mean low tide levels. Being a worldwide phenomenon, one might assume that they result from variations in the astronomical factors defining the tidal potential. A clear correlation, however, is still lacking. As far as sandy tidal environments are concerned, accurate sediment budgets and transport pathways have remained elusive problems whose solution becomes more pressing in view of the predicted acceleration in sea-level rise. The distinction between strictly local features and others of global relevance requires more attention. A number of other unresolved issues have been addressed in the text.

Cross-References

- ► Barrier Island Landforms
- ► Beach Processes
- ► Bioerosion
- ► Estuaries
- ► Holocene Coastal Geomorphology
- ► Littoral
- ► Microtidal Coasts
- ► Rock Coast Processes
- ► Sandy Coasts
- ► Tidal Flats
- ► Tides
- ► Wave-Dominated Coasts

Bibliography

Allen PA (1997) Earth surface processes. Blackwell Science, Oxford

Allen JRL, Pye K (eds) (1992) Salt marshes, morphodynamics, conservation and engineering significance. Cambridge University Press, Cambridge

Alongi DM (1998) Coastal ecosystem processes. CRC Press, Boca Raton

Archer AW, Kvale EP, Johnson HR (1991) Analysis of modern equatorial tidal periodicities as a test of information encoded in ancient tidal rhythmites. In: Smith DG, Reinson GE, Zaitlin BA, Rahmani RA (eds) Clastic tidal sedimentology. Canadian society of petroleum geologist, Memoirs, vol 16, pp 189–196

Bird EC, Schwartz ML (eds) (1985) The world's coastline. Van Nostrand Reinhold, New York

Borrego J, Morales JA, Pendon JG (1995) Holocene estuarine facies along the mesotidal coast of Huelva, south-western Spain. In: Flemming BW, Bartholomä A (eds) Tidal signatures in modern and ancient sediments. Special publication international association of sedimentologists, vol 24. Blackwell Science, Oxford, pp 151–170

Chapman VJ (1974) Salt marshes and salt deserts of the world, 2nd edn. Cramer, Lehre

Davies JL (1964) A morphogenetic approach to world shorelines. Z Geomorphol 8:127–142

Davies JL (1980) Geographical variation in coastal development. Geomorphology texts, vol 4. Longman, London

Davis RA Jr (ed) (1994) Geology of Holocene barrier island systems. Springer, Berlin

de Boer PL, Smith DG (eds) (1994) Orbital forcing and cyclic sequences. Special publication international association of sedimentologists no. 19. Blackwell Science, Oxford

Delafontaine MT, Flemming BW (1989) Physical factors in barnacle community structure: a conceptual model. In: Ros JD (ed) Topics in marine biology. Scientia Marina, vol 53, pp 405–410

Dietrich G, Kalle K, Krauss W, Siedler G (1975) Introductory oceanography, 3rd edn. Gebr. Borntraeger, Berlin

Doodson AT (1922) The harmonic development of the tide-generating potential. Proc R Soc Lond A100:305–329

Flemming BW, Hertweck G (eds) (1994) Tidal flats and barrier systems of continental Europe: a selective overview. Senckenberg Marit 24:1–209

French PW (1997) Coastal and estuarine management. Routledge, London

Gray AJ (1992) Salt marsh plant ecology: zonation and succession revisited. In: Allen JRL, Pye K (eds) Salt marshes. Cambridge University Press, Cambridge, pp 63–79

Hayes MO (1979) Barrier island morphology as a function of tidal and wave regime. In: Leatherman SP (ed) Barrier islands. Academic, New York, pp 1–27

Horikawa (1989) Nearshore dynamics and coastal processes: theory, measurement, and predictive models. University of Tokyo Press, Tokyo

Kjerfve B, Magill KE (1989) Geographic and hydrodynamic characteristics of shallow coastal lagoons. Mar Geol 88:197–199

Lewis JR (1972) The ecology of rocky shores. The English University Press, London

Lugo AE, Snedaker SC (1974) The ecology of mangroves. Annu Rev Ecol Syst 5:39–64

McLachlan A, Erasmus T (eds) (1983) Sandy beaches as ecosystems. Developments in hydrobiology, vol 19. Dr. W. Junk Publishers, The Hague

McLellan HJ (1975) Elements of physical oceanography. Pergamon Press, Oxford

Newell RC (1979) Biology of intertidal animals. Marine Ecological Surveys Ltd., Faversham

Oost AP, de Haas H, Ijnsen F, van den Boogert JM, de Boer PL (1993) The 18.6 year nodal cycle and its impact on tidal sedimentation. Sediment Geol 87:1–11

Raffaeli D, Hawkins S (1996) Intertidal ecology. Chapman & Hall, London

Streif H (1990) The East Frisian Coast. North Sea, Islands, Wadden Sea, and Marshes (in German). Borntraeger, Berlin

Thomas MLH (1985) Littoral community structure and zonation on the rocky shores of Bermuda. Bull Mar Sci 37:857–870

Williams GE (1991) Upper Proterozoic tidal rhythmites, South Australia: sedimentary features, deposition, and implications for the earth's paleorotation. In: Smith DG, Reinson GE, Zaitlin BA, Rahmani RA (eds) Clastic tidal sedimentology. Canadian society of petroleum geologists, Memoir, vol 16, pp 161–178

Tidal Flats

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Definition and Introduction

Tidal flats are low-gradient tidally inundated coastal surfaces. Jackson (1997) defines them as extensive, nearly horizontal, marshy, or barren tracts of land alternately covered and uncovered by the tide, and consisting of unconsolidated sediment. Tidal flats may be muddy, sandy, gravelly, covered in shell pavements, or locally underlain by rock pavement and, compositionally, be underlain by siliciclastic or carbonate sediments. They are complex coastal systems combining elements of coastal geomorphology, sedimentology, hydrology, hydrochemistry, diagenesis, biology, and ecology.

Geologically, tidal flats have been of great interest to sedimentologists and stratigraphers as coastal systems that are readily accessible to sampling and study, and rich in processes and products resulting from oceanographic, sedimentologic, geohydrologic, hydrologic, hydrochemical, mineralogic, and biotic interactions (Ginsburg 1975; Klein 1976; Alexander et al. 1998; Black et al. 1998). They contrast with steeper-gradient wave-dominated sedimentary coasts such as sandy beaches composed dominantly of sand and with a relatively limited biota, because tidal flats with their generally lower-energy conditions and less scope for physical reworking develop a profusion of natural history coastal features. For instance, there are the sedimentologic products of interactions between waves and tides (e.g., cross-laminated sand, ripple-laminated sand, lenticular bedding, flazer bedding, laminated mud, ripple-laminated silt lenses in clay), the products of interactions between sediments and biota (e.g., various burrow forms zoned tidally across the shore, various types of root-structuring, skeletal remains related to tidal levels), the geomorphic products of tides (e.g., tidal run-off on low-gradient slopes to form meandering tidal creeks), the effect of water temperature and salinity (Krogel and Flemming 1998), and the products of hydrochemical interactions with sediments resulting in diagenetic products (e.g., dissolution of carbonate by acidic pore water; cemented crusts and their breccia and sand-sized intraclast derivatives; carbonate nodules; gypsum precipitates; and products of redox reactions such as biologically mediated precipitation of iron sulfide). For stratigraphers and students of sedimentary rocks, identifying tidal flats in the geologic record is often an important step in the reconstruction of palaeoenvironments, the location of facies associated with coastlines, and the recognition of such markers in stratigraphic sequences in basin analyses – tidal-flat signatures derived from studies of modern environments provide important analogs in such analyses.

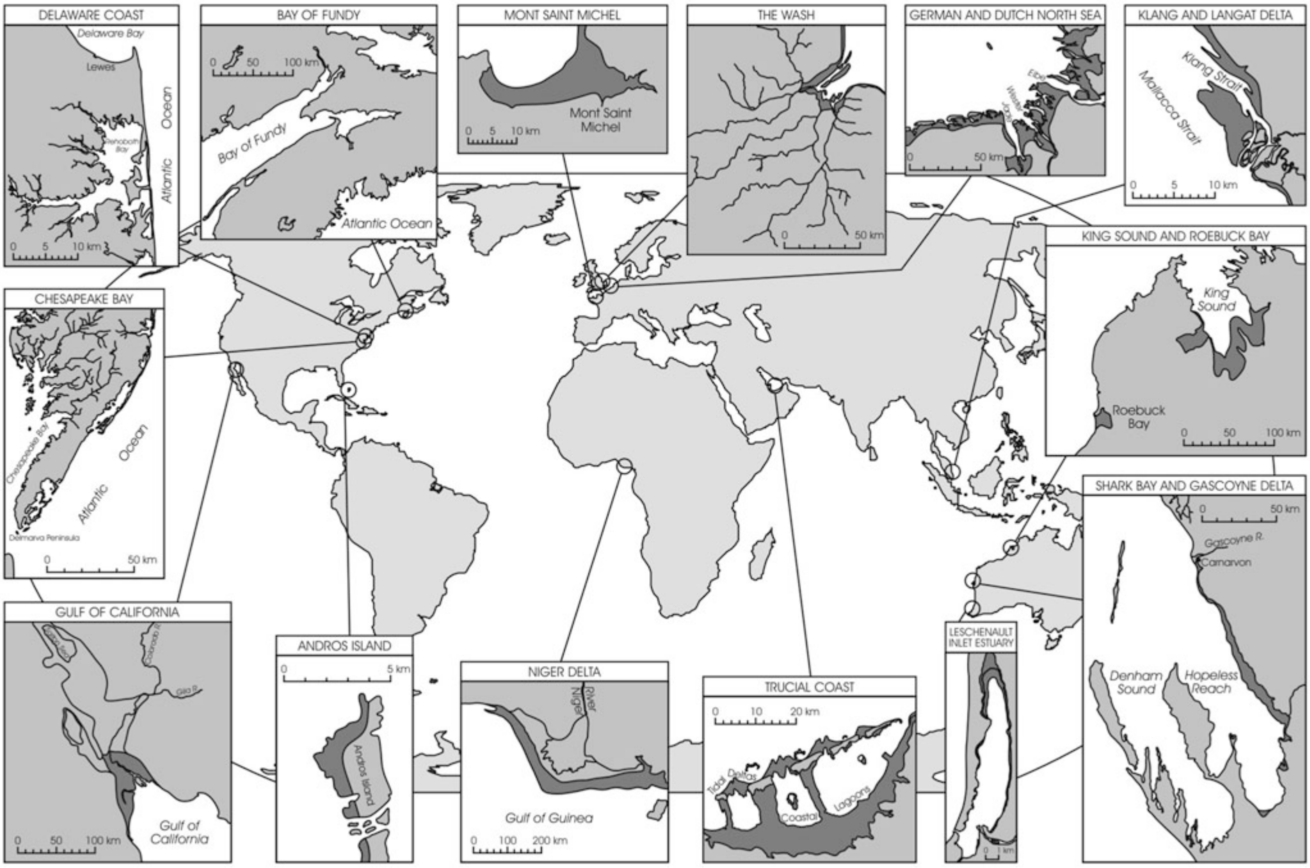
Tidal flats have been of great interest also to biologists and ecologists – firstly, because these systems are habitats for a variety of biota; and secondly, because there are processes and products ranging from the macroscale (such as mangrove forests) to the microscopic (such as microbial communities), with biological responses to and, conversely, biological effects on the sedimentologic, geohydrologic, hydrologic, hydrochemical, and mineralogic features of the environment (Watzin 1983; Stal and de Brouwer 2003); the variation in substrates has an influence on the composition of communities (Albrecht 1998; Semeniuk et al. 2000). Further, because of their biodiversity, ecological processing, and productivity, tidal flats are important in their function in the food chain in coastal zones, as food sources for migrating nekton (fish, crabs, snakes), demersal fish, and waterbirds (de Sylva 1975; Dankers et al. 1983; Wolff 1983; Reise 1985, 1991; Hutchins and Saenger 1987; Paterson et al. 2009), and as fish nurseries. In effect, tidal flats are an interactive system of sediments and hydrology/ hydrochemistry influencing biota, and biota effecting and structuring sediments. Again, with their biodiversity and ecological functioning, tidal flats are biologically more complex, and contrast with the ecologically simpler, steeper-gradient wave-dominated sandy shores.

Settings of Tidal Flats

Tidal flats around the globe occur in a variety of regional geomorphic settings (Fig. 1 and Table 1). Since they are surfaces exposed and inundated by tides, they may simply be part of larger coastal systems (Semeniuk 1996, 2008, 2015a; Fan 2012; Flemming 2012), that is, the shores of deltas, estuaries, lagoons, gulfs, bays, straits, rias, sounds, and cuspate forelands. Alternatively, they may be the sole coastal form developed along an open coast or broad embayment, or may comprise wholly tidal lagoons leeward of barriers. The best-developed tidal flats occur along estuarine coasts, protected embayments, or barred lagoons where the shore slopes are gentle due to sediment accretion, and tides are large (Fig. 2). Along many coasts, tidal flats are part of prograded shores (Kendall and Skipwith 1968; Thompson 1968; Hagan and Logan 1975; Reineck and Singh 1980); but in some instances, they may comprise modern sediment veneers on wave- or tidal-cut unconformities on rock or Pleistocene sediment, or earlier Holocene sediments (Semeniuk 1981a).

Oceanographically and meteorologically, tidal flats can be tide-dominated, wave-dominated, mixed tide- and wave-influenced, cyclone- and storm-influenced, and/or strongly wind-influenced. Consequently, and depending on the type of sediment delivery, they can be sandy tidal flats, muddy tidal flats, or sedimentologically mixed and zoned tidal flats, with implications for varied sedimentary structures developed across the tidal gradient reflecting the availability of grain sizes and the effects of tides, waves, storms, and wind (Reineck and Singh 1980; Flemming 2012; Zhu et al. 2014).

Sediment types and sedimentation style on tidal flats can also be influenced by climate, viz., tropical humid or tropical arid conditions, at one extreme to boreal and arctic conditions at the other (with ice interacting with coastal deposits, or annual freezing of coastal deposits; cf. Reineck and Singh 1980; Dionne 1998) which would influence rainfall, run-off volumes, wind direction and intensities, storms, water



Tidal Flats, Fig. 1 Location, settings, and sizes of various tidal flats around the globe. Table 1 provides more detailed information and references

temperatures, evaporation, style of diagenesis, and effect of biodiversity, amongst others.

The variety of tidal flats, their substrates, and their various oceanographic and geomorphic settings lend themselves to various types of classification. For instance, Semeniuk (1981b) classified the tidal flats of King Sound into categories based on underlying stratigraphy and local coastal geomorphology, and Fan et al. (2013) classified them and their associated sedimentary features and facies into nine types that presented a continuum of open-coast depositional settings from tidally dominated muddy tidal flats with wave influence through to sandy tidal flats of mixed energy (tide-dominated) to tidal beaches of mixed energy (wave-dominated) to wave-dominated beaches with tide influence.

Tides and Tidal Levels

The tidal ranges that expose tidal flats vary globally from less than 1 m to *ca* 15 m amplitude, and are diurnal (one tide daily), semidiurnal (two tides daily), or mixed (two tides daily, but with inequality between tide maxima and tide minima across the day). Over a lunar cycle, tides vary from a lower amplitude neap range (during quarter and three-quarter Moon phases) to a higher amplitude spring range (during new and full Moon phases). Higher than normal tides occur annually during equinoctial periods and on an 18.6-year turnaround in response to the Lunar Nodal Periodicity. As a result and depending on shore slope, tidal flat width may vary from being a narrow coastal strip to being broad and expansive coastal forms.

Part of the coast emergent during low tide and submerged during high tide is the *intertidal zone*; that part of the coast permanently submerged below the low-water line is the *subtidal zone*; that occurring above the zone of high-tide inundation is the *supratidal zone* (Fig. 3). Some authors consider the "supratidal zone" as the zone above the mean high-water line but sometimes under water during extremely high tides, or even spring tides, but it is preferable to refer to all gently inclined surfaces and terrain *above* the highest tides as supratidal, and to treat all surfaces flooded by neap, spring, and equinoctial spring tides as intertidal, and to separate these various tidal zones and levels.

Tidal ranges have been classed by Davies (1980) into three groups: *microtidal* <2 m, *mesotidal* 2–4 m, and *macrotidal* >4 m. While this classification generally has been accepted, large tidal ranges >8 m might be further classed as *extreme macrotidal.* Tidal range amplification may occur due to bay

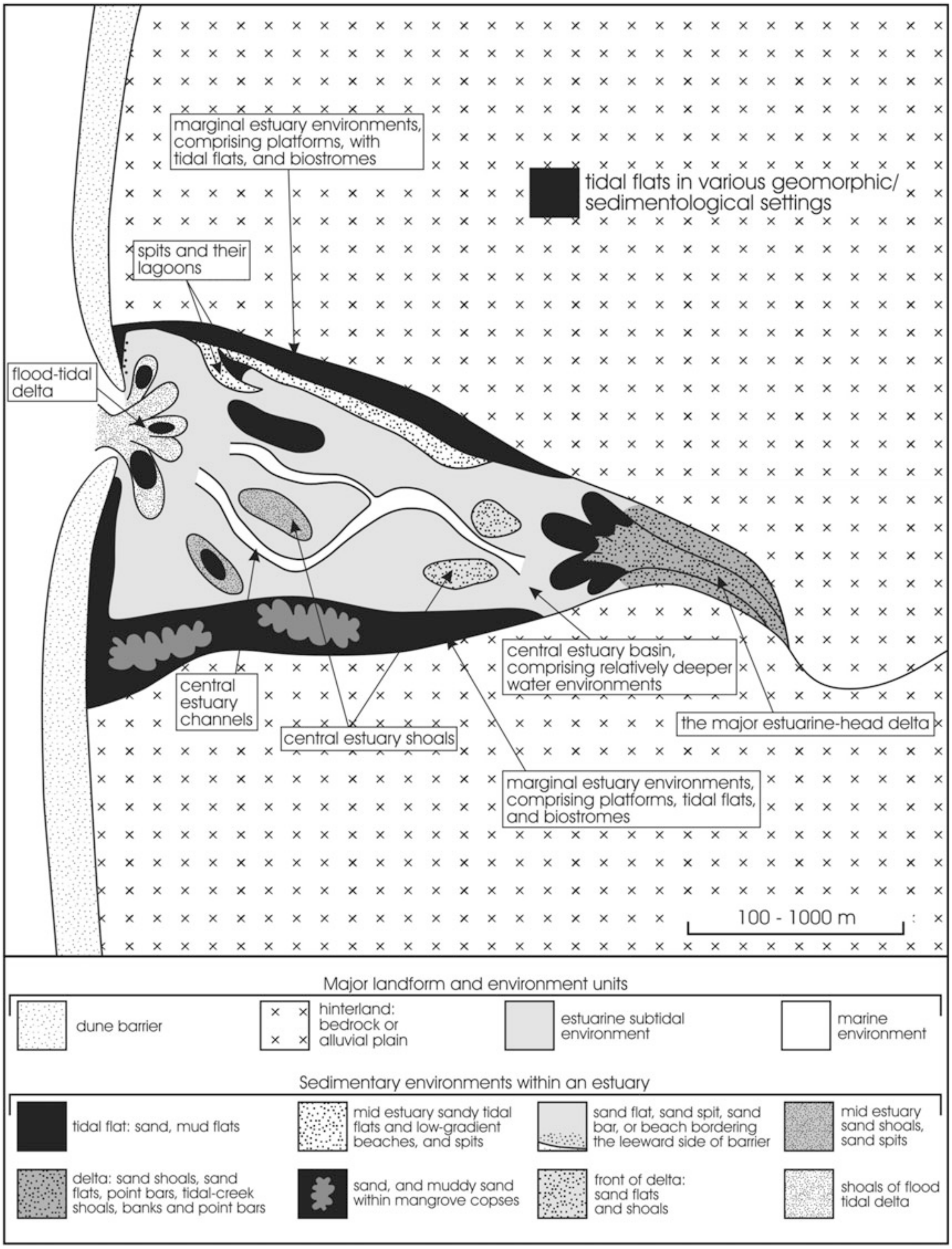
Tidal Flats, Table 1 Some well-known and documented tidal flats ordered in tidal range

Tidal flat location	Tidal range (m)	Composition	Tidal flat setting
Bay of Fundy (Nova Scotia)	15.0 m Extreme macrotidal	Siliciclastic	Broad tidal flats of gravel, sand, and mud, with local salt marsh peripheral to an estuarine gulf in a humid temperate climate (Knight and Dalrymple 1975)
Bay of Mont St Michel (NW France)	15.0 m Extreme macrotidal	Siliciclastic	Broad tidal flats of sand and mud, with salt marsh within a complex of a funnel-shaped estuary in humid temperate climate (Larsonneur 1975)
King sound (NW Australia)	11.0 m Extreme macrotidal	Siliciclastic	Broad tidal flats of sand and mud, with some cheniers, and erosional tidal channels fringed by mangroves; peripheral to a seasonal estuarine gulf in a semi-arid tropical climate (Semeniuk 1981a)
Roebuck Bay (NW Australia)	10.5 m Extreme macrotidal	Carbonate	Broad tidal flats along semi-sheltered embayment, dominated by mud; erosional tidal channels, fringed by mangroves; in a semi-arid subtropical climate (Semeniuk 1993, 2008)
Gulf of California (USA)	6–8 to 10 m Macrotidal to extreme macrotidal	Siliciclastic	Broad tidal flats dominated by mud, with intermittent beach ridges, with salt marsh; part of the Colorado River Delta within a gulf in a semi-arid subtropical climate (Thompson 1968)
The Wash (England)	7 m Macrotidal	Siliciclastic	Broad tidal flats of sand and mud, with salt marsh; along the shore of a large embayment in a humid temperate climate (Evans 1975).
Delta of the Klang and Langat Rivers (Malaysia)	4.5 m Macrotidal	Siliciclastic	Compound delta with insular/peninsular development of tidal flats, traversed by tidal creeks with mangrove; in a humid tropical climate (Coleman et al. 1970)
The Jade and the Dutch Wadden Sea (North Sea)	2.6–4.1 m Mesotidal	Siliciclastic	Broad tidal flats of sand and mud, with salt marsh, leeward of barriers in a humid temperate climate (Reineck 1975)
Niger Delta (western Africa)	1.0–2.8 m Microtidal	Siliciclastic	Extensive mangrove-vegetated tidal flats of mud and sand developed behind a beach barrier in a delta system in a humid tropical climate (Allen 1970)
Gascoyne Delta (Western Australia)	2 m Microtidal	Siliciclastic	Local narrow tidal flats of sand and mud, with mangrove fringed lagoons in a delta in an arid subtropical climate (Johnson 1982)
Trucial Coast (western Persian Gulf)	2 m Microtidal	Carbonate	Broad tidal flats of carbonate muds and gypsum, with algal mats, salt marsh and mangroves, shoreward of prograding carbonate complex fringing a large gulf in an arid tropical climate (Purser 1973)
Chesapeake Bay (eastern USA)	1.5–2.1 m Microtidal	Siliciclastic	Narrow to broad tidal flats, with salt marsh, within inlets and along the shore of an estuary in a humid temperate climate (Stevenson et al. 1985; Lippson and Lippson 1997)
Delmarva Peninsula to Sapelo Island (eastern USA)	<1 m Microtidal	Siliciclastic	Broad protected tidal flats, with salt marsh, leeward of barriers in a humid subtropical climate (Howard et al. 1972; Harrison 1975)
Andros Island (Bahamas)	0.5 m Microtidal	Carbonate	Broad tidal flats of pelleted mud, with mangrove, salt marsh and algal mats, developed capping the Bahama Bank Carbonate Complex in a humid subtropical climate (Shinn et al. 1969)
Shark Bay (Western Australia)	0.5 m Microtidal	Carbonate	Local tidal flat of sand or pelleted mud, with salt marsh, algal mats, and stromatolites, shoreward of prograding seagrass banks and hypersaline platforms in large, elongate embayments in an arid subtropical climate (Hagan and Logan 1975)
Leschenault Inlet estuary (Western Australia)	0.5 m Microtidal	Siliciclastic	Low-tidal sand, muddy sand / mud bordered by high-tidal salt-marsh-vegetated mud; locally with mangroves; tidal flats border an elongate estuarine lagoon in a humid subtropical climate (Semeniuk et al. 2000)

geometry and coastal constriction, for example, the Bay of Fundy in Nova Scotia, which, because of its basin geometry, amplifies the tide from *ca* 5.4 m at the entrance to the bay to 15 m at its head.

Zoning on Tidal Flats

Tidal flats are typically zoned in terms of geomorphology, sediments, hydrology, hydrochemistry, and biota in response to gradients of inundation frequency (and conversely, extent of exposure), hydrodynamic energy (wave and tidal-current energy), and salinity. The best zonation is manifest sedimentologically and biologically in response to hydrodynamic variations and physicochemical gradients, respectively (Semeniuk 1983, 2015b). Sedimentologic and biologic zones across the tidal flats are best exhibited in macrotidal settings where there are marked distinctions in slope, sediments, and biology within the interval of the tidal range responding to inundation frequency, wave and

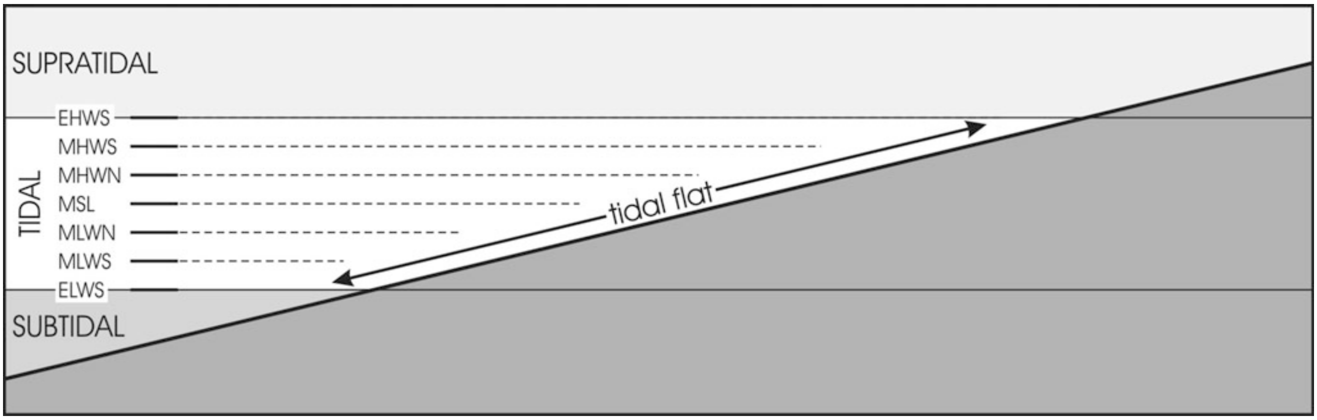


Tidal Flats, Fig. 2 Typical geomorphic and sedimentologic location of tidal flats within an idealized estuary. (From Semeniuk 2015a)

tidal-current energy, and pore-water salinity. On microtidal flats, these various differences related to tidal levels are less pronounced.

Various levels within a tidal flat, often delineated by sediment and/or biological zones, can be distinguished as follows:

- Low tidal flats – exposed by the mean and extreme low spring tides, generally underlain by sand, and vegetation-free
- Middle tidal flats – the flats and low-gradient slopes centered around mean sea level, exposed and inundated by neap tides; the upper parts of these flats may be vegetated



Tidal Flats, Fig. 3 Tidal flat in profile showing the various tidal levels (inclination of tidal flat is exaggerated). Located between the supratidal and subtidal zones, the tidal flat has the following levels: the lowest tidal level at equinoctial low-water spring tide (ELWS), mean low-water spring tide (MLWS), mean low-water neap tide (MLN), mean sea level (MSL), mean high-water neap tide (MHN), mean high-water spring tide (MHWS), and the highest tide level at equinoctial high-water spring tide (EHWS). (From Semeniuk 2015a)

by samphire in temperate latitude areas, and by mangrove in tropical latitudes
- High tidal flats – inundated by the mean and extreme high spring tides, generally underlain by mud, and vegetated by salt marsh or mangrove, or, in more arid settings, vegetation-free and salt-encrusted (salt flat)

Typical cross sections through some macrotidal to microtidal flats are shown in Fig. 4.

Geomorphic Features of Tidal Flats

The macroscale, mesoscale, and smaller-scale features are the result of wave action or tidal currents, the strength of the waves and tidal currents, and the duration that part of the tidal flat is subject to waves or tidal currents. At the macroscale, the surface of a tidal flat generally is flat to gently inclined, but there may be a range of mesoscale to microscale features therein (Figs. 4 and 5; Table 2) reflecting the effects of position within either the low or high spring tidal zones, or the neap tidal zone. For example, the low tidal zone may be nearly flat or very gently inclined, the middle tidal flat may be more moderately inclined, and the high tidal flat again may be nearly flat or very gently inclined.

At mesoscale, the geomorphic features of tidal flats may include plain flats; local cliffs; spits; cheniers; sand waves; shell mounds; skeletal reefs; and gullies, channels, and creeks (also called tidal creeks). Cliffs, commonly cut into mud, can separate vegetated and vegetation-free plain flat zones, but some cliffs are formed due to either the effect of wave energy concentrated at a specific tidal level or the undercutting of mud through erosion of underlying sand. Tidal creeks may be ramifying or meandering, with point bars and steep banks. At smaller scales, the surface of tidal flats may be planar and smooth; or hummocky to slightly irregular; or may exhibit linear scours, fish and ray excavation hollows, snail, worm and crab tracks, feeding pellets, exhalent mounds of worm or shrimp burrows, carbonate crust mounding and teepees, desiccation polygons, or mud cracks; or may exhibit silt ripples on a clay floor.

In a geomorphic overview, recently, Zhou et al. (2016) numerically modelled tidal flats in relation to sediments and vegetation with interactions between tides, waves, salt marshes, sediment transport, and sea level rise to determine and predict of tidal flat profile shape and sediment distribution – the tidal flats were depositional or erosional, and varying from convex to concave in profile depending on tide versus wave action, and presence of vegetation.

Tidal Flats and Their Particle Sizes and Sediment Composition

Tidal flats may be underlain by mud, sand, rock gravel, shell pavements and, locally, rock pavements, or mixtures of these. Often, where all particle sizes are present, there is a zonation of sediment types across the flats, and an interlayering at a specific tidal level, but in many instances, one sediment type may dominate across the entire tidal flat. This partitioning of sediments across the tidal flat lends itself to a classification of tidal flats, or zones within tidal flats, according to particle size. For example, those composed wholly of mud may be termed muddy tidal flats, and those composed wholly of sand are sandy tidal flats. Tidal level zones within the tidal flat may be classed according to substrate, for example, sandy low tidal flats, muddy high tidal flats. Many sandy tidal flats, when exposed at low tide, have a glistening film of wet clay on the surface which gives the impression that they are mud flats – scraping away the film of clay will reveal an underlying

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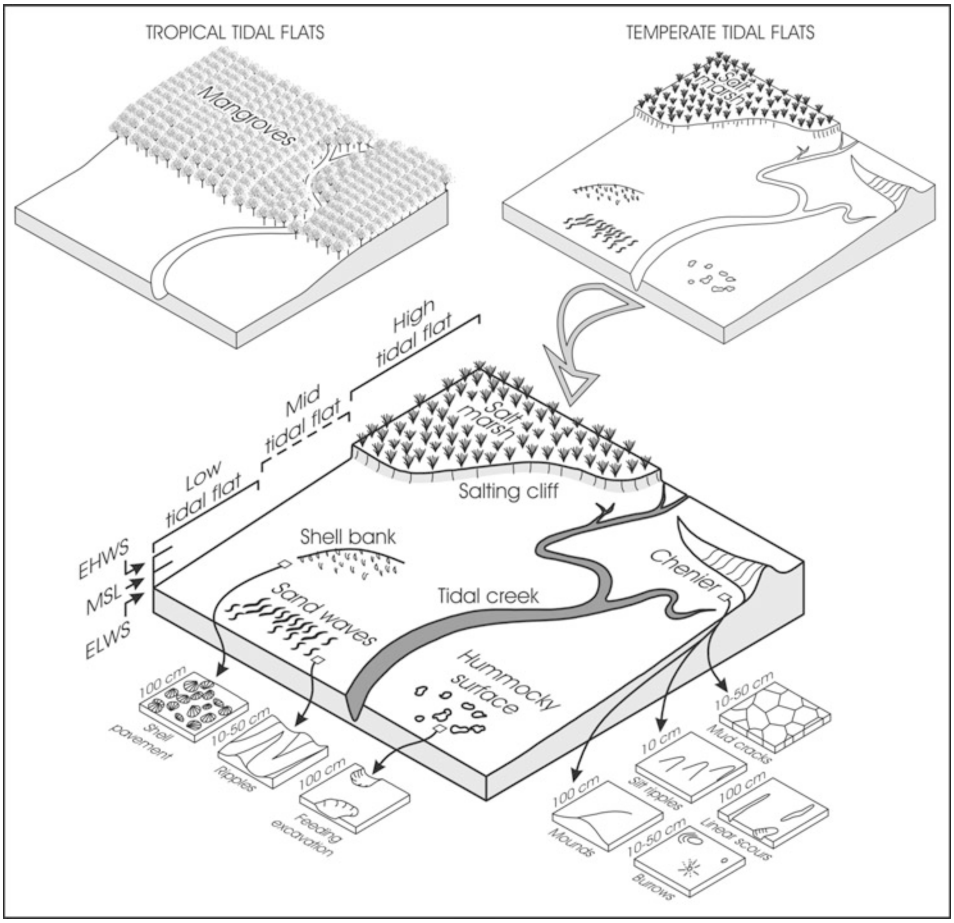
Tidal Flats, Fig. 4 Generalised geomorphology of tidal flats. Macroscale geomorphology of tropical-climate tidal flats with mangroves and temperate-climate tidal flats with salt marsh. More detail of mesoscale and microscale features is shown for a temperate climate tidal flat

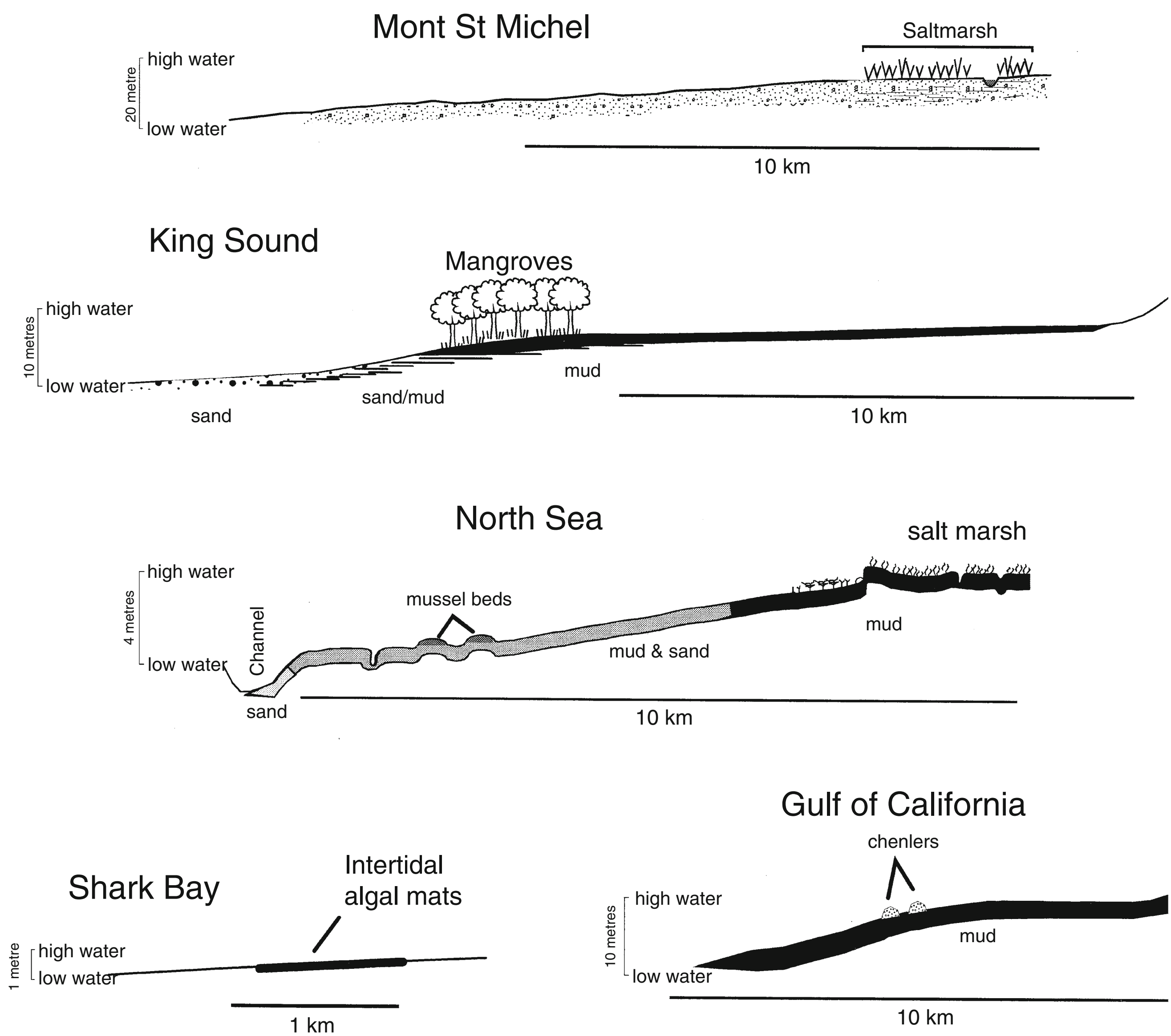


sand substrate and, as such, many a sandy tidal flat with this wet clay surface film has erroneously been called a "mud flat." A range of possible tidal flat types based on substrate and tidal zone slopes is shown in Fig. 6. A range of possible tidal flat types based on substrate, with field examples, is presented in Table 3.

In regard to sediment composition, two major groups are recognized: *siliciclastic tidal flats* composed of terrigenous sediments such as quartz sand, quartz silt, and phyllosilicate clay, and *carbonate tidal flats* composed of carbonate silt and clay, various sand-sized carbonate grains, and products of cementation (e.g., crusts, breccias, intraclasts). These major groups reflect two extremes in settings: an abundant supply of terrigenous sediment to the tidal coast such as in deltas or estuaries versus a low supply relative to the rate of carbonate sediment production (as along terrigenous sediment-starved coasts). From a historical perspective, the majority of earlier investigations of tidal flats were centered on siliciclastic systems, and much information emerged from studies in the North Sea (Reineck 1972; Evans 1975). Later, as interest in carbonate rocks grew during the 1960s, linked to their petroleum reservoir potential, a range of studies was undertaken in carbonate tidal flats (Shinn et al. 1969; Purser 1973; Hagan and Logan 1975; Shinn 1983).

Generally, regardless of whether the tidal flats are dominantly siliciclastic or carbonate, their sediments commonly contain both siliciclastic *and* carbonate particles. In dominantly siliciclastic settings, there may be minor to moderate carbonate components of shell gravel, shell grit, skeletal sand (e.g., shell fragments, foraminifera), skeletal silt-sized material, and carbonate clay transported to or generated on the flats. Similarly, in dominantly carbonate environments, there may be siliciclastic sand, mud, or gravel from oceanic, aeolian, or local eroding sources. The range and origin of mud, sand, and gravel-sized particles comprising tidal-flat sediments are noted in Table 4.

Some of the best-known siliciclastic tidal flats are the North Sea coast (for example, the Jade and the Dutch Wadden Sea, with detailed information on sediment dynamics, sedimentary structures, sediment types, and tidal-flat stratigraphy), The Wash in south-eastern England, the Gulf of California, the Bay of Fundy, the compound high-tidal delta of the Klang and Langat Rivers, King Sound in north-western Australia, Bay of Mont St Michel in France (Postma 1961; Klein 1963; Thompson 1968; Allen 1970; Coleman et al. 1970; Reineck 1972; Evans 1975; Larsonneur 1975; Semeniuk 1981a; Amos 1995). With most of these examples,



Tidal Flats, Fig. 5 Profiles across various macrotidal to microtidal siliciclastic and carbonate tidal flats (see Table 1) showing nature of slopes, sediments, vegetation, or tidal flat morphology. (From Semeniuk 2005)

there is a grain-size variation across the flats from sand in low-tidal zones, with specific biogenic contributions in particular tidal zones depending on climate setting and biogeography, and sediment types and sedimentary structures are dominantly the result of physical and biologic processes. With increase upslope in pore water salinity, particularly in semiarid and arid climates, the upper parts of siliciclastic tidal flats may develop carbonate nodules or gypsum crystals, or be salt-encrusted.

Carbonate tidal flats generally occur in mid- to low-latitude warm climates. The best known are Andros Island of the Bahama Banks (Shinn et al. 1969), the Trucial Coast along the Persian Gulf Coast (Kendall and Skipwith 1968; Purser 1973), and Shark Bay in northwestern Australia (Hagan and Logan 1975). An example of macrotidal carbonate tidal flat is Roebuck Bay (Semeniuk 2008). In all these examples, there is little or no terrigenous influx from terrestrial sources to dilute the carbonate accumulation contributed by local biogenic and abiotic sources, and hence the sediments are carbonate-rich. There is a range of diagnostic sediments and structures formed on carbonate tidal flats as a result of tidal deposition, biogenic contributions and alteration, and primary and secondary effects of cementation. Cementation of sediments and formation of their (secondary) structural and sedimentary derivatives is an important and common feature on upper parts of carbonate tidal flats. Under conditions of hypersalinity on the

Tidal Flats, Table 2 Geomorphic features of tidal flats

Geomorphic or surface feature	Origin
Mesoscale surface features (>metre-sized, up to tens of metres long)	
Meandering gullies, channels, creeks, meandering or ramifying	Tidal erosion with local deposition on point bars
Crust-lined and locally brecciated meandering channels	Tidal erosion with local deposition on point bars with mineral precipitation in surface sediments and resultant surface crust expansion
Sand waves	Large bodies of sand developed in low-tidal zones
Spits	Shoestring and sandy gravel body across tidal flat from local headland formed by tidal currents and wave action
Cheniers	Isolated shoestring sand and sandy gravel body on tidal flat, variably formed by tidal currents, wave action, and storms/cyclones
Salting cliff	Small cliff 30–100 cm high, cut into salt marsh, marking junction between high-tidal salt marsh and vegetation-free mid-tidal to low-tidal flat
Mid-tidal cliff	Small cliff up to 100 cm high, marking junction between mangrove front to *ca* MSL and vegetation-free mid-tidal to low-tidal flat
Microscale surface features (<metre-sized)	
Smooth planar surface	Deposition on, and erosion of the surface
Linear scours (mm to cm deep)	Tidal erosion
Slightly irregular	Tidal erosion of the surface, and/or bioexcavations by small biota and fish
Hummocky surface	Tidal erosion of the surface, and/or excavations by stingrays, fish and large burrowing benthos
Pot-holed surface	Excavations by stingrays, fish, large burrowing benthos
Mud cracks	Desiccation
Surface moundings grading to teepees and brecciation	Mineral precipitation in surface sediments and resultant surface crust expansion
Mounded surface	Mineral precipitation in surface sediments

higher zones of such tidal flats, precipitation of carbonate minerals often is prevalent, and in contrast to siliciclastic tidal flats, since there is an abundance of carbonate grains to act as nuclei for interstitial cements, there is a plethora of diagenetic and sedimentary products such as cemented layers and crust development, progressing to surface mounding, formation of compressional polygons and teepees, and then fragmentation, brecciation, and the formation of intraclasts. Carbonate tidal flats set in the more arid climates also develop evaporitic mineral suites such as beds of gypsum nodules, gypsum platey crystals, gypsum mud, and halite crusts (Kendall and Skipwith 1968; Hagan and Logan 1975).

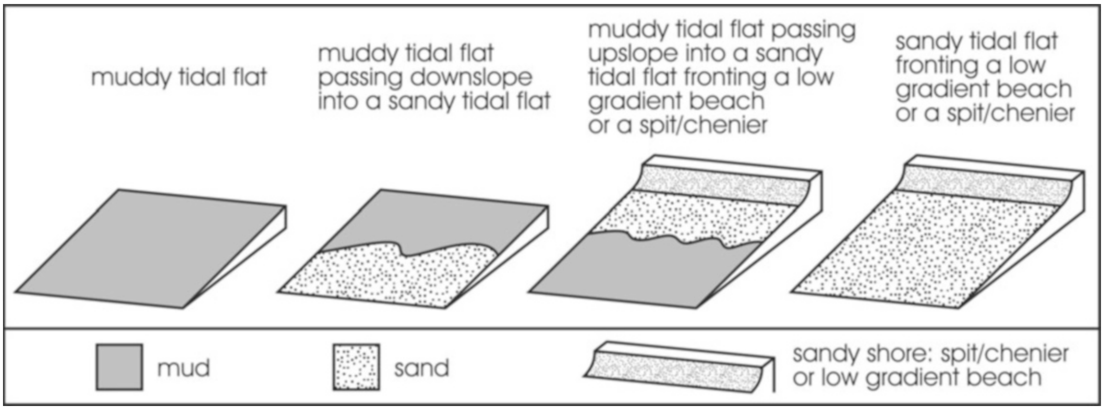
Sedimentology, Sedimentary Structures, and Stratigraphic Sequences

Sediment bedforms, surface features, and near-surface features on tidal flats are produced by oceanographic, and other physical, biotic, and hydrochemical processes. Wave action, tides, and winnowing result in ripples, megaripples, sand waves, sandy plane beds, linear scours, plane mud beds, and gravel pavements. A range of other physical processes result in mud cracks, air escape holes, and bubble structures. Biological activity results in burrow-pocked surfaces, animal tracks, invertebrate and fish burrow structures, fish and ray excavation feeding depressions, crab burrow workings, vesicular structures, crab balls, and accumulation of shell banks and shell gravel. Chemical and physical processes combine to develop sheets of gypsum mush, gypsum crystal boxwork and gypsum nodules, gypsum crystals embedded in sediment, platey gypsum pavements, carbonate crusts, and intraclast breccia pavements.

Sedimentary structures deriving from the burial of sediment bedforms, and the surface and near-surface features include cross-bedding and cross-lamination, herring bone cross-lamination, sand ripple cross-lamination, silt ripple cross-lamination, lenticular bedding, flazer bedding, laminated mud, sand dykes, mud dykes, bubble sand, vesicular mud, root-structuring, vertical burrows, u-burrows, to labyrinthoid burrow networks, shell laminae and beds, shell reefs, silt and sand balls, bioturbation and swirl structures, breccias, nodular gypsum beds, platey gypsum beds, and teepee structures (Fig. 7).

Key sediments, diagnostic of their formative processes, occur in different parts of the tidal flat. For example, mangrove-vegetated muddy tidal flats develop root-structured, burrow-structured, and bioturbated (shelly) mud and crustacean-dominated and polychaete-dominated mixed tidal flats develop burrow-structured, interbedded sand and mud varying to bioturbated muddy sand.

With progradation, siliciclastic tidal flats and carbonate tidal flats develop characteristic stratigraphic sequences (Kendall and Skipwith 1968; Thompson 1968; Coleman et al. 1970; Evans 1975; Hagan and Logan 1975; Harrison 1975; Larsonneur 1975; Semeniuk 1981a, b, 1996, 2008; Shinn 1983; Berkeley and Rankey 2012; Maloof and Grotzinger 2012). A range of stratigraphic sequences is shown in Fig. 8, from various macrotidal to microtidal settings, from



Tidal Flats, Fig. 6 Idealized diagram showing a range of tidal flats underlain by mud, or mud grading down-slope to sand flats, muddy tidal flat grading upslope to sand flats fronting a low-gradient beach or sandy spit/chenier, and sandy tidal flat fronting a low-gradient beach or sandy spit/chenier. (From Semeniuk 2015a)

Tidal Flats, Table 3 Tidal flat types according to substrate

Substrate type underlying tidal flat	Tidal flat type	Examples
Whole tidal flats		
Mix of particle sizes across the whole tidal flat, or differentiation not intended	Tidal flat	North sea; The Wash; Bay of Mont St Michel; King Sound
Tidal flats wholly underlain mainly by:		
Mud	Muddy tidal flat	Gulf of California
Sand	Sandy tidal flat	Southern Tasmania tidal flats
Gravel	Gravelly tidal flat	Parts of the Bay of Fundy
Shelly pavement across tidal flat	Tidal shell pavement	Parts of Shark Bay
Specific zones on tidal flats		
High-tidal flats wholly underlain mainly by mud	Muddy high-tidal flat	King Sound
Mid-tidal flats wholly underlain mainly by mud	Muddy mid-tidal flat	King Sound
Mid-tidal flats underlain mainly by mud and sand	Mixed mid-tidal flat	North Sea
Low tidal flats wholly underlain mainly by sand	Sandy low-tidal flat	North Sea; Bay of Mont St Michel
Low tidal flat underlain by pavement of shell	Low-tidal shell pavement	Parts of Shark Bay
High-tidal flat underlain by crust pavement	High-tidal crust pavement	Parts of Shark Bay
High-tidal flat underlain by breccia	High-tidal breccia pavement	Dampier Archipelago; Shark Bay

flats that are mud-dominated, to sand-to-mud sequences, from temperate to tropical climates. Some examples of sediments and the processes involved in their development from siliciclastic tidal flats and carbonate tidal flats are noted in Table 5.

Hydrology and Hydrochemistry

The groundwater hydrology and hydrochemistry of tidal flats, expressed as the hydrological variation and in the salinity gradient of the watertable under the tidal flat at low tide, or pellicular water in the sediment at low tide (Fig. 9) are important for several reasons. Interstitial pore-water salinity gradients and moisture gradients, for instance, influence macrophytes (such as mangroves and samphires), microbial mats, and invertebrate biota in relation to their occurrence and zonation (Semeniuk 1983, 2015a). Interstitial pore water salinity and moisture gradients also influence precipitation of evaporitic minerals. Microscale shallow groundwater hydrologic recharges and discharges influence development of sedimentary structures (e.g., seepage zones out of sand mounds to initiate sand erosion, or to initiate hydrochemical exchanges and cementation; formation of bubble sand). The hydrologic functioning of tidal flats additionally can drive geochemical processes that diagenetically modify sediments (e.g., formation of iron sulfide precipitation to form grey sediments or the oxidation of buried iron-sulfide-impregnated vegetation to form goethitic pseudomorphs).

Tidal flat groundwater levels fluctuate on a diurnal to semidiurnal basis following the tides, with a dampened effect from mid-tidal levels to upslope. All tidal flat groundwater rises during flood tide and, of course, is inundated on high tide. Recharge and discharge, and lateral groundwater flow

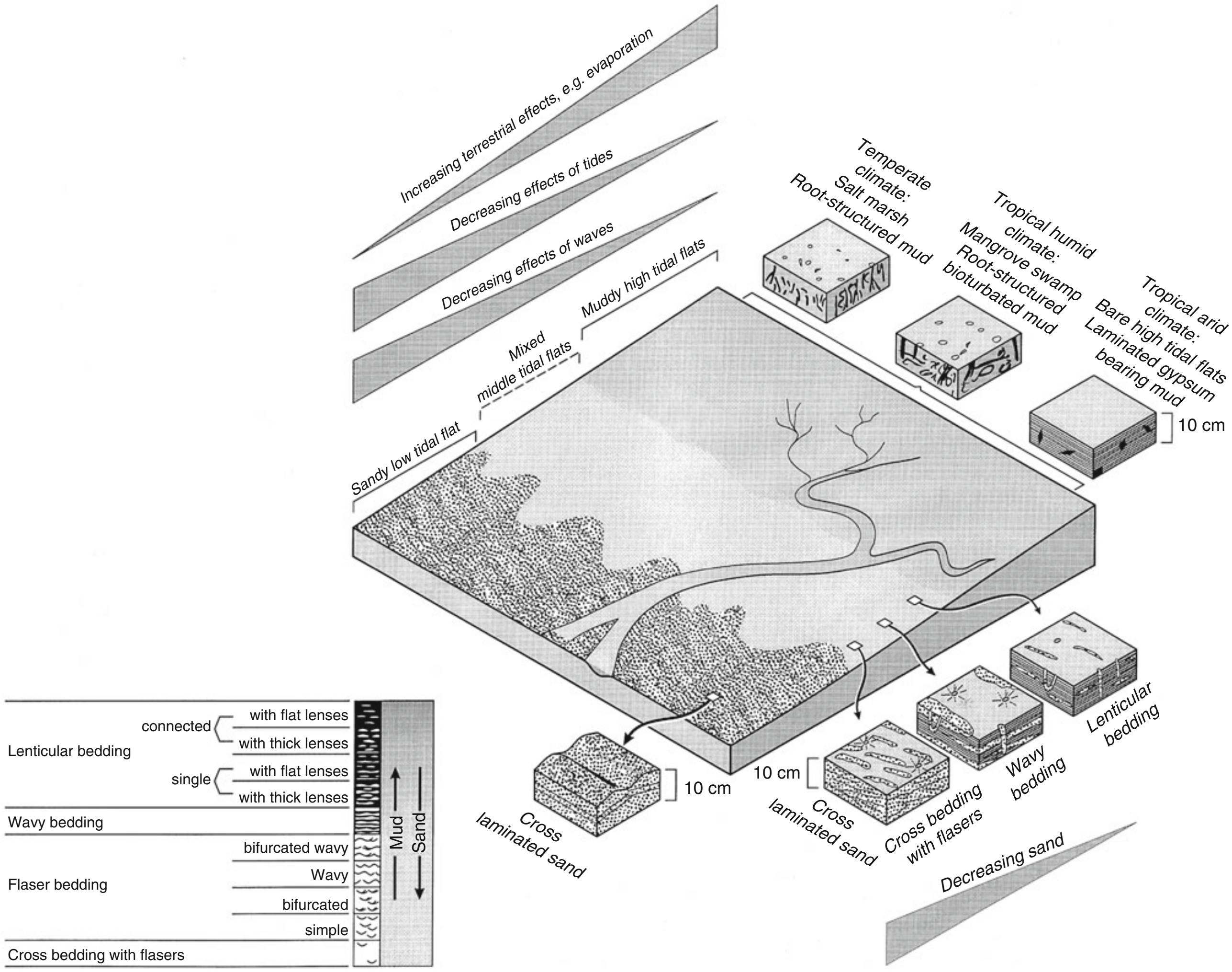
Tidal Flats, Table 4 Types of sedimentary particles on tidal flats and their origin

Sediment particle	Origin (information from various tidal flats)
Clay (<4 μm particle size)	
Phyllosilicate clay (kaolinite, illite, montmorillonite)	1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits 4. Aeolian
Calcite and aragonite clay	1. Reworked, comminuted skeletons 2. Precipitated from seawater 3. Disintegrated calcareous algae
Goethite	1. Fluvially delivered to the coastal system 2. Aeolian
Quartz clay	Aeolian
Amorphous silica	Diatom (in situ or transported)
Silt (4–63 μm particle size)	
Quartz, feldspar, various silicate minerals	1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits 4. Aeolian
Skeletal silt	Reworked and in situ comminuted shelly exoskeletons
Amorphous silica	Diatom (in situ or transported)
Sand (63–2000 μm particle size)	
Quartz, feldspar, various silicate minerals, rock fragments	1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits 4. Aeolian
Skeletal sand	Comminuted to whole reworked and in situ exoskeletons, e.g., shell fragments, foraminifera
Carbonate sand (ooids, pellets)	Generated nearshore and reworked onto tidal flat, and for pellets, carbonate grain destruction by boring algae
Carbonate intraclast sand	Reworking of cemented carbonate crusts
Gravel (<2000 μm particle size)	
Quartz pebbles, rock fragments	1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits
Mud pebbles and cobbles	Eroded tidal mud
Armoured mud balls	Mud pebbles and cobbles with adhering gravel and shell
Skeletal gravel	Comminuted to whole, reworked and in situ shell
Carbonate intraclast gravel	Reworking of cemented carbonate crusts

through tidal-flat sediments may be facilitated by specific lithologic layers, or stratigraphic intervals, and at the small scale by burrow and root structures.

Groundwater salinity across tidal flats is commonly zoned, generally with near-marine water salinities at about mean sea level, grading to hypersaline and extremely hypersaline upslope (unless the marine waters fronting the tidal flats are hypersaline as at Shark Bay, Australia). In humid wet climates where there is discharge of freshwater into the coastal zone, tidal flat groundwater becomes fresh or brackish where tidal flats adjoin terrestrial freshwater (Semeniuk 1983, 2015a). The main source waters for groundwater of tidal flats are marine water, rain, and (through seepage and land overflow) land-derived freshwater. These water sources recharge, reside in, and interact with the stratigraphic framework underlying the tidal flat (Fig. 10).

Evaporation, macrophyte transpiration, and increasing infrequency of tidal inundation upslope combine to develop a gradient of increasing salinity across tidal flats (Semeniuk 1983). This gradient results in the zonation of biota, exemplified by zonation of mangroves, and zonation of evaporitic minerals and pore-water precipitates. Where marine waters are oceanic (*ca* 35,000 ppm salinity) and evaporation is extreme, high-tidal groundwater may reach 100,000–200,000 ppm salinity, that is, carbonate mineral- and gypsum-precipitating, but where source waters are already hypersaline, tidal-flat groundwater reaches up to *ca* 300,000 ppm salinity, resulting in the precipitation of halite. Hypersaline tidal flats with precipitation of gypsum nodules, gypsum platey crystals, gypsum mud, and halite crusts have been recorded by Kendall and Skipwith (1968), Thompson (1968), Hagan and Logan (1975), and Semeniuk (1981a, b).

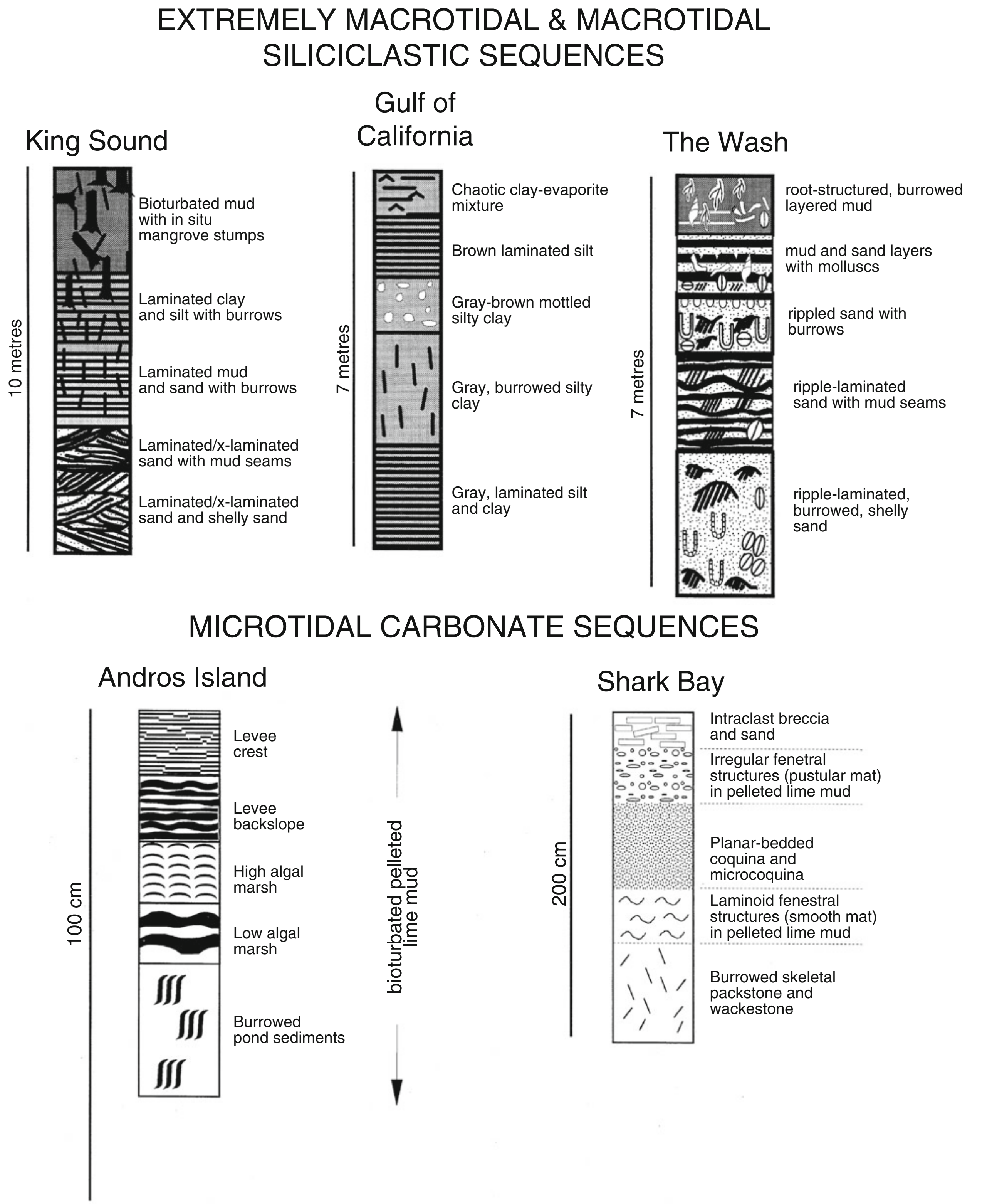


Tidal Flats, Fig. 7 Generalised sedimentology of a typical tidal flat, relating sediment types to oceanographic and terrestrial processes, and inset detail of some sediment types in relation to facies setting and position on tidal flat. (From Semeniuk 2005). Also shown in the systematic variation in bedding types as the sand to mud ratio changes. (Modified after Reineck and Singh 1980)

Some Key Biota of Tidal Flats

Depending on climate, tidal level, substrate, hydrology, and salinity, tidal flats may be inhabited in parts by salt marsh, mangroves, seagrass, algal mats, microbial mats, and biofilms (Figs. 11 and 12), as well as mussel beds, oyster beds and reefs, and worm-tube beds and reefs, and by a burrowing benthos of molluscs, polychaetes, and crustacea (Reise 1991; Little 2000; Spalding et al. 2010) and a meiofauna (also called meiobenthos) and microbiota including diatoms, foraminifera, and bacteria (Mitbavkar and Anil 2004; Coull 2009). As biologically productive areas, they are feeding grounds for nekton, demersal fish, and shore birds (Fig. 13). Skeletal organisms such as mussels and oysters can form banks, reefs, biostromes, and bioherms on the tidal flat. Mussels and oysters, where they abundant enough to form continuous sheets over the tidal flat surface, develop distinctive sedimentary deposits termed “biostromes.” Where organisms such as oysters and worm tube form rigid interlocking skeletal frames as sheets, they are biostromal reefs and, if emergent above the tidal flat surface, form biohermal reefs (or “bioherms”). Terms for biostromes, bioherms, banks, and reefs are defined and discussed in Nelson et al. (1962) and Kershaw (1994).

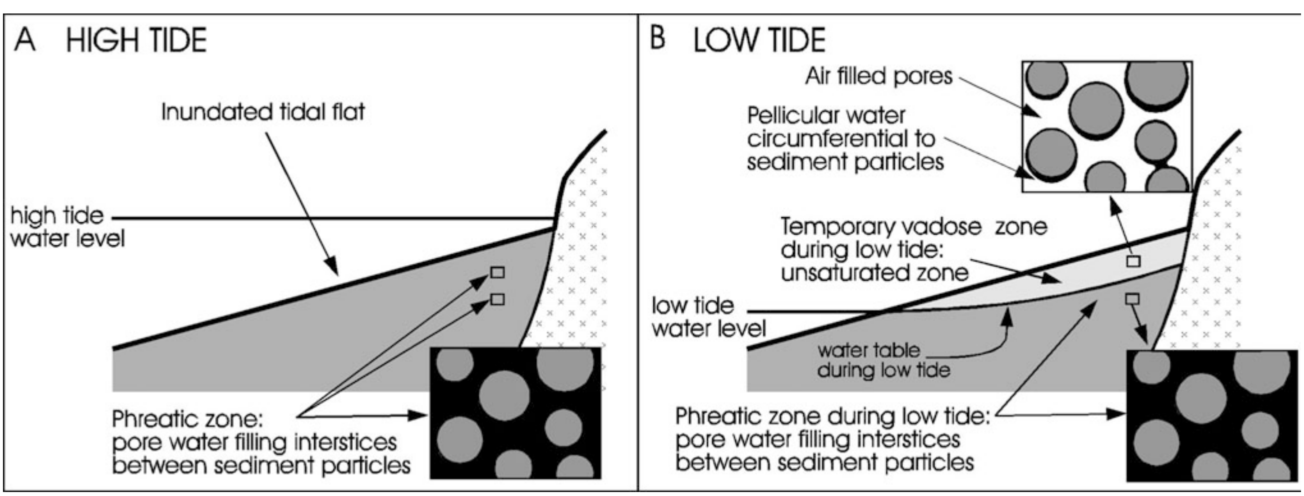
The well-known biota of tidal flats include mangroves, salt marsh, algal mats and stromatolites, polychaetes, molluscs, crustacea, resident fishes, and invading nektonic and demersal fishes and avifauna (Table 6). Biogeography and climate, substrate, hydrology, and hydrochemistry are major factors determining what biota inhabits tidal flats. Species abundance and zonation at site-specific level are determined by physicochemical and biological conditions (Semeniuk 1983; Adam 1990; Silvestri et al. 2005). For macrophytes, at a global scale, mangroves dominate mid- to upper-tidal flats in tropical climates and are replaced by salt marsh in temperate climates.



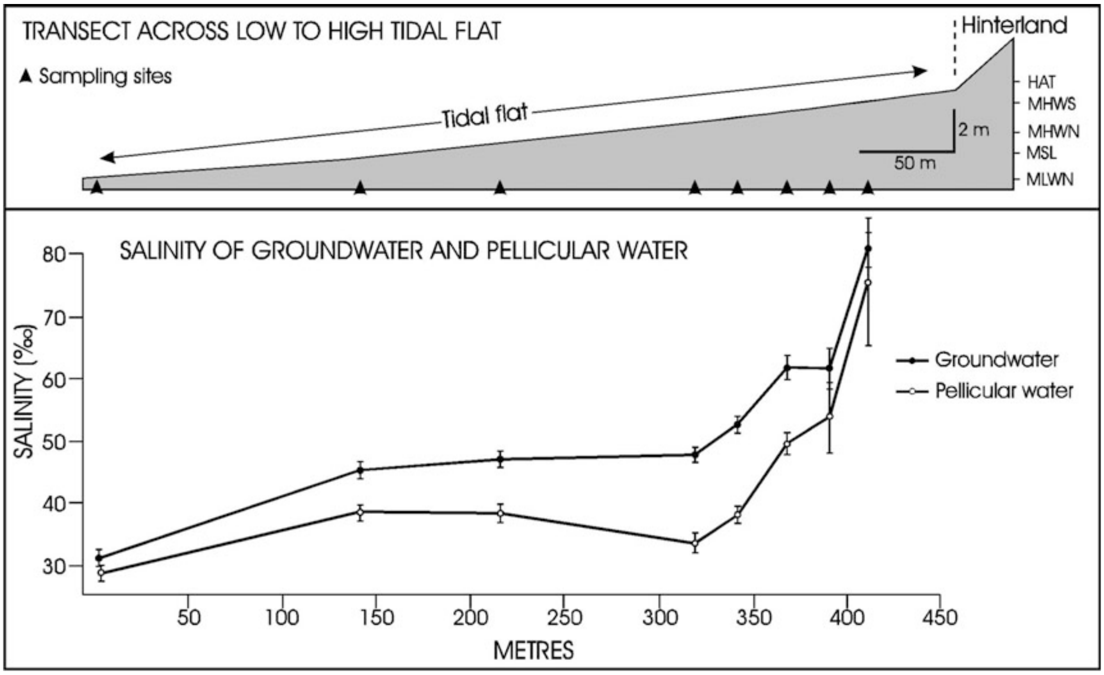
Tidal Flats, Fig. 8 Stratigraphic sequences from various tidal flats (see Table 1). For the macrotidal siliciclastic settings there is a comparison for three sequences: a tropical semiarid mangrove-vegetated tidal flat, shoaling from sand to mud, with burrows, root structures, and in situ mangrove stumps; a subtropical semiarid vegetation-free tidal flat dominated by mud, with local burrows, and evaporitic mineral structures; and a temperate humid salt marsh vegetated tidal flat, shoaling from sand to mud, with burrows, root structures, and shell. The microtidal carbonate sequences compare the structures of sub-tropical humid tidal flat with that of a subtropical arid tidal flat

Tidal Flats, Table 5 Examples of sediments in their setting, and processes in their development

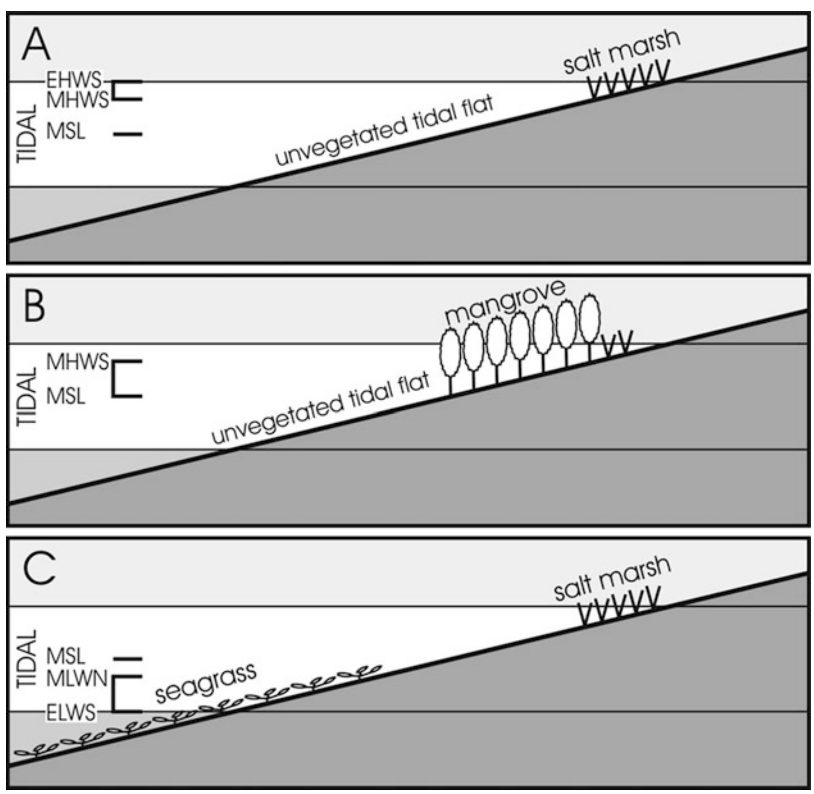
Environment	Main processes	Resulting sediment(s)
Siliciclastic sediment settings		
Mangrove or salt marsh vegetated high-tidal mudflat	Mud accumulation; root-structuring, bioturbation; shell contribution; groundwater alteration	Grey bioturbated root-structured (shelly) mud
Algal mat-covered high-tidal mudflat	Mud accumulation; binding; trapping; redox reactions; cracking	Laminated mud; desiccated laminated mud
Bare high-tidal mudflat	Mud accumulation; surface shear; cracking of mud; reworking of desiccation polygons; gypsum precipitation	Laminated mud; desiccated mud; mud-chip breccia; gypseous mud
Burrow-structured mid-tidal mudflat	Mud accumulation; surface shear; benthic fauna burrowing	Burrow-structured laminated mud; bioturbated mud
Burrow-pocked mid-tidal mudflat	Mud accumulation; surface shear; benthic fauna burrowing	Burrow-structured laminated mud; bioturbated mud
Mollusc-inhabited mid-tidal mudflat	Mud accumulation; surface shear; accumulation of shell winnowing to concentrate shells	Laminated shelly mud; shell gravel bed
Hummocky to “crated” low-tidal sand flat	Sand accumulation; surface shear; benthos inhabited; nekton and demersal fish feeding on benthos creating excavation craters	Thoroughly bioturbated sand to shelly sand
Mid-tidal mudflat with sand ripples	Mud accumulation; surface shear; traction transport of sand	Flazer bedding
Megarippled low- to mid-tidal sand flat	Traction transport of sand; air trapped by rise and fall of tide	Cross-laminated sand; bubble sand
Mid-tidal burrow-pocked sand flat	Traction transport of sand; benthic fauna burrowing	Burrow-structured cross-laminated sand; bioturbated sand
Carbonate sediment settings		
High-tidal breccia pavement	Mud accumulation; carbonate cementation; root-structuring; groundwater alteration	Limestone breccia sheet
High-tidal alga mat-covered mudflat	Mud accumulation; binding; trapping; redox reactions; cracking	Laminated mud; desiccated laminated lime mud
High-tidal bare mudflat	Mud accumulation; surface shear; cracking of mud; reworking of cracks; gypsum precipitation	Laminated lime mud; desiccated lime mud; mud-chip breccia; gypseous lime mud; laminated gypsum; gypsum nodule bed
Mid-tidal burrow-pocked mudflat	Mud accumulation; surface shear; benthic fauna burrowing	Burrow-structured laminated mud; bioturbated mud



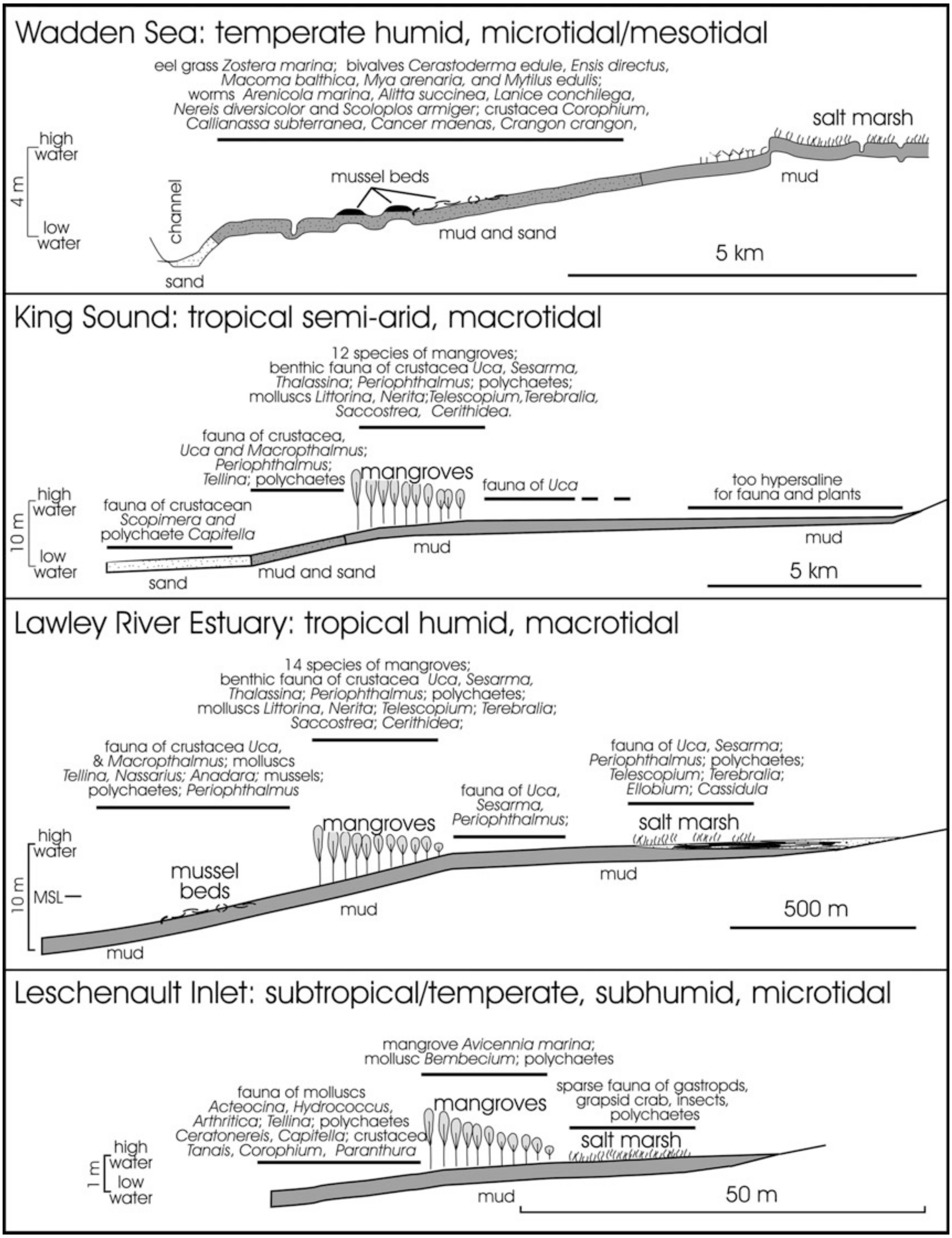
Tidal Flats, Fig. 9 The characteristics of groundwater residing under tidal flats during high and low tide. (From Semeniuk 2015b)



Tidal Flats, Fig. 10 Salinity of groundwater and pellicular water across a tropical tidal flat in north-western Australia. (From Semeniuk 1983, 2015b). The salinity of the groundwater and pellicular increases from the low-tidal zone to the high-tidal zone, with the groundwater being of a slightly higher salinity than the pellicular water. There is no freshwater seepage in this location, and so the hypersalinity of the high-tidal flats is not diluted



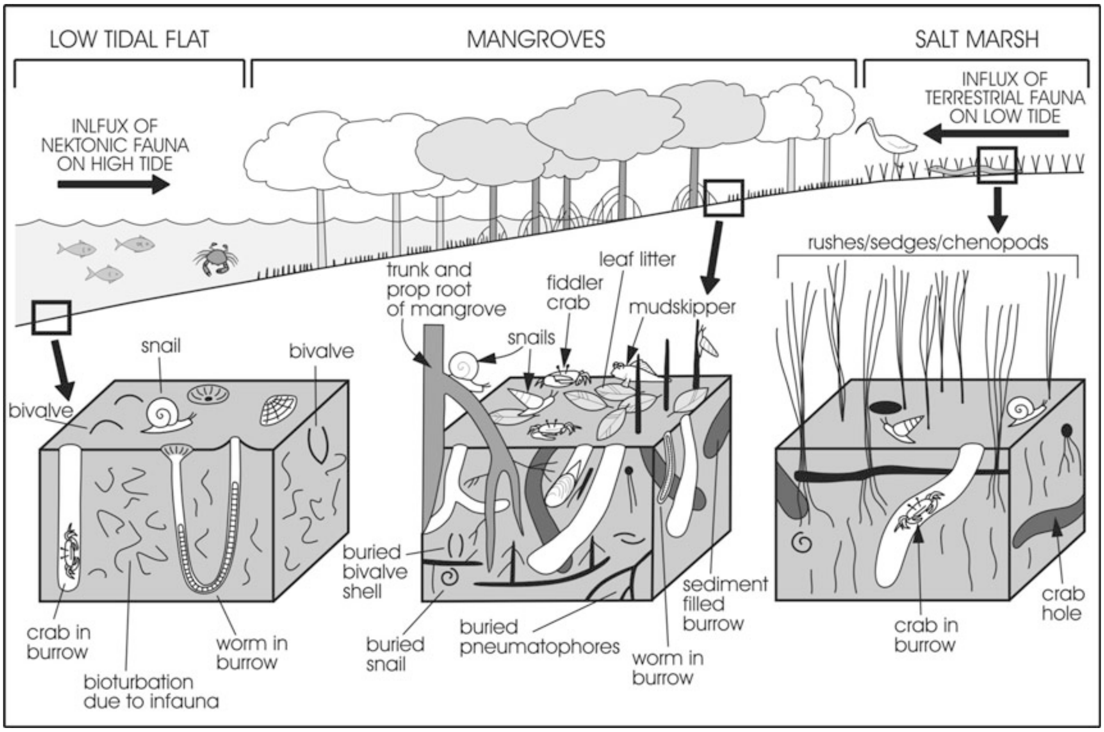
Tidal Flats, Fig. 11 Idealized diagram of tidal flat surfaces showing a range of vegetation and plant life that may occupy specific tidal zones. The positions of the various tide levels for these profiles are shown in Fig. 3: (**a**) salt marsh on the high tidal flats usually between MHWS and EHWS; (**b**) mangroves on the high tidal flats usually between MSL and MHWS, bordered in this example by salt marsh on the landward side; (**c**) seagrass between MLWN and subtidal zone, and salt marsh between MHWS and EHWS. (From Semeniuk 2015a)



Tidal Flats, Fig. 12 Profiles of some typical tidal flats showing substrate types and generalized and simplified composition of biota (mangrove, salt marsh, invertebrates, mussels). (After Semeniuk 2015a)

With increased salinity, the upper tidal interval may be inhabited by algal mats and stromatolites. Diversity of flora and fauna is linked to climate setting, with high species richness and abundance in tropical areas and relatively lower species richness in temperate areas.

Primary production within specific parts of the tidal flat, for example, from mangroves and salt marsh, often drives the ecosystems of tidal flats. With mangroves and salt marshes, these macrophytes fix nutrients and carbon on the mid- to upper tidal flats, supporting the local resident fauna and the



Tidal Flats, Fig. 13 Diagram showing the large scale ecological relationships of primary production, ecological functioning at a site, and the nekton to terrestrial utilisation/feeding invasions and feeding and also showing blocks of sediment with different types of biota commensurate with substrate type and tidal level setting and the effects of biota on the substrates. (Modified from Semeniuk et al. 1978; Semeniuk 2015a)

Tidal Flats, Table 6 Key biota of the tidal flats

Biota	Occurrence and function
Mangroves	Tropical climate mid- to high-tidal flats; massive primary production in the mid-upper tidal zone; plant detritus sustains biota in the immediate and in the adjoining tidal zones (Tomlinson 1986; Hutchins and Saenger 1987)
Salt marsh – (comprising chenopod vegetation and/or *Spartina*)	Temperate to tropical climate tidal flats; primary production in the mid-upper tidal zone; plant detritus sustains biota in the immediate and in the adjoining tidal zones (Chapman 1977; Beeftink et al. 1985; Adam 1990; Pennings et al. 2005; Silvestri et al. 2005)
Algal mats and stromatolites	Tropical climate tidal flats; primary production in the mid-upper tidal zone (Kendall and Skipwith 1968; Ginsburg and Hardie 1975); algal mats provide grazing grounds for benthos and fish.
Molluscs, polychaetes, crustacea	These invertebrates occur generally on all tidal flats, although species diversity may decrease towards the temperate climate regions; molluscs, polychaetes, and crustacea are primary and secondary consumers, and sustain higher-level trophic feeders (Dankers et al. 1983; Knox 1986; Semeniuk et al. 2000).
Fish and avifauna	On tidal flats; fish and avifauna generally are primary and secondary consumers, and sustain higher-level trophic feeders; in many instances, they are the highest trophic level in the region (Knox 1986; de Sylva 1975; Owen and Black 1990)

export of detritus sustains benthic biota of polychaetes, molluscs, and crustacea elsewhere on the mid- to low-tidal flats. The biologically rich tidal flat environments also support nekton, demersal fish, and avifauna. Nektonic and demersal fish and other nekton invade the tidal zone for feeding on the high tide, and the avifauna invade the tidal flats at low tide (Fig. 13).

Tidal flats typically are biologically zoned (Figs. 11 and 12). For any benthic group such as polychaetes, molluscs, or crustacea, there is a species zonation across the flats related to frequency of inundation, substrate type, substrate wetness, pore-water salinity, inter-species competition, and predation pressure, amongst other factors (Semeniuk and Cresswell 2015). Macrophytes (mangrove and salt marsh) also exhibit zonation as related to groundwater salinity, substrates, and elevation of habitat above mean sea level. Many of the benthos are burrowing forms, and the macrophytes have diagnostic root structures, and hence sedimentologically, zonation

Tidal Flats, Table 7 Key processes on tidal flats

Some selected processes	Examples of products on the tidal flat
Oceanographic	
Flood and ebb-tidal currents and slack water	Deposition of mud from suspension, and sand transport by traction; silt ripples, sand ripples, sand waves and megaripples; laminated mud, lenticular bedding, and flazer bedding; scour, small cliffs, and cut-and-fill; tidal creek formation; erosion of mud beds along creek banks and cliff-lines to form mud-ball conglomerate; rolling of mud balls on sandy/gravelly floors to form armoured mud balls
Waves	Winnowed sand sheets and shell gravel; rippling; erosion of cliff-lines cut into mud
Meteorologic/atmospheric	
Wind (erosion, transport, deposition, evaporation)	Sand and silt transport and fall-out deposition onto tidal flats; formation of adhesion ripples; evaporation of wet surfaces at low tide
Solar-induced and/or wind induced evaporation	Mud desiccation and cracking; increasing pore water salinity of groundwater; increasing salinity of groundwater leading to precipitation of minerals
Rain, ice crystallization	Rain imprints; ice crystal imprints; cryogenic disruption
Water temperature variation	Mud deposition from suspension; mortality of benthos
Groundwater hydrologic/ hydrochemical	
Rising and falling of tide	Wetting then drying to form desiccated sediment; erosion of desiccated sediment to form mud flakes; development of bubble sand
Solution/precipitation of carbonate minerals	Shell voids and other vughs; cemented crusts, teepees
Evaporite mineral precipitation	Beds of nodular to platey crystalline gypsum; precipitation of gypsum disrupting primary structures
Iron mineral precipitation	Staining of sediment to dark grey with iron sulfide; staining of sediments to orange-brown with iron oxides
Biological	
Accumulation of shell beds and biostromes, and biostromal to biohermal reefs	Shelly sediments and coquinas, and skeletal biostromes
Plant detritus accumulation	Organic-rich sediments, peat
Sediment trapping and binding by vegetation and algal mats	Root-structured and plant-structured sediment; algal-laminated sediment
Feeding/foraging by nekton and demersal fish	Pocked, pot-holed, excavated, and hummocky surfaces
Burrowing by benthos	Burrow-structured to fully-bioturbated sediment

of the biota results in facies and tidal-level-specific sedimentary signatures across tidal flats; sand-constructed *Arenicola* burrows, for instance, are diagnostic of low-tidal sand flats, vertical to u-shaped to labyrinthoid crustacean burrows in a root-structure-free mud are diagnostic of mid- to low-tidal flats, coarse root-structured substrates and associated faunal burrows are diagnostic of mangrove-vegetated high-tidal flats, while fine root-structured substrates are diagnostic of salt marsh-vegetated high-tidal flats. Some diagnostic biogenic structures and biofacies related to tidal assemblages are often signatures of specific tidal levels and lithofacies within a given region.

Summary

The coastal zone is one of the most complex environments on Earth, located at the triple junction between land, sea, and atmosphere (Brocx and Semeniuk 2009). In this context, as low-gradient shores, tidal flats exhibit a myriad of products resulting from interactive, interrelated and overlapping exogenous and endogenous agents and processes, which include oceanographic, meteorologic, atmospheric, fluvial, hydrologic and hydrochemical, and biological processes (Table 7). As outlined above, these processes commonly are distributed along physicochemical gradients (e.g., gradients of tidal effects, hydrology, hydrochemistry, geochemistry) and operate on a range of basic sediment types such as mud, sand, and shell gravel to develop a complex of geomorphic, sedimentologic, and diagenetic products which are commonly zoned across the tidal flats and are often specific to a coastal setting, sediment setting, climate, and biogeography.

Cross-References

▶ Bioherms and Biostromes
▶ Coastal Sedimentary Facies
▶ Coastal Wind Effects
▶ Mangroves, Ecology
▶ Microtidal Coasts
▶ Muddy Coasts
▶ Salt Marsh
▶ Spits

- ► Tidal Creeks
- ► Tidal Datums
- ► Tidal Environments
- ► Tide-Dominated Coasts
- ► Vegetated Coasts

Bibliography

Adam P (1990) Saltmarsh ecology. Cambridge University Press, Cambridge

Albrecht AS (1998) Soft bottom versus hard rock: community ecology of macro-algae on intertidal mussel beds in the Wadden Sea. J Exp Mar Biol Ecol 229:85–109

Alexander CR, Davis RA, Henry VJ (eds) (1998) Tidalites: processes and products. SEPM (Society for Sedimentary Geology), special publication, Tulsa, Oklahoma, vol 61

Allen JRL (1970) Sediments of the modern Niger Delta: a summary and review. In: Morgan JP (ed) Deltaic sedimentation: modern and ancient. Society of Economic Paleontologists and Mineralogists, special publication, Tulsa, Oklahoma, vol 15. pp 138–151

Amos CL (1995) Siliciclastic tidal flats. In: Perillo GM (ed) Geomorphology and sedimentology of estuaries. Elsevier, Amsterdam, pp 273–306

Beeftink WG, Rozema J, Huiskes AHL (eds) (1985) Ecology of coastal vegetation. Dr W. Junk Publishers, Dordrecht

Berkeley A, Rankey EC (2012) Progradational Holocene carbonate tidal flats of Crooked Island, south-East Bahamas: an alternative to the humid channelled belt model. Sedimentology 59:1902–1925

Black KS, Paterson DM, Cramp A (eds) (1998) Sedimentary processes in the intertidal zone. Special publication, vol 139. Geological Society, London

Brocx M, Semeniuk V (2009) Coastal geoheritage: encompassing physical, chemical, and biological processes, shoreline landforms and other geological features in the coastal zone. J R Soc West Aust 92:243–260

Chapman VJ (ed) (1977) Ecosystems of the world, vol 1, wet coastal ecosystems. Elsevier Scientific Publishing, Amsterdam

Coleman JM, Gagliano SM, Smith WG (1970) Sedimentation in a Malaysian high tide tropical delta. In: Morgan JP (ed) Deltaic sedimentation: modern and ancient. Society of Economic Paleontologists and Mineralogists, special publication, Tulsa, Oklahoma, vol 15. pp 185–197

Coull BC (2009) Role of meiofauna in estuarine soft-bottom habitats. Austral Ecol 24(4):327–343

Dankers N, Wolff WJ, Zijlstra JJ (eds) (1983) Fishes and fisheries of the Wadden Sea, report 5. In: Wolff WJ (ed) Ecology of the Wadden Sea, vol 2. A.A. Balkema, Rotterdam

Davies JL (1980) Geographical variation in coastal development, 2nd edn. Longman, London

de Sylva DP (1975) Nektonic food webs in estuaries. In: Cronin LE (ed) Estuarine research, vol. 1, chemistry, biology, and the estuarine system. Academic, New York, pp 420–447

Dionne J-C (1998) Sedimentary structures made by shore ice in muddy tidal-flat deposits, St. Lawrence estuary, Québec. Sediment Geol 116:261–274

Evans G (1975) Intertidal flat deposits of the wash, western margin of the North Sea. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 13–20

Fan D (2012) Chapter 9. Open-coast tidal flats. In: Davis RA Jr, Dalrymple RW (eds) Principles of tidal sedimentology, 1st edn. Springer, Dordrecht, pp 187–229. https://doi.org/10.1007/978-94-007-0123-6_9

Fan D, Wang Y, Lui M (2013) Classifications, sedimentary features and facies associations of tidal flats. J Palaeogeogr 2:66–80

Flemming BW (2012) Siliciclastic back-barrier tidal flats. In: Davis RA Jr, Dalrymple RW (eds) Principles of tidal sedimentology. Springer, Dordrecht, pp 231–267

Ginsburg RN (ed) (1975) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin

Ginsburg RN, Hardie LA (1975) Tidal and storm deposits northwestern Andros Island, Bahamas. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 201–208

Hagan GM, Logan BW (1975) Prograding tidal-flat sequences: Hutchinson embayment, Shark Bay, Western Australia. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 215–221

Harrison SC (1975) Tidal flat complex, Delmarva Peninsula, Virginia. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 31–38

Howard JD, Frey RW, Reineck H-E (1972) Georgina coastal region, Sapelo Island, U.S.A.: sedimentology and biology. VIII conclusions. Senckenberg Marit 4:217–222

Hutchins P, Saenger P (1987) Ecology of mangroves. University of Queensland Press, St. Lucia

Jackson JA (1997) Glossary of geology, 4th edn. American Geological Institute, Alexandria

Johnson DP (1982) Sedimentary facies in an arid zone delta: Gascoyne delta, Western Australia. J Sediment Petrol 52:547–563

Kendall CGSC, Skipwith SPA d'E (1968) Recent algal mats of a Persian Gulf lagoon. J Sediment Petrol 38:1040–1058

Kershaw S (1994) Classification and geological significance of biostromes. Facies 31:81–92

Klein G dV (1963) Bay of Fundy intertidal zone sediments. J Sediment Petrol 33(4):844–854

Klein G dV (1976) Holocene tidal sedimentation. Dowden, Hutchinson and Ross, Stroudsburg

Knight KJ, Dalrymple RW (1975) Intertidal sediments from the south shore of Cobequid Bay, Bay of Fundy, Nova Scotia, Canada. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 47–55

Knox GA (1986) Estuarine ecosystems: a systems approach, vol II. CRC Press, Boca Raton

Krogel F, Flemming B (1998) Evidence for temperature-adjusted sediment distributions in the back-barrier tidal flats of the East Frisian Wadden Sea (southern North Sea). In: Alexander CR, Davis RA, Henry VJ (eds) Tidalites: processes and products. Special publication, vol 61. Society for Sedimentary Geology (SEPM), Tulsa, pp 31–41

Larsonneur C (1975) Tidal deposits, Mont Saint-Michele Bay, France. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 21–30

Lippson AJ, Lippson RL (1997) Life in the Chesapeake Bay, 2nd edn. John Hopkins University Press, Baltimore

Little C (2000) The biology of soft shores and estuaries. Oxford University Press, Oxford. 252 pp

Maloof AC, Grotzinger JP (2012) The Holocene shallowing-upward parasequence of north-west Andros Island, Bahamas. Sedimentology 59:1375–1407

Mitbavkar S, Anil AC (2004) Vertical migratory rhythms of benthic diatoms in a tropical intertidal sand flat: influence of irradiance and tides. Mar Biol 145:9–20

Nelson HF, Brown CWM, Brineman JH (1962) Skeletal limestone classification. In: Ham WE (ed) Classification of carbonate rocks – a symposium. American Association of Petroleum Geologists Memoir, vol 1. The American Association of Petroleum Geologists, Tulsa, pp 224–252

Owen M, Black JM (1990) Waterfowl ecology. Chapman and Hall, New York

Paterson DM, Aspden RJ, Black KS (2009) Intertidal flats: ecosystem functioning of soft sediment systems. In: Perillo GM, Wolanski E,

Cahoon DR, Brinson MM (eds) Coastal wetlands – an integrated approach. Elsevier, Amsterdam, pp 317–343
Pennings SC, Grant M-B, Bertness MD (2005) Plant zonation in low-latitude salt marshes: disentangling the roles of flooding, salinity and competition. J Ecol 93:159–167
Postma H (1961) Transport and accumulation of suspended matter in the Dutch Wadden Sea. Neth J Sea Res 1(1, 2):148–190
Purser BH (ed) (1973) The Persian Gulf: Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea. Springer, Berlin
Reineck H-E (1972) Tidal flats. In: Rigby JK, Hamblin WK (eds) Recognition of ancient sedimentary environments. Society of Economic Paleontologists and Mineralogists, special publication, Tulsa, Oklahoma, vol 16. pp 146–159
Reineck H-E (1975) German North Sea tidal flats. In: Ginsburg RN (ed) Tidal deposits: a casebook of recent examples and fossil counterparts. Springer, Berlin, pp 5–12
Reineck H-E, Singh IB (1980) Depositional sedimentary environments, 2nd edn. Springer, Berlin
Reise K (1985) Tidal flat ecology. Springer, Berlin
Reise K (1991) Macrofauna in mud and sand of tropical and temperate tidal flats. In: Elliott M, Ducrotoy J-P (eds) Estuaries and coasts: spatial and temporal intercomparisons. Olsen and Olsen, Fredensborg, pp 211–216
Semeniuk V (1981a) Sedimentology and the stratigraphic sequence of a tropical tidal flat, North-Western Australia. Sediment Geol 29:195–221
Semeniuk V (1981b) Long term erosion of the tidal flats King Sound, NW Australia. Mar Geol 43:21–48
Semeniuk V (1983) Mangrove distribution in Northwestern Australia in relationship to freshwater seepage. Vegetatio 53:11–31
Semeniuk V (1993) The mangrove systems of Western Australia – 1993 presidential address. J R Soc West Aust 76:99–122
Semeniuk V (1996) Coastal forms and quaternary processes along the arid Pilbara Coast of Northwestern Australia. Palaeogeogr Palaeoclimatol Palaeoecol 123:49–84
Semeniuk V (2005) Tidal flats. In: M L Schwartz (ed) Encyclopaedia of coastal science. Springer, Dordrecht
Semeniuk V (2008) Sedimentation, stratigraphy, biostratigraphy, and Holocene history of the Canning Coast, North-Western Australia. J R Soc West Aust 91:53–148
Semeniuk V (2015a) Tidal flat. In: Kennish J (ed) Encyclopaedia of estuaries. Springer, Dordrecht, pp 665–678. ISBN: 9789401788021
Semeniuk V (2015b) Tidal flat salinity gradient. In: Kennish J (ed) Encyclopaedia of estuaries. Springer, Dordrecht, pp 678–683. ISBN: 9789401788021
Semeniuk V, Cresswell ID (2015) Species zonation. In: Kennish J (ed) Encyclopaedia of estuaries. Springer, Dordrecht, pp 613–621. ISBN: 9789401788021
Semeniuk V, Kenneally KF, Wilson PG (1978) Mangroves of Western Australia. Handbook, vol 12. Western Australian Naturalists Club, Perth, 90pp
Semeniuk V, Semeniuk TA, Unno J (2000) The Leschenault inlet estuary – an overview. J R Soc West Aust 83:207–228. Special Issue on the Leschenault Inlet Estuary
Shinn EA (1983) Tidal flats. In: Scholle PA, Bedout DG, Moore CH (eds) Carbonate depositional environments. The American Association of Petroleum Geologists, Tulsa, pp 171–210
Shinn EA, Lloyd RM, Ginsburg RN (1969) Anatomy of a modern carbonate tidal-flat, Andros Island, Bahamas. J Sediment Petrol 39(3):1202–1228
Silvestri S, Defina A, Marani M (2005) Tidal regime, salinity and salt marsh plant zonation. Estuar Coast Shelf Sci 62:119–130. https://doi.org/10.1016/j.ecss.2004.08.010
Spalding M, Kainuma M, Collins L (2010) World atlas of mangroves. Earthscan/Guttenberg Press, Malta. ISBN 978-1-84407-657-4
Stal LJ, de Brouwer FC (2003) Biofilm formation by benthic diatoms and their influence on the stabilization of intertidal mudflats. Ber Forschungszentrum Terramare 12:109–111
Stevenson C, Kearney MS, Pendleton EC (1985) Sedimentation and erosion in a Chesapeake Bay brackish marsh system. Mar Geol 67:213–235
Thompson RW (1968) Tidal flat sedimentation on the Colorado River Delta, Northwestern Gulf of California. Geological Society of America Memoir, vol 107. Geological Society of America, Boulder
Tomlinson PB (1986) The botany of mangroves. Cambridge University Press, Cambridge
Watzin M (1983) The effects of meiofauna on settling macrofauna: meiofauna may structure macrofaunal communities. Oecologia 59:163–166
Wolff WJ (ed) (1983) Ecology of the Wadden Sea. A. A. Balkema, Rotterdam
Zhou Z, Ye Q, Coco G (2016) A one-dimensional biomorphodynamic model of tidal flats: sediment sorting, marsh distribution, and carbon accumulation under sea level rise. Adv Water Resour 93:288–302
Zhu Q, Yang S, Ma Y (2014) Intra-tidal sedimentary processes associated with combined wave-current action on an exposed, erosional mudflat, southeastern Yangtze River Delta, China. Mar Geol 347:95–106

Tidal Inlets

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Introduction

Tidal inlets are an integral part of coastal barrier systems throughout the world. They serve as natural conduits for the exchange of water, nutrients, and organisms between coastal ocean and the backbarrier. In addition, along many coastal plain settings, including much of the East and Gulf Coasts of the United States, the southern and western coasts of the North Sea, and along many deltaic coasts, the only safe harborages, including major ports, are found behind barrier islands. The large number of improvements that are performed at the entrance to inlets such as the construction of jetties and breakwaters, dredging of channels, and the operation of sand bypassing facilities demonstrate the importance of inlets in providing navigation routes to these harborages.

Diversity in the morphology, hydraulic signature, and sediment transport patterns of tidal inlets attest to the dynamics and complexity of their processes. The variability in oceanographic, meteorologic, and geologic parameters, such as tidal range, wave energy, sediment supply, storm magnitude and frequency, freshwater influx, geologic controls, and the

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Encyclopedia of Coastal Science
Finkl, C.W.; Makowski, C. (Eds.)
2019, XXXVI, 1983 p. 991 illus., 260 illus. in color. In 2 volumes, not available separately., Hardcover
ISBN: 978-3-319-93805-9