991; Roep, 1991; Chan et al., 1994; Choi and Park, 2000; Kvale, 2003; Mazumder and Arima, 2005; Greb and Archer, 2007). The term rhythmite may also be applied to some laterally accreting deposits, if there is a clear rhythmicity (see discussion in Coughenour et al., 2009). However, it should be noted that thin rhythmic layering need not always originate from tidal processes.

To unravel the periodicity of tidal signals in the rock record, many sedimentologists have applied common statistical tests that became standardized in analyses of ancient tidalites. Tidal rhythms consist of harmonic variations of bed lamina thickness that reflect cyclical

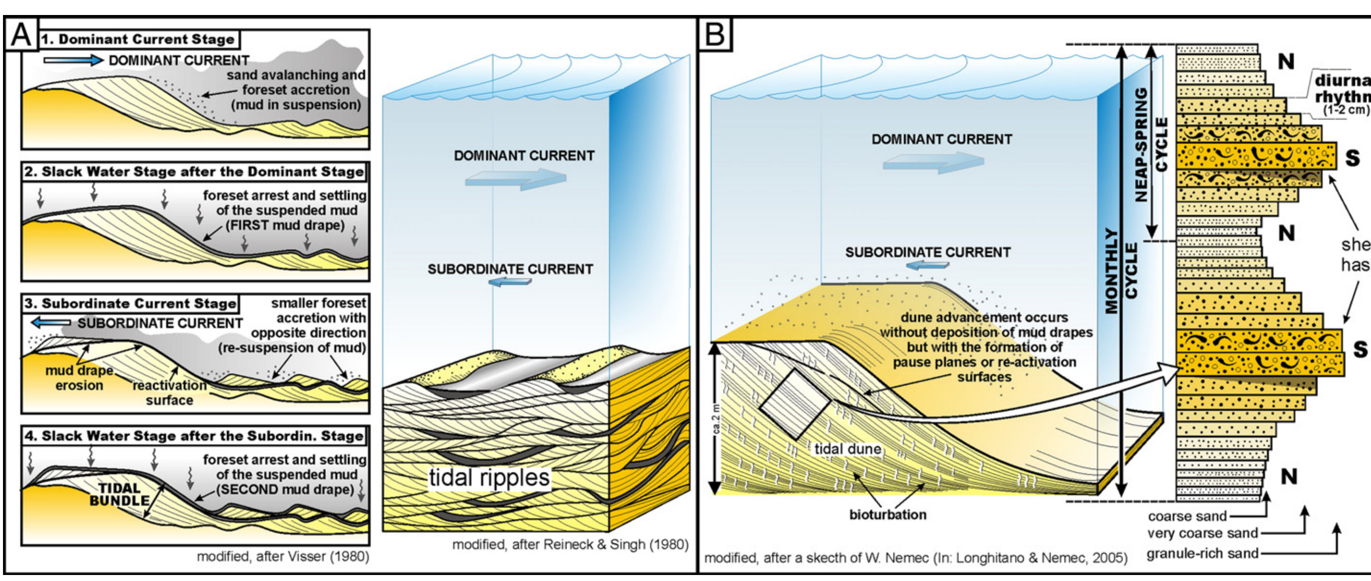

Fig. 9. (A) Typical dune bedform generated in a mud-rich system after a complete tidal cycle and characterized by a strongly asymmetric current (modified, from Visser, 1980). Flaser bedding and mud drapes may result depending on the dominance of high vs. low energy current (modified, from Reineck and Singh, 1980). (B) Bundles of coarsening- and fining-upward laminasets are observable within cross-stratified deposits that develop in mud-free siliciclastic subtidal systems. Mud can be absent or kept perennially in suspension. Dunes are mostly unidirectional and exhibit reactivation surfaces as consequence of momentary arrest of the current during the slack water periods (Longhitano and Nemec, 2005; Longhitano, 2011).

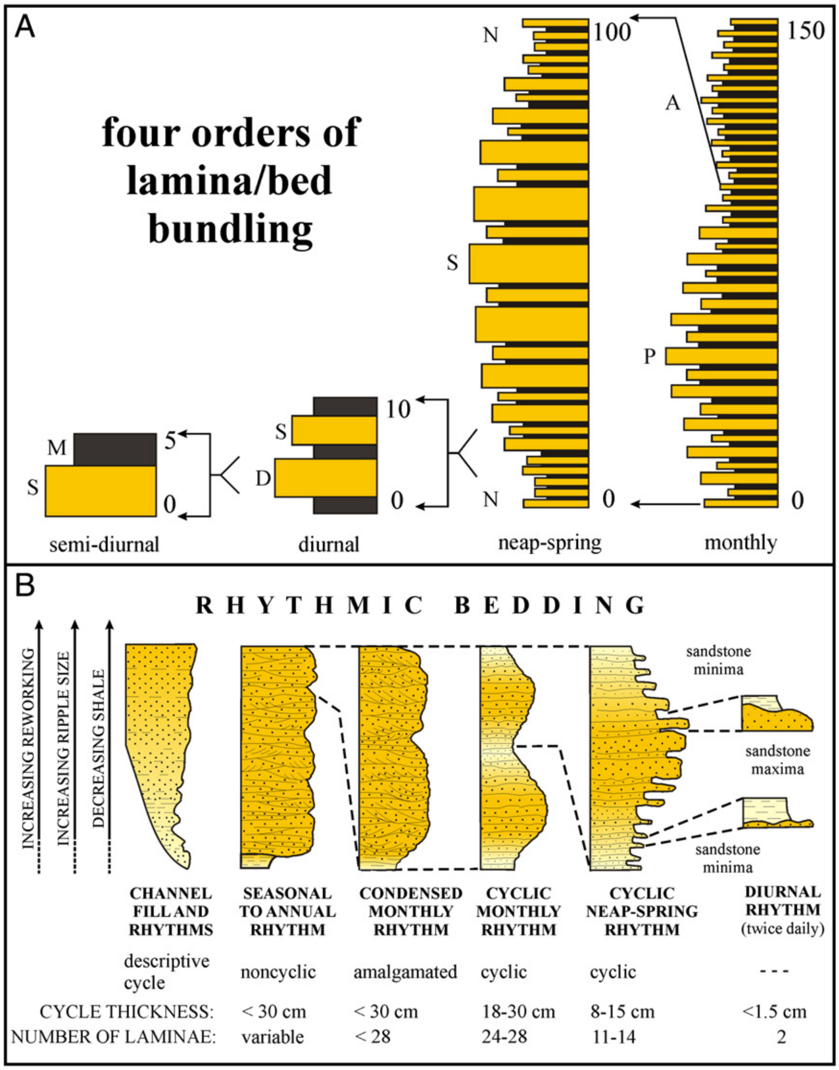

Fig. 10. (A) Hierarchy of strata observed in the Magoffin Member Sandstone (eastern Kentucky, USA). Repeated couplets of sandy (*S*) and muddy (*M*) laminae indicate semi-diurnal tidal cycles. Diurnal cycles are represented by alternating dominant (*D*) and subordinate (*S*) couplets. Thickening- and thinning-upward trends of laminae record neap (*N*) to spring (*S*) tidal (semi-monthly) cycles. Alternating apogean (*A*) and perigean (*P*) deposits record monthly cycles. Thicknesses are in centimetres (redrawn, from Adkins and Eriksson, 1998). (B). Other examples of tidal deposits indicating cycles of rates of various orders of tidal rhythmites documented in the Pennsylvanian Hazel Patch Sandstone (redrawn, from Greb and Archer, 1995).

variation in the current competence and accumulation capacity. Cyclicity within these deposits can be detected easily by combining the lamina thickness and relative number in appropriate plots where the main tidal components can be recognized in the quasi-sinusoidal, harmonic variations (Fig. 12).

Since regular rhythms of heterolithic strata may arguably represent the record of tidal phenomena through time, one of the most used tests to unravel such a cyclicity within tidal deposits is the “time-series analyses” (Fig. 12). Time-series analyses applied to couplet thickness variation have shown direct correlation with tidal cycles and can be a

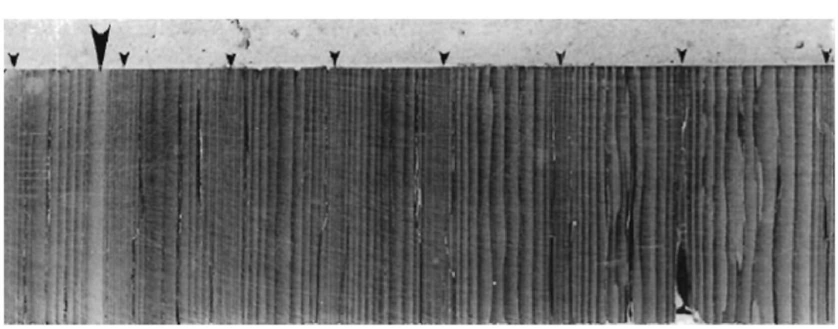

Fig. 11. Well developed tidal rhythmites detected in core from deposits of the tidal mudflats of the lowest sulphur Pennsylvanian coals (eastern Illinois Basin, USA). The sequence (top of the core is to the left; total core length is ~20 cm) shows neap tide deposits (small arrows) alternated with a coarser-grained siltstone layer (large arrow) that possibly indicates a storm deposit.
From Kvale and Mastalerz (1998).

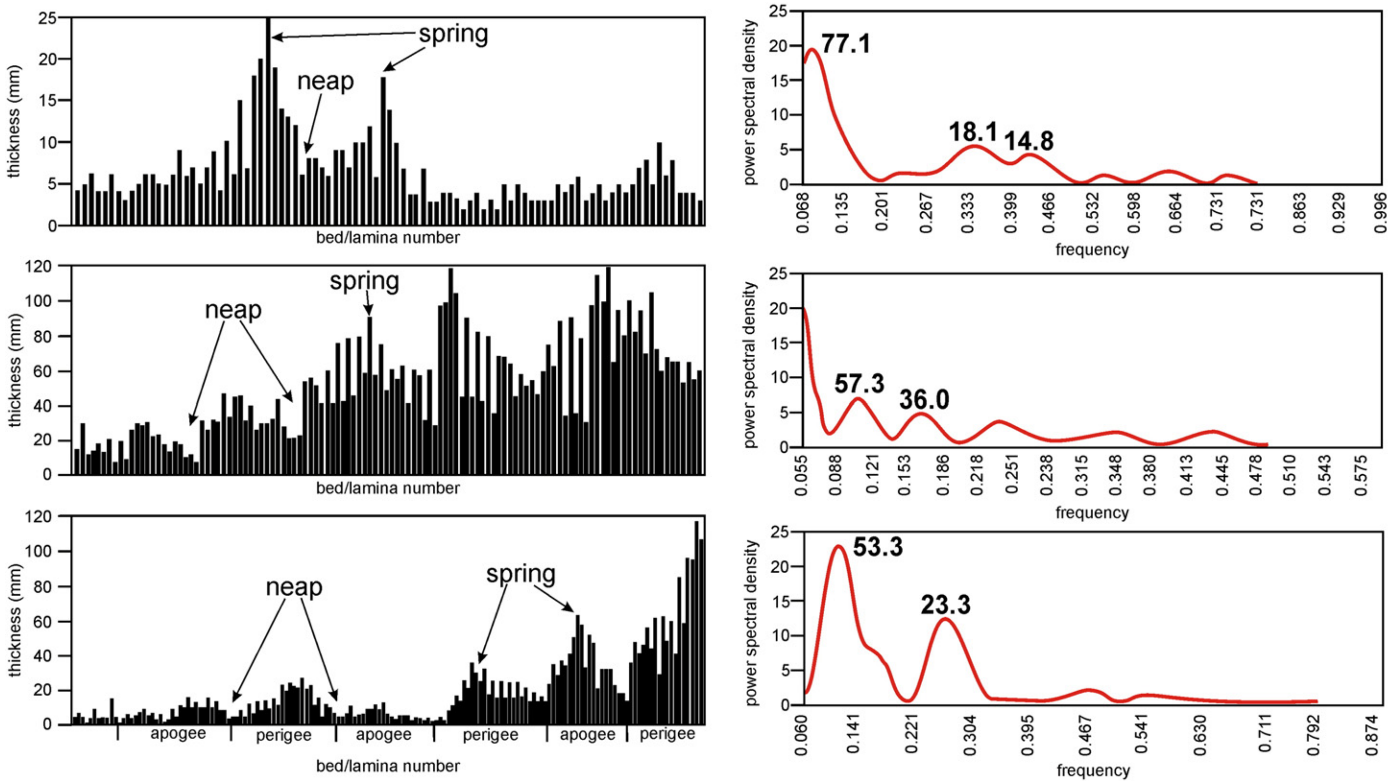

Fig. 12. Histograms obtained from rhythmite thicknesses. Semi-monthly, neap-spring-neap cycles are marked by tick marks along the x axes. Monthly perigee apogee cycles are marked along the x axes. Arrows along the x axes indicate the dataset used for harmonic analyses in the diagrams on the right side. Here, the correspondent Power spectral plots are reported. The numbers are the most recurrent power spectral densities for each dataset, indicating different tidal cycles.
Modified from Adkins and Eriksson (1998).

useful indicator of tidal harmonics, tidal-pattern dynamics and the astronomical forcing factors involved (Klein, 1998). Other statistical and mathematical techniques can also be applied to rhythmite thickness series in order to test for the presence of tidal signals (see discussion in Archer, 1998). These include Fast-Fourier and probabilistic analyses or most sophisticated spectral tests which allow the extraction of the periodicities and amplitudes in a given dataset (e.g., Archer, 1996). Other interesting examples are discussed by de Boer et al. (1989), Nio and Yang (1989) and Archer et al. (1995).

Analyses of ancient tidal rhythmite may also help to estimate the palaeolunar orbital periods in terms of lunar days/month accurately (Mazumder and Arima, 2005). Determination of absolute Earth–Moon distances and Earth's palaeorotational parameters in the distant geological past from tidal rhythmite remains, however, uncertain because of the difficulties in determining the absolute length of the ancient lunar sidereal month.

Tidal currents are commonly characterized by bidirectional flows that produce different bedforms with different orientations in tidal depositional environments dominated by flood or ebb conditions (Allen, 1980, 1984a,b).

4.2. Tidal dunes, tidal compound dunes and sand sheets in the rock record

Although mudstone layers and drapes in variously configured rhythmic successions are normally cited as the key criterion for recognizing tidal environments, it can also be argued that in sand-rich, marginal-marine and open-marine settings, thick and orderly stacked sets of cross-stratified sandstones are the other key tidal signal. In many tide-dominated estuaries and delta-fronts, as well as in shelf settings where there are strong tidal currents in low turbidity water, dunes are the dominant bedform (Davis and Dalrymple, 2012). This criterion for recognizing tidal sandstones was also suggested by H.D. Johnson (in Reading, 1978, p. 229). Such successions usually can be distinguished from cross-bedded fluvial units by their orderliness and abundance of tabular and wedge-shaped cross strata, by a scarcity of channelized erosion surfaces and by a sparse marine ichnofauna. Large-scale dunes commonly migrate in the direction of the dominant current, although they may exhibit small structures that reflect the flow in the opposite (subordinate) direction (Figs. 9 and 13). Some tidal bedforms are also influenced by the effects of relative high frequency sea-level changes (e.g., Longhitano and Nemec, 2005; Longhitano et al., 2010).

Cross-stratified sands generated by tidal dunes occur within a variety of larger forms, from compound dunes (crest transverse to flow) that scale with water depth and reach heights of 10–15 m, to tidal bars or ridges (crest sub-parallel to dominant tidal flow) that reach tens of metres in height in offshore areas. Tide-generated simple dunes and compound dunes accrete in a forward manner sub-parallel to the dominant tidal current direction. They occur in both coastal and offshore (shelf) environments, and in the latter areas they form tidal-transport pathways (Belderson et al., 1982; Renyaud and Dalrymple, 2012) that stretch parallel with some coasts. In some areas the dunes and compound dunes amalgamate to form tidal sheet sands (Berné et al., 1993; Bartholdy et al., 2002) that have some tendency to crudely thicken and coarsen upwards.

As argued by Allen (1984b), tidally generated ripples and dunes represent hydraulic bedforms whose dimension or height can be expected to scale with the flow strength or water depth. The relationship

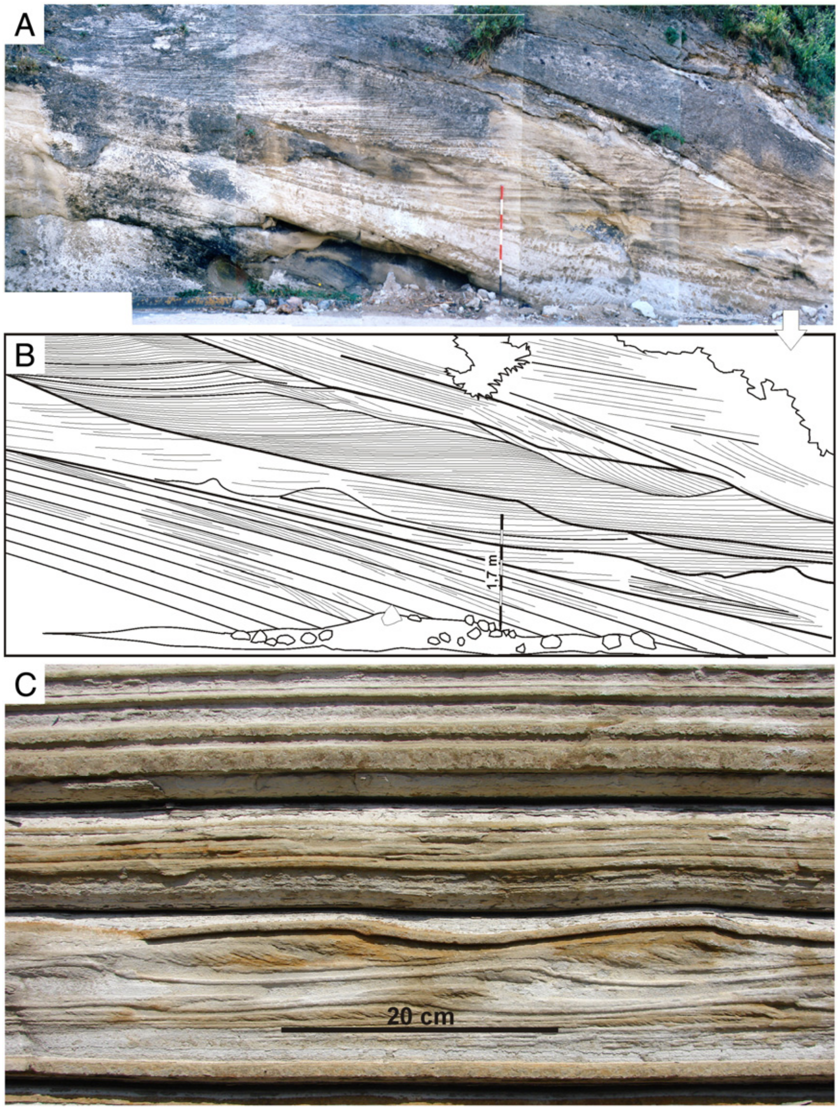

Fig. 13. (A) Cross-stratified beds showing opposing foresets and (B) interpreted as generated from oscillating, tidally-driven currents (Monte Pellegrino palaeostrait, Tortonian Amantea Basin, southern Italy). (C) Rhythmic, cross- and plane-parallel laminations (Eocene, Itu, Brazil).

between the height of large dunes (h) and the water depth (H) is defined explicitly in the Allen's empirical equation (1984b):

$$h = 0.086\,H^{1.19} \quad (1)$$

The scaling of the dune thickness also depends on the flow strength and boundary layer conditions, as suggested by the Gill's equation (Allen, 1984a):

$$h = H\frac{\left(1-Fr^2\right)}{2\varepsilon\varphi}\left(1-\frac{t_{cr}}{\tau_0}\right) \quad (2)$$

where Fr is the Froude number; ε is the exponent of the Meyer-Peter and Müller equation of bedload transport; φ is a coefficient which makes up between 1/2 and 2/3 of the dune cross-section shape; τ_{cr} is the threshold bottom shear stress for sedimentary particle motion; and τ_0 is the mean bottom shear stress. Since the bottom shear stress in free-surface flow is proportional to Fr^2 for constant flow depth and resistance, the relative dune height h/H can have a maximum in either Fr or τ_0 (Longhitano and Nemec, 2005).

From this relationship and because the strength of tidal currents varies greatly in different depositional systems, the sedimentary structures that can be generated from tidal hydrodynamics exhibit a huge variability (Fig. 13A, B and C). The large- to small-scale bedforms that are abundant in tidal systems have had a confusing terminology history (e.g., Olariu et al., 2009), although a consensus terminology (Ashley, 1990), was attained and largely accepted. The terminology used by Dalrymple et al. (1978), Dalrymple (1984) and Dalrymple et al. (1990) follows this consensus.

4.3. Laterally accreting tidal bars in the rock record

Another key component of tidal systems is the laterally accreting tidal bar, which occurs both in fluvial–tidal and marine (tidal) environments. In offshore areas they are often referred to as tidal ridges. *Tidal bars*, common in both deltas and estuaries, are associated with and laterally infill channels, from small tidal gullies up to distributary channels 15–20 m deep. Such bars are often bank attached (point bars) but become free-standing towards the mouths of deltas and estuaries (Dalrymple, 2010). Tidal bars accrete laterally and create an upward-fining grain size profile, with a lithological variability from mud-rich tidal creek point bars (Dashtgard and Gingras, 2005), through the classic 'inclined heterolithic strata' (Thomas et al., 1987) to more sand-rich inclined strata (Fig. 14). These point-bar deposits tend to be dominated by ripple-lamination, though the sand-rich examples also contain stacked sets of cross-strata. It has been suggested by Dalrymple (2010) that on the higher levels on such point bars in the tidal–fluvial transition zone, flood-tide palaeocurrents can be registered in the deposits of the flood-barb channel. Well logs from offshore mid-Norway portray these channel-filling bars (blocky to upward-fining gamma-ray signatures) in the estuarine transgressive half-cycle of stacked estuarine–deltaic sequences (Fig. 15A). Fig. 15A also illustrates another common feature of such channel-filling tidal bars; they contain distinctive unbioturbated and unlaminated mud layers up to a centimetre thick (Fig. 15B), originating as fluid mud-layers (see below, and discussion by Ichaso and Dalrymple, 2009). A tell-tale feature of channel fills with fluid muds is their characteristic grain-size bimodality, with the muds interlayering with medium or coarse-grained sandstones. Upward-fining tidal bars in inshore areas tend to be capped by inter-tidal and supratidal deposits, the latter sometimes with coal layers.

Tidal bars or *tidal ridges of the shelf areas* occur as a series of regularly-spaced sand ridges and are much larger (up to 50 m high) than the inshore tidal bars. However they have a similar oblique accretional growth style, as first demonstrated by Houbolt (1968) and

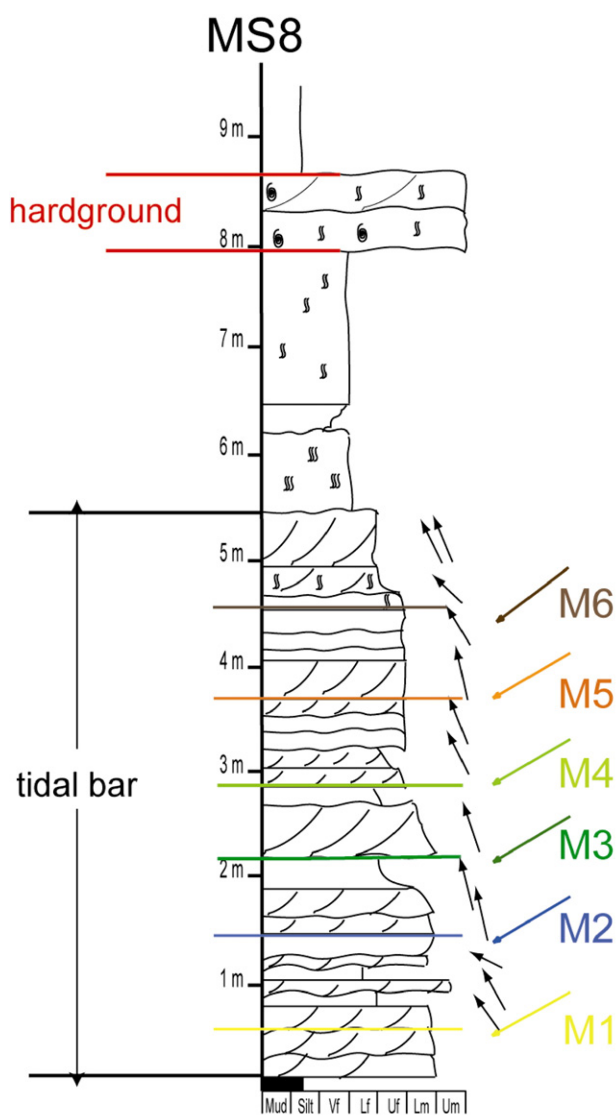

Fig. 14. Vertical section across the Esdolomada sandstones, Pyrenees, illustrating the main sedimentary features recognizable across a tidal bar.
From Olariu et al. (2011).

are produced by rectilinear bi-directional tidal currents (Huthnance, 1982). They tend to develop during transgressions, and so are underlain by a transgressive ravinement surface and overlain by a maximum flooding surface (Cattaneo and Steel, 2003; Davis and Dalrymple, 2012). The important geometric differences between tidal compound dunes and tidal bars are elaborated further below with reference to newly documented ancient case studies.

5. Modelling of ancient tidal depositional systems

Research on tidal depositional systems was re-energized in the 1980s after the introduction of the concepts of sequence stratigraphy. Studies on estuaries in particular have also shown major advances, with the development of the first comprehensive facies model in the 1990s (Dalrymple et al., 1992) and improvements thereafter.

5.1. Tidal influence during rising and falling of sea level

In the context of the regressive–transgressive cycles that make up much of the stratigraphic record during the building of shelves, Porebsky and Steel (2006) noted how sea-level change indirectly impacts process regime change on deltas. For example, it is well known that oceanic swells and storms approaching the shallower water shelf break and outer shelf can cause significant wave action in that region and that there is frictional attenuation of waves across the shelf (Yoshida et al., 2007a,b). For this reason, wave influence on a shoreline that is close to the shelf break (e.g., during lowered sea level) would tend to be greater than one sited on the inner shelf (e.g., Cram, 1979; Swift and Thorne, 1991). However, shelf incision during sea-level fall tends to locally invaginate the shelf-edge area, thus locally providing protection from waves and allowing the preserved delta deposits to be dominantly fluvial–tidal, at least in 'pockets' along the shelf edge (e.g., Mellere et al., 2003; Cummings et al., 2006b; Carvajal and Steel, 2009). Further, we know that the amplitude of the incoming oceanic tidal wave and associated current velocities increases across the shelf edge due to a rapid increase in the tidal prism (Fleming and Revelle, 1939; Renyaud and Dalrymple, 2012) so that protected shelf edge sites (e.g., re-entrants) can be strongly tide influenced (e.g., Cummings et al., 2006a), and perhaps relatively more so at lowered sea level when shorelines would be closer to the shelf edge and sediment supply greater.

During sea-level rise and the submergence of a shelf, it is generally accepted that tidal processes are significant, mainly because of the constriction of tidal flows in the estuaries and embayments that are characteristic of transgressive shorelines. Additionally, as shelf width increases the tidal wave may become amplified if shelf width falls into resonance with the tidal wavelength. However, such generalizations do not always fully describe all possibilities of shoreline process dominance during transgression, as discussed below in Section 5.3.

In shallow seaways, sea-level fall produces an increase in tidal influence because as the seaway narrows, wave fetch is reduced and tidal currents can become constricted. Sea-level fall during shoreline regression, in the Cretaceous Western Interior Seaway, caused wave-dominated highstand shorelines to change dramatically to strongly tide-influenced deltas far into the basin (Mellere and Steel, 1995, 2000; Steel et al., 2012).

The above relationships and many others (e.g., Willis and Gabel, 2001, 2003) clearly show that strong tidal influence is common during sea-level fall as well as during rise, and that it is factors such as shoreline morphology, basin width, bathymetry, proximity to shelf edge and shelf width that directly produce tidal responses. The 'indirect' control by sea level on regime change leads to a further problem. We have become increasingly aware that changes in shoreline morphology, bathymetry and facies are just as likely to happen along strike on a coastline as they are due to sea-level changes through time (Bhattacharya and Giosan, 2003). The lateral variability, and short term changes in autogenic process responses on shorelines are discussed further below. Nevertheless, there

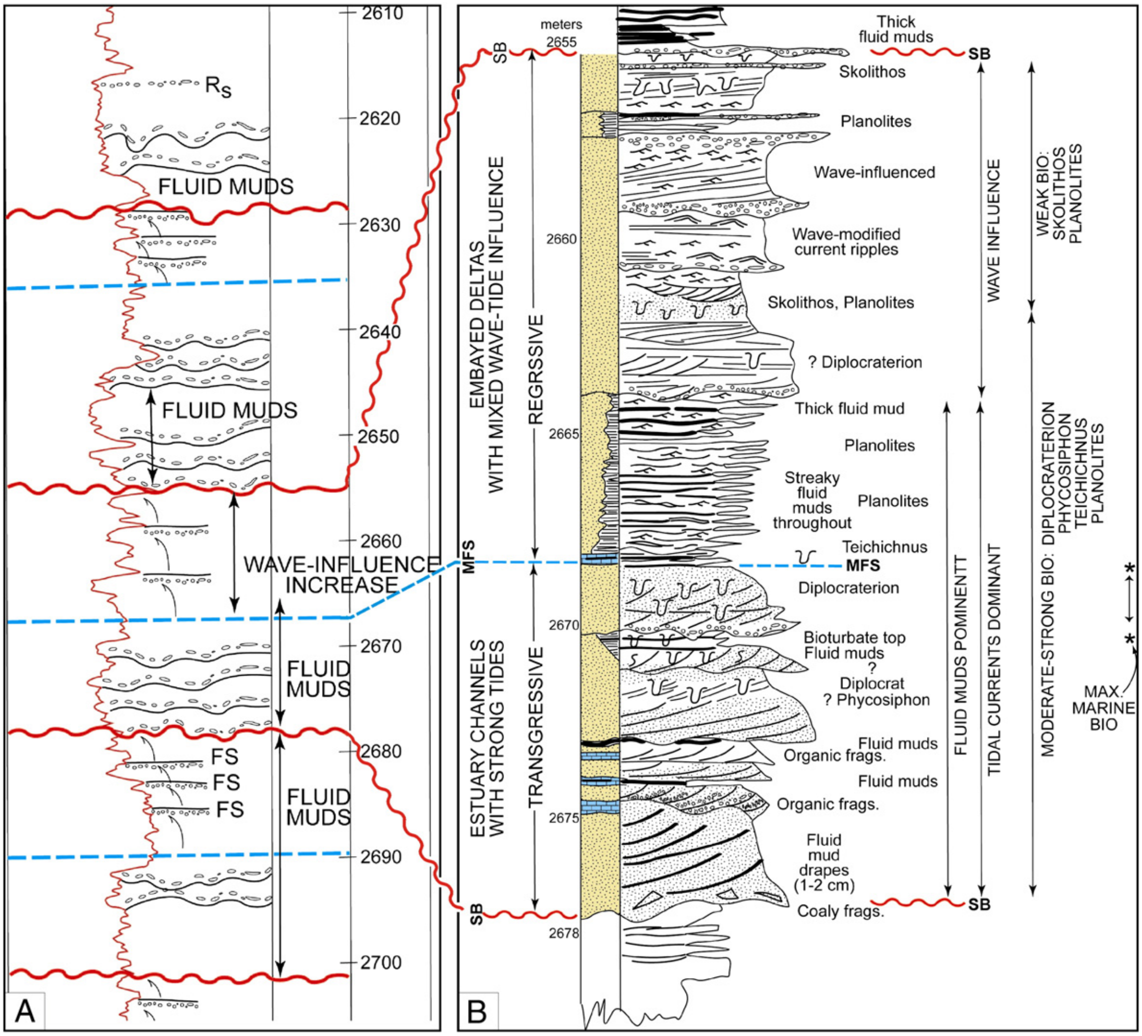

Fig. 15. (A) Gamma-ray log from Lower Jurassic strata offshore Mid-Norway, showing 4 sequences with tidal channels in lower half of each sequence (between red erosion surface and blue flooding surface). Fluid mud layers are common in the amalgamated channel half cycles. (B) Core detail of one of the sequences in (A) showing tidal channels from 2655 m to 2678 m. The tidal character of the channels is shown by the mud-draped cross strata, the fluid mud layers and the trace fossils.

is a need to insert more process sensitivity to sequence stratigraphic models, not least for reservoir modelling where relationships between sequence stratigraphy, depositional systems and reservoir connectivity are being developed (Ainsworth, 2003, 2005; Ainsworth et al., 2008).

5.2. Modelling the fluvial–marine transition on tide-dominated estuaries and deltas

Dalrymple and Choi (2007) recently synthesized the character of the deposits occurring in the fluvial–marine transition zone of tide-dominated estuaries and deltas (Fig. 16A). In doing this, they firmly took the 'tidal' focus away from the classic tidal flat setting to the much larger scale of tidal depositional system. The authors treated the systems in terms of a seaward decrease in intensity of river flow and an accompanying seaward increase in the intensity of tidal currents, together with the attendant net seaward and net landward movement of sediment respectively (Fig. 16B). The model contains landward and seaward grain-size trends, with predicted preferential areas of mud drapes and fluid muds, as well as gradients in salinity and accompanying ichnofossil assemblages (Fig. 16C). One of the key values of this type of model for tide-dominated systems is for rock record application. It allows specific tidal deposits that lack much context (e.g., subsurface cores) to be placed/interpreted within the spatial and temporal frame of the larger tidal depositional system.

5.3. Models for predicting tidal influence using shoreline morphology, shelf width and accommodation to sediment supply ratios

Prediction of tidally influenced deposits in ancient successions has been hampered by the lack of robust models that can predict the change of dominant depositional processes acting at a shoreline through time and space. New models have recently been developed that can reduce the uncertainty in predicting the probable dominant and subordinate processes acting at a shoreline (Ainsworth, 2003; Ainsworth et al., 2008, 2011). These models incorporate palaeogeography, palaeo-shelf morphology and accommodation to sediment supply ratios. They utilise a process classification system which can handle the combination of the three key processes acting at shorelines; waves, rivers and tides (Ainsworth et al., 2011). This classification separates marginal marine systems into fifteen process categories (*W*, *Wt*, *Wf*, *Wtf*, *Wft*, *T*, *Tw*, *Tf*, *Twf*, *Tfw*, *F*, *Fw*, *Ft*, *Fwt*, *Ftw*), where '*w*', '*t*', and '*f*' stand for 'wave', 'tide' and 'fluvial', respectively (Fig. 17). The capital letter signifies the dominant process, whilst the second and third lower case letters represent the secondary and tertiary processes that influence and affect a system, respectively. A *Twf* system could thus be described as being 'tide-dominated, wave-influenced, fluvial-affected'.

The predictive models and classification expand on the previous process-based models of Galloway (1975) and more recent models of Boyd et al. (1992) that predicted shoreline process variation by their

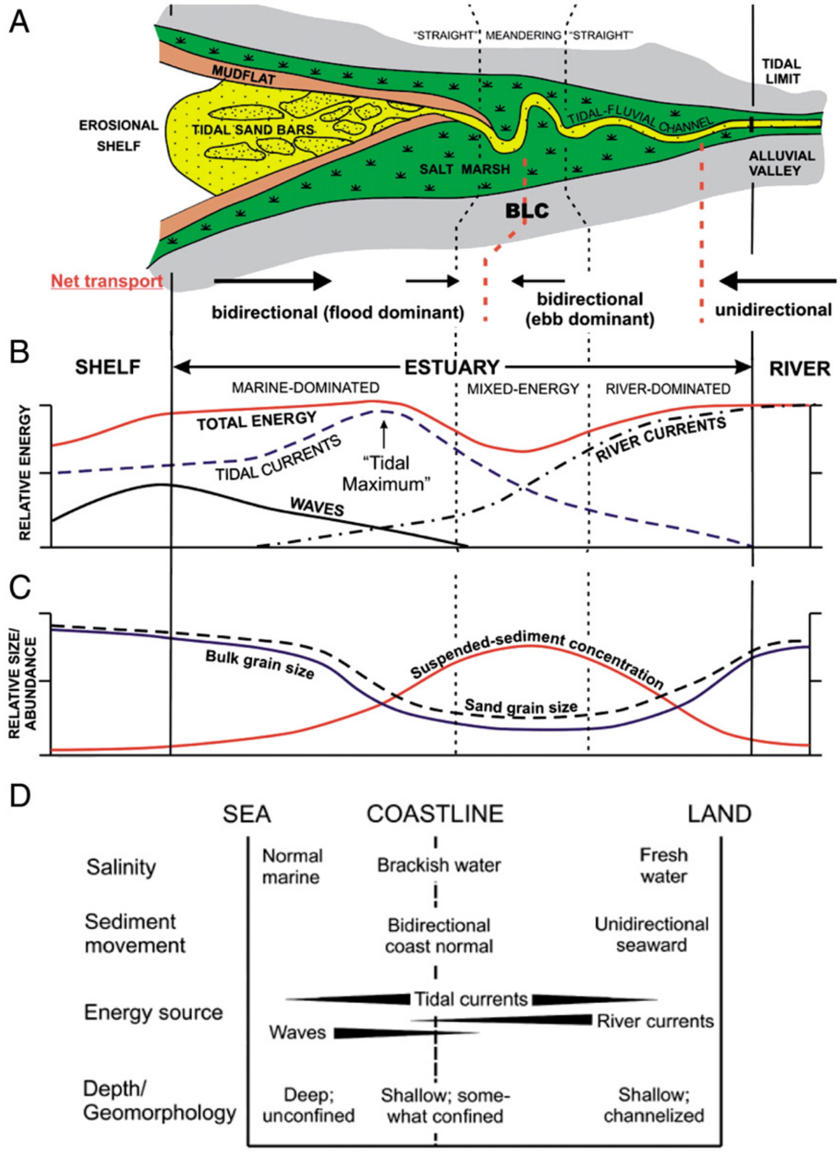

Fig. 16. (A) Schematic map of a tide-dominated, funnel-shaped estuary. Note the presence of elongate tidal bars in the seaward part, and the fringing muddy tidal flats and saltmarshes. (B) Longitudinal variation in the intensity of the three main physical processes, river currents, tidal currents and waves, and the resulting directions of net sediment transport (at the bottom of A). (C) Longitudinal variation of the grain size of the sand fraction, the suspended sediment concentration and "bulk" grain size of the resulting deposits. (D) Transition from purely fluvial settings ("land"), through the tide-dominated coastal zone, to shelf environments ("sea") and relative coast-normal variation in the controls on sedimentation.
Modified, from Dalrymple and Choi (2007).

relation to transgressive and regressive shoreline episodes. Transgressive episodes were thought to be more prone to be tidally influenced due to the development of more embayed shorelines during transgression. Whilst this assumption is correct in many cases, it does not describe the whole suite of possibilities of shoreline process dominance during transgression. These models also assume that tidally-influenced systems are uncommon in regressive systems. Inspection of modern coastal systems suggests that this assumption will also only be partially correct. There is also evidence of tidal process dominance on many ancient regressive shoreline systems (Ainsworth, 1994, 2003; Ainsworth et al., 2008, 2011; Dashtgard et al., 2012–this issue; Vakarelov et al., 2012–this issue).

Coastline morphology, shelf width and latitude play a major role in determining whether a coastline will be tidally-influenced. Hence predictive models in the ancient must take account of these parameters as well as including factors such as proximity to fluvial input points and wave energy (Fig. 17A). Predictive models for the ancient must also be shown to be applicable to modern systems. Empirical studies of modern shelves indicate that shelf widths greater than 75 km have the potential to amplify the tidal wave at the shoreline (Fig. 17B) (Ainsworth et al., 2011) and hence increase the velocity of tidal currents and their potential to transport sediment. These wider shelves also have the potential for dampening wave energy at the shoreline by increasing the probability of frictional energy loses to the sea floor as the waves move across a shallow wide shelf. Hence wide shelves have a relatively high potential to produce tidal dominance at the coastline. This effect increases the probability of tidal process dominance or influence in regressive coastal systems situated adjacent to wide shelves (>75 km). By the same degree, highly embayed or funnel-shaped shorelines have been well documented as having the potential to amplify tidal currents by constriction of the tidal wave. These coastal geometries can also protect areas of the coastline from the direct impact of oceanic waves, thereby also reducing the potential for wave-dominance along highly embayed shorelines.

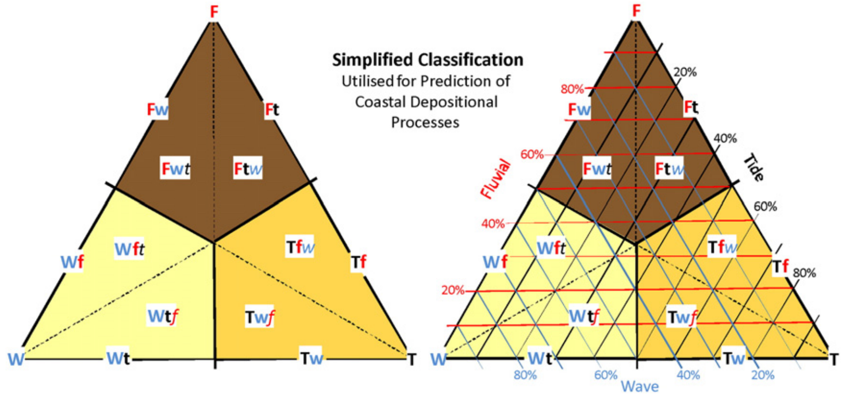

Fig. 17. Coastal process classification ternary plots (from Ainsworth et al., 2011). Ternary plots modified from Galloway (1975). The bottom side of the triangles represents classification of non-fluvial shorelines. All other portions of the plots represent some degree of fluvial influence. This classification is utilised for the predictive matrices (Fig. 18) and decision tree (Fig. 19) which can be used to predict tidal influence at shorelines. F = fluvial-dominated; W = wave-dominated; T = tide-dominated; Fw = fluvial-dominated, wave-influenced; Ft = fluvial-dominated, tide-influenced; Tf = tide-dominated, fluvial-influenced; Tw = tide-dominated, wave-influenced, Wt = wave-dominated, tide-influenced; Wf = wave-dominated, fluvial-influenced; Fwt = fluvial-dominated, wave-influenced, tide-affected; Ftw = fluvial-dominated, tide-influenced, wave-affected; Tfw = tide-dominated, fluvial-influenced, wave-affected; Twf = tide-dominated, wave-influenced, fluvial-affected; Wtf = wave-dominated, tide-influenced, fluvial-affected; Wft = wave-dominated, fluvial-influenced, tide-affected.

The relative changes in rates of development of accommodation space and sediment supply at a shoreline can also have a first degree influence on the processes acting at the shoreline. For example, low ratios of rates of accommodation to sediment supply may result in the rapid infill of an embayed shoreline and hence a reduction in the probability of tidal-influence at the shoreline through time as the embayment is infilled.

Recent approaches for prediction of tidal influence at coastlines have involved the use of matrices (Ainsworth, 2003; Ainsworth et al., 2008, 2011) and decision trees (Ainsworth et al., 2011) convolving shelf width and coastal morphology (both used as a proxy for tidal influence), fluvial energy, wave energy and accommodation to sediment supply ratios (Figs. 18 and 19). These matrices and decision tree can be utilised in a predictive manner to reduce the uncertainty in the prediction of the dominant and subordinate depositional processes acting at ancient shorelines through time and space (Ainsworth, 2003; Ainsworth et al., 2008, 2011).

5.4. Palaeo-ocean models

There are now a range of numerical computations of tidal dynamics in some ancient epicontinental seas and seaways, such as in the Carboniferous seaway of northwest Europe (Wells et al., 2005, 2007), Devonian seas (Slingerland, 1986) and the Cretaceous Western Interior Seaway (Ericksen and Slingerland, 1990; Slingerland and Keen, 1999). These models were originally developed because there were few present-day analogues for these very large epicontinental seas. Using the Imperial College Ocean Model (ICOM), Wells et al. (2007) have validated their model using the present-day North Sea, and applied it to predict tidal range in the late Pennsylvanian Midcontinent Seaway of North America. The ICOM model simulates the effects of the principal tidal constituents (astronomical tides) as well as the co-oscillating tide from the adjacent open ocean. Palaeo-water depth and coastline uncertainty were key input parameters for the prediction of tidal range, and the model was successfully applied (consistent with geological ground truthing studies) for cases of sea-level highstand and transgressive conditions. At this stage of development, the models are as good as the palaeogeographical input, and are especially useful for basin-scale predictions of tidal bed shear stress and palaeotidal range. Along-strike and local variability of tidal conditions, for example due to current funnelling and constriction within estuaries and embayments, are more difficult to model and rely on detailed input of coastline morphology and bathymetry.

6. New insights on tidal processes and products

6.1. Fluid muds, a new tidal criterion

Fluid muds are a relatively new criterion for identifying tidal conditions within distributary channel deposits. They can be recognized in the rock record as thick (often up to 1 cm), unbioturbated and unlaminated mud layers, and in the distributary channels they occur in the lower parts of the channel fill associated with relatively coarse-grained sands. The characteristic grain-size bi-modality of these channel-fill deposits (Fig. 20), as well as the layers and ripped-up clasts of fluid mud (Fig. 21) are often key criteria for recognizing a tidal origin. The muds themselves come from high (>10 g/l) suspended mud concentrations (Faas, 1991) that arise in the high mud-flocculation, turbidity maximum zone of estuaries (middle reaches) or deltas (channels on the delta plain) (Dalrymple and Choi, 2007), and from there tend to move seawards through the estuarine and deltaic channels, and sometimes far seawards (Kuehl et al., 1996). The mud layers are a product of slack water within a single tidal cycle, and are thought to be especially related to strong Spring tides that have the potential to re-suspend large volumes of mud (Harris et al., 2004). Fluid muds can be far travelled and occur in a variety of environments seawards of deltas and estuaries, but when they occur in estuarine and deltaic distributary channels they are likely to indicate tidal mixing of fresh and marine waters.

6.2. Bars versus dunes in tidal depositional systems

Current-generated dunes are ubiquitous bedforms in tidal environments. They are preserved either as simple cross-strata with "herring-bone" structure reflecting the bidirectional character of the currents, or as stacked unidirectional cross-strata indicating the direction of the locally dominant tidal current. Reactivation surfaces and tidal bundles may also be present. Simple dunes, which form a single set of cross-strata, represent the simplest architecture element, the "bricks", of high-energy tidal deposits. The large-scale architecture of tidal deposits, or the arrangement of simple dunes, reflects a type of large-scale macroform (bar or compound-dune).

In modern depositional environments it is easy to distinguish between tidal bars and tidal dunes because they have distinctly different map geometries. Modern tidal bars have their long axis oriented almost parallel to the tidal currents whereas the crestlines of large compound dunes are oriented nearly at right-angles (90°) to the main tidal currents. Consequently, the simple dunes that cover both

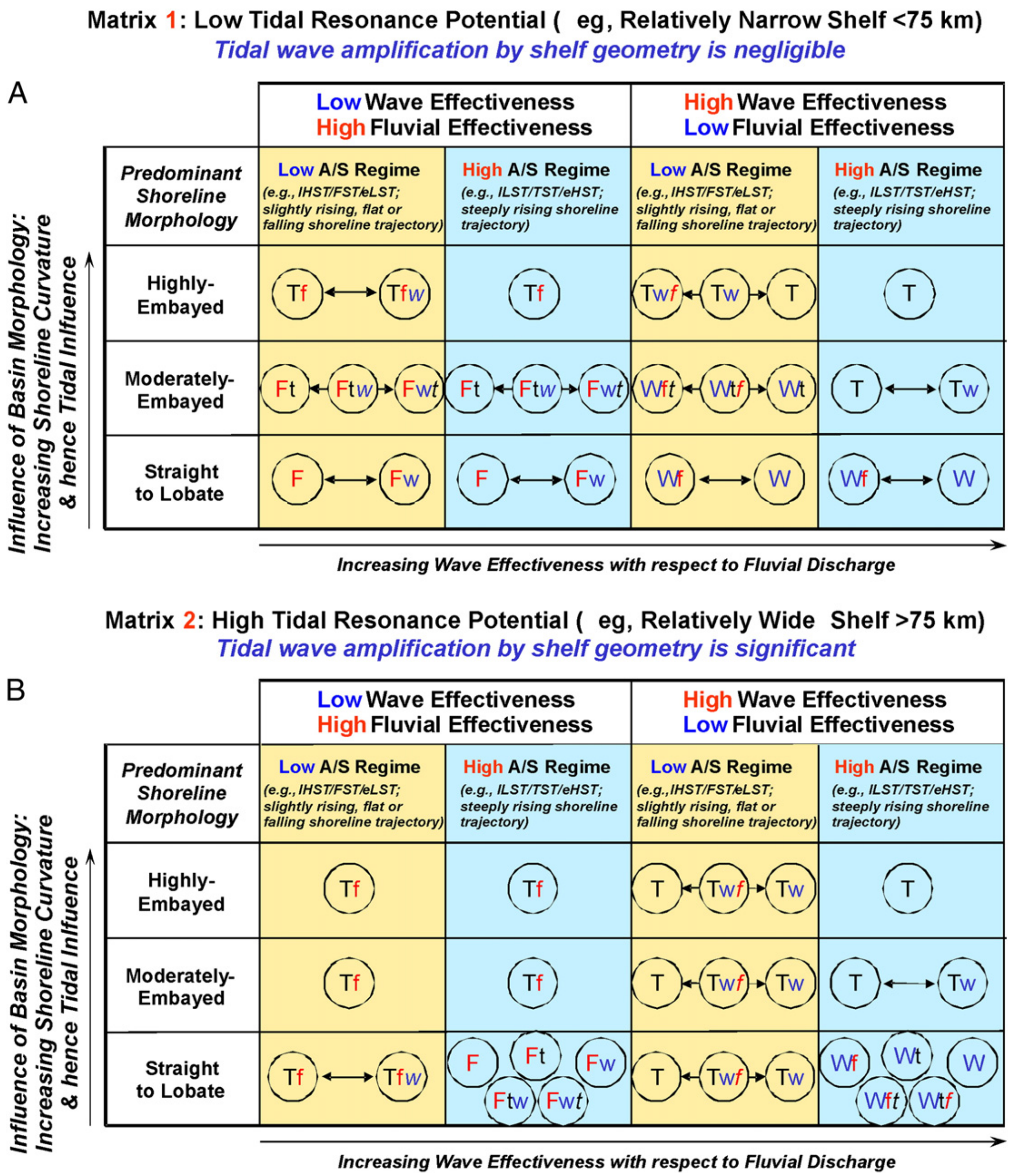

Fig. 18. Matrices for prediction of depositional process dominance for clastic coastal systems (Ainsworth et al., 2011). (A) Matrix 1 is for settings with low tidal resonance potential (e.g., narrow, <75 km shelves) (modified from Ainsworth et al., 2008). (B) Matrix 2 is for settings with high tidal resonance potential (e.g., wide, >75 km shelves). In both (A) and (B), on the high wave effectiveness side of the diagrams, in high *A/S* regimes and in highly and moderately embayed settings, waves are attenuated by shoreline morphology thus allowing tidal processes to dominate. The matrices can also be represented as a decision tree (Fig. 19). *TST* = transgressive systems tract; *eHST* = early highstand systems tract; *lHST* = late highstand systems tract; *FST* = falling-stage systems tract; *eLST* = early lowstand systems tract; *lLST* = late lowstand systems tract. See Fig. 17 for definition of coastal process dominance acronyms.

tidal bars and compound dunes migrate at very different orientations relative to the master bedding planes that are created by the migration of the larger feature: the simple dunes migrate essentially parallel to the crest of tidal bars, but many modern examples show simple dunes drifting nearly perpendicular to the crestline of tidal dunes. Thus, tidal dunes produce forward-accretion deposits because of the superimposition of simple dunes in the same direction, whereas tidal bars result in lateral-accreted deposits because the bars migrate sideways.

These two types of macroforms can be similar in scale and in 2-D, cross sections of tidal bars may look identical, consisting of stacked dunes on a series of gently dipping master surfaces. Recent works (Olariu et al., 2009; 2011; Olariu et al., 2012–this issue) have now provided criteria to distinguish between these deposits. The key observations have to do with the angular relationship between the migration direction of the smaller component dunes and the accretion direction of the larger macroform as measured by the orientation of the master bedding surfaces.

6.3. Tidal straits

Tidal straits are narrow seaways through which constricted tidal currents flow, usually uni-directionally, but sometimes bi-directionally. They frequently have a tectonic origin, and the currents in them develop because of elevation differences between the water basins at either ends (Pratt, 1990). Strait deposits are little known in the rock record, but better known in the modern because of their frequent strong tidal currents (sometimes with an added oceanic current component) and their prominent infilling by siliciclastic or bioclastic dune fields. There

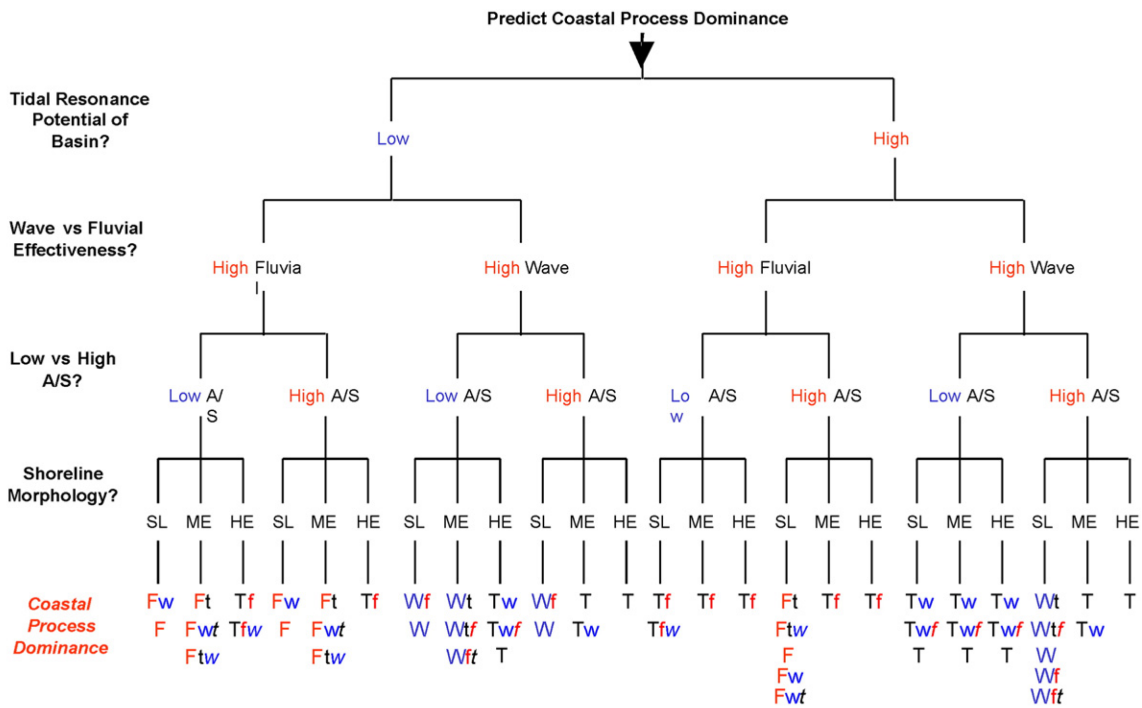

Fig. 19. Decision tree for prediction of depositional process dominance for clastic coastal systems (Ainsworth et al., 2011). This tree is derived from the two matrices shown in Fig. 18. See Fig. 17 for definition of coastal process dominance acronyms. *SL* = straight to lobate; *ME* = moderately-embayed; *HE* = highly-embayed.

Fig. 20. Fluid mud layers (light coloured in lower half of core) up to 1 cm thick, alternating with medium-grained sandstones of a tidal channel fill (Jurassic Tilje Formation, offshore Norway).

has been a recent increase in the published literature on the context and deposits of ancient tidal straits. The eye-catching feature of strait deposits is the abundance of stacked sets of planar or trough cross stratification, the huge size of some of the dunes (because of deep water and strong currents), and the absence of channels or other subaerial indicators. In addition they often occur in a context of relatively narrow tectonic corridors. The geometry of straits and the absence of associated intertidal deposits or laterally-accreting bar forms also set them apart from regular dune fields in large tide-dominated estuaries or on the open shelf.

Ancient tidal strait deposits are best known from the Burgidalian peri-Alpine seaway (connecting Atlantic and para-Tethys) of southern Europe (Martel et al., 1994; Bieg and Suess, 2006), from a series of Tortonian to Messinian straits around the Betic Cordillera of southern Spain and north Africa (connecting Atlantic and Mediterranean) (Betzler et al., 2006; Martin et al., 2009), from the Neogene–Quaternary trans-Calabrian straits, including the Tortonian Monte Pellegrino palaeostrait

Fig. 21. Cross-stratified sandstones with light-coloured fluid mud layers and rip-up clasts in tide-dominated delta-front facies of Fox Hills delta, Rawlins area, S. Wyoming.

(Longhitano and Nemec, 2005) and the Pleistocene Catanzaro and Siderno palaeostraits (Chiarella, 2011; Longhitano et al., 2012–this issue), from the Oligo-Miocene (Te Kuiti Group) seaway on north island of New Zealand (Anastas et al., 1997, 2006), from the Eocene La Baronia Fm in Ager Basin in the Pyrenees of SE Spain (Olariu et al., 2009; 2012–this issue) and from the extending and rotating mid-Jurassic half grabens (Bearreraig Fm) of Hebridean Scotland.

These studies of palaeostraits have not yet been fully integrated into a well-tried model, but there are several features of strait successions that stand out: (i) on the local spatial (<1 km) and vertical (5–15 m) scale, in some successions there is a thickening-to-thinning upward trend of set thickness (Anastas et al., 2006) that probably reflects the overall growth and forward migration of the dune field. The largest dunes at the centre of the field over-ride smaller flanking dunes (Anderton, 1976; Dalrymple and Rhodes, 1995), sometimes with marked basal erosion associated with the largest dunes. (ii) On the basin scale (tens of metres vertically) it has been suggested that changes in water depth in the strait is the main driver of longer term dune size changes or changes between tide-dominated and wave-dominated regimes (Anastas et al., 2006). The strongest tidal currents at a certain critical water depth would associate with the largest dunes, with overlying successions of smaller dunes representing slower current velocities and deeper water. Blackwood (2006) also followed this changing water depth model in the context of syn-tectonic rotation of extensional fault blocks, but he interpreted stronger currents and larger dunes to imply the times of active block rotation. At these times, the straits would have become narrower because of footwall uplift, and tidal currents would have become more constricted. Subsequently, dune size decreased as broader subsidence widened the seaway. This repeated several times at 50–100 m vertical scale in the strait-infill record (Figs. 22 and 23) (Blackwood, 2006).

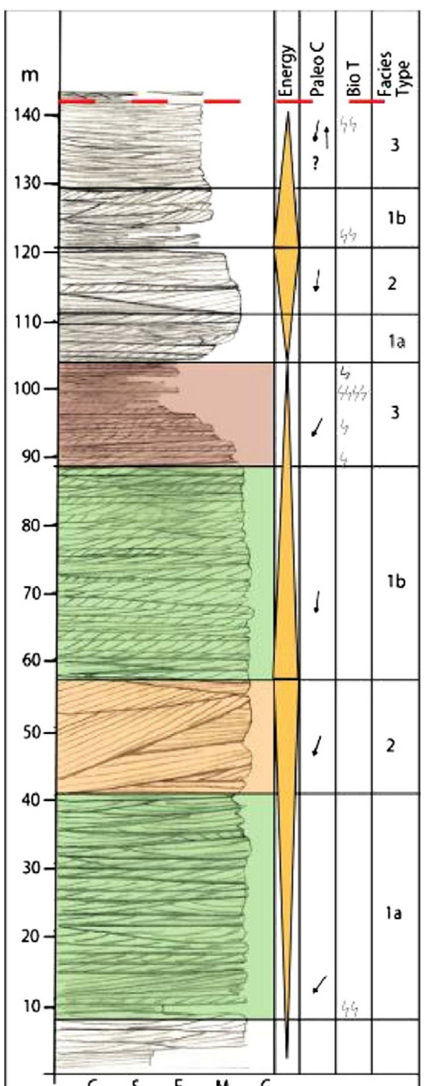

Fig. 22. Cross-stratified tidal strait succession the lower 100 m of which shows an upward-thickening to upward-thinning trend of set thicknesses. Blackwood (2006) interpreted the upward thickening portion to reflect increasing tidal current strengths due to narrowing of the straits during syn-tectonic block rotation, and the subsequent thinning as widening of the straits during post-rift subsidence.

In the Monte Pellegrino palaeostrait described by Longhitano and Nemec (2005), a detailed documentation of vertical trends of set thickness again suggested the largest dunes in the central or axial reaches of the strait, alternating (on a scale of few tens of metres) with groups of smaller dunes, possibly reflecting the basic forward growth pattern of the dunefield (Fig. 24). Based on lateral correlations and the existing knowledge of dune population dynamics, the bed packages are considered to constitute aggradational parasequences, whose varied lateral development is attributed to the differential response of the axial zone and lower-lying margin of the tidal system to tectonically forced bathymetric changes. The data set indicates that the dune cross-set thicknesses are self-similar, but have different fractal dimensions in different thickness ranges. The thinner beds (<250 cm) are attributed to the system's local or temporal conditions in which dunes were subject to erosion, whereas the thicker beds represent conditions in which dunes were better preserved. The spatial pattern of bed-thickness variation is considered to be a result of internal forcing of a depositional system in a state of self-organized criticality, combined with the system's differential responses to tectonically forced episodes of water deepening (Longhitano and Nemec, 2005).

7. The importance of tidal depositional systems

Modern tidal systems include important depositional environments that have widespread significance for human land use. The deposits of these environments are economically important for hydrocarbon exploration and production (Boyd et al., 2006). In shallow marine meso- to macrotidal environments, and less commonly in microtidal settings, tidal currents may produce significant sediment movement on the sea bed that cause serious problems for ships in congested shipping lanes (e.g., the English Channel), and for oil and gas drilling platforms and pipelines (e.g., the North Sea, the Gulf of Mexico, the Messina Strait) (Dean and Dalrymple, 2004). In each of these cases, geologists are called upon to

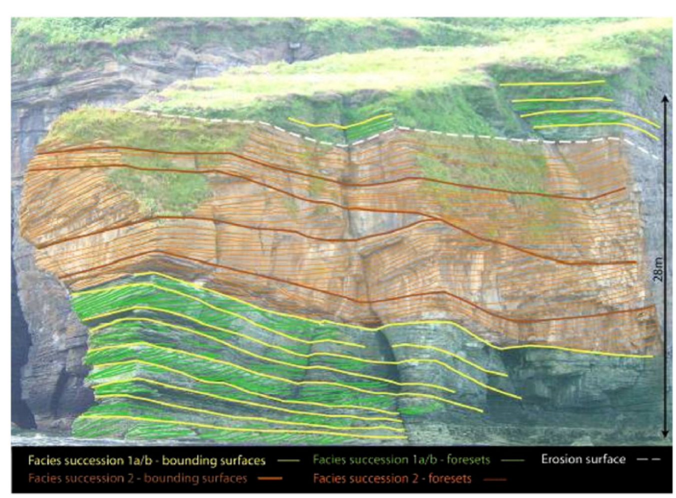

Fig. 23. Photo of upward-thickening to thinning succession of dunes in Bearreraig Sandstone, interpreted in terms of increased strength of tidal currents in the Inner Hebridean Strait due to constrictive strait narrowing during syn-rift block tilting. From Blackwood (2006).

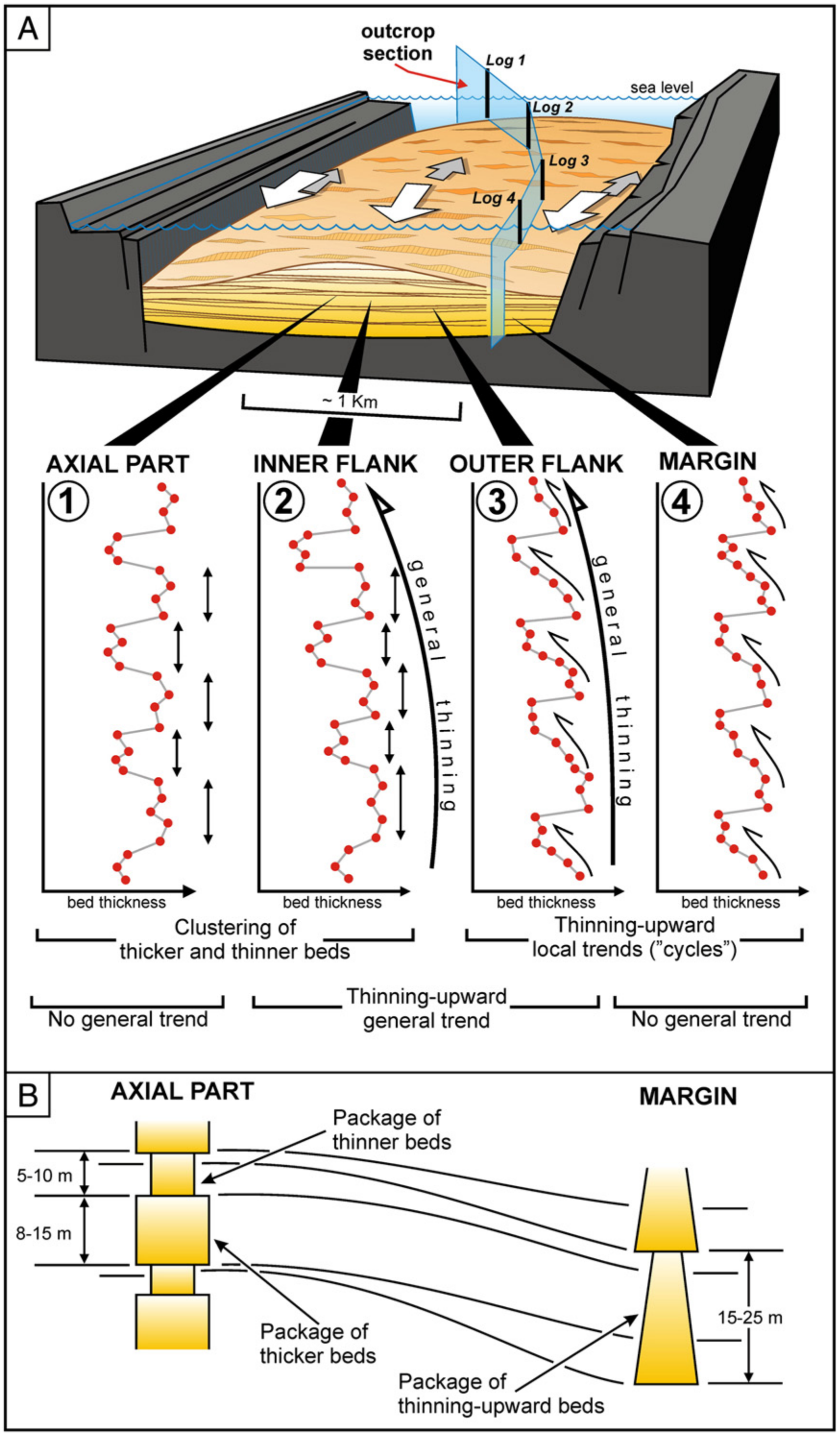

Fig. 24. Strait-fill model interpreted from the Tortonian Monte Pellegrino palaeostrait (western Calabria, south Italy). (A) The dune-bedded succession in the axial zone of the palaeostrait shows alternating clusters of thinner and thicker (5 to 15 m thick) beds, passing laterally into thinning-upward (15 to 25 m thick) bed packages, in the marginal zone. The transition zone is characterized by an overall thinning-upward trend. (B) Lateral correlations suggest that: (i) the thinner-bedded clusters in the axial zone are thinning towards the palaeostrait margin, where they correspond to the thinnest-bedded upper parts of the thinning-upward packages; (ii) the thickest-bedded lower parts of the latter packages in the marginal zone correspond to the topmost parts of the thinner-bedded clusters in the axial zone, or virtually pinch out in this direction; and (iii) the thicker-bedded clusters in the axial zone correspond to the middle portions of the thinning-upward packages in the marginal zone. This tentative correlation is assumed to approximate chronostratigraphic relationships.
Modified from Longhitano and Nemec (2005).

provide detailed models of shallow-marine water flow and sediment transport pathways. Recently, projects of monitoring and modelling of specific segments of coastal areas subjected to a tidal hydrodynamics have been undertaken using very advanced techniques of data acquisition and computer programs that allow reliable prediction of tidal and sediment transport dynamics (Li et al., 2009).

On the other hand, human activities or engineering interventions along coasts to prevent tidal damage have also caused considerable problems to shallow marine ecosystems (Dean and Dalrymple, 2004).

Another important aspect in the study of ancient tidal coastal and shallow-marine successions is their reservoir potential. Tidally-generated sandstone (and gravelstone) bodies, particularly when encased in mudstone intervals, are important sources of fluids such as water, oil and gas (e.g., Mesozoic to Cenozoic strata in North America and the Gulf of Mexico). Such sandstone bodies may be deposits of distributary channels and mouth bars on deltas, tidal inlets, and associated flood and ebb-tidal deltas, beaches, or shallow-marine sand waves. Calcareous sandstone-gravelstone bodies may be associated with organic buildups (e.g., coral reefs) and shoal deposits, both of which are particularly prone to diagenetic modification of primary porosity and permeability. The lithosome geometry and sedimentary characters (including rock fabric, porosity, permeability and saturation) of these sandstone bodies depend on the original sedimentary processes that occurred in specific depositional environments, and the nature of subsequent diagenesis (Moore, 1989). In tide-dominated settings, cyclical changes in current competence may generate deposits that are internally organized into a series heterolithic laminae or set of laminae [the sandy/muddy intervals (Visser, 1980), or the silici-bioclastic bundles (Longhitano, 2011)] that may act as barriers, or baffles if subjected to eventual, post-diagenetic fluid transmission (Nemec et al., 2007; Ainsworth, 2010). The distribution of 3D petrophysical properties evaluated through geostatistical analyses was also applied as a useful methodological approach. This approach permits the determination of rock fabric flow layers of sequence stratigraphic significance (Slatt, 2006).

Recently, many unpublished oil company reports and laboratory studies have evaluated the two dimensional physical attributes of tidally generated heterolithic sediments. If correctly predicted in space and time, they may generate useful models for fluid motion and conduction (e.g., Mikes and Bruining, 2006; Messina et al., 2009).

8. Conclusions

Recent insights into ancient tidal depositional systems include the recognition criterion for fluid mud generated in the turbidity maximum zone of deltas and estuaries, the differences between the growth direction of compound dunes and tidal bars, the importance of palaeogeographic reconstructions, and the recognition of tidal-strait successions as distinct depositional systems. Modelling of ancient tidal depositional systems has included *observations* on how tidal influence is preserved during falling and rising of sea level during cross-shelf transits of deltas and estuaries, *recognition* of the systematic changes in tidal and other processes that occur within the fluvial–marine transition zone of coasts, *prediction* of tidal influence in ancient coastal deposits based on shoreline morphology, shelf width and accommodation to supply ratios, and *the generation* of large-scale palaeo-ocean models for ancient seas and seaways.

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