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

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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, flaser 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 diageneric 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/chemistry 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 cuspatc 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
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 supra-tidal, 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 classified as extreme macrotidal. Tidal range amplification may occur due to bay
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-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. 2** Typical geomorphic and sedimentologic location of tidal flats within an idealized estuary. (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...
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,
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

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

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 compositional 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; Larsson 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
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 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

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**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)

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**Tidal Flats, Table 3** Tidal flat types according to substrate

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

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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).

<table>
<thead>
<tr>
<th>Sediment particle</th>
<th>Origin (information from various tidal flats)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phyllosilicate clay (kaolinite, illite, montmorillonite)</td>
<td>1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits 4. Aeolian</td>
</tr>
<tr>
<td>Calcite and aragonite clay</td>
<td>1. Reworked, comminuted skeletons 2. Precipitated from seawater 3. Disintegrated calcareous algae</td>
</tr>
<tr>
<td>Goethite</td>
<td>1. Fluvially delivered to the coastal system 2. Aeolian</td>
</tr>
<tr>
<td>Quartz clay</td>
<td>Aeolian</td>
</tr>
<tr>
<td>Amorphous silica</td>
<td>Diatom (in situ or transported)</td>
</tr>
<tr>
<td>Quartz, feldspar, various silicate minerals</td>
<td>1. Reworked, comminuted skeletons 2. Precipitated from seawater 3. Disintegrated calcareous algae</td>
</tr>
<tr>
<td>Skeletal silt</td>
<td>Reworked and in situ comminuted shelly exoskeletons</td>
</tr>
<tr>
<td>Amorphous silica</td>
<td>Diatom (in situ or transported)</td>
</tr>
<tr>
<td>Quartz, feldspar, various silicate minerals, rock fragments</td>
<td>1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits 4. Aeolian</td>
</tr>
<tr>
<td>Skeletal sand</td>
<td>Commuted to whole reworked and in situ exoskeletons, e.g., shell fragments, foraminifera</td>
</tr>
<tr>
<td>Carbonate sand (ooids, pellets)</td>
<td>Generated nearshore and reworked onto tidal flat, and for pellets, carbonate grain destruction by boring algae</td>
</tr>
<tr>
<td>Carbonate intraclast sand</td>
<td>Reworking of cemented carbonate crusts</td>
</tr>
<tr>
<td>Gravel (&lt;2000 μm particle size)</td>
<td>1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits</td>
</tr>
<tr>
<td>Quartz pebbles, rock fragments</td>
<td>1. Fluvially delivered to the coastal system 2. Reworked Pleistocene coastal deposits 3. Reworking of glacial deposits</td>
</tr>
<tr>
<td>Mud pebbles and cobbles</td>
<td>Eroded tidal mud</td>
</tr>
<tr>
<td>Armoured mud balls</td>
<td>Mud pebbles and cobbles with adhering gravel and shell</td>
</tr>
<tr>
<td>Skeletal gravel</td>
<td>Commuted to whole, reworked and in situ gravel</td>
</tr>
<tr>
<td>Carbonate intraclast gravel</td>
<td>Reworking of cemented carbonate crusts</td>
</tr>
</tbody>
</table>
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 (Mithavkar 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 biothermal 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 physico-chemical 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.
**EXTREMELY MACROTIDAL & MACROTIDAL SILICICLASTIC SEQUENCES**

**King Sound**
- Bioturbated mud with in situ mangrove stumps
- Laminated clay and silt with burrows
- Laminated mud and sand with burrows
- Laminated/x-laminated sand with mud seams
- Laminated/x-laminated sand and shelly sand

**Gulf of California**
- Chaotic clay-evaporite mixture
- Brown laminated silt
- Gray-brown mottled silty clay
- Gray, burrowed silty clay
- Gray, laminated silt and clay

**The Wash**
- root-structured, burrowed layered mud
- mud and sand layers with molluscs
- rippled sand with burrows
- ripple-laminated sand with mud seams
- ripple-laminated, burrowed, shelly sand

**MICROTIDAL CARBONATE SEQUENCES**

**Andros Island**
- Levee crest
- Levee backslope
- High algal marsh
- Low algal marsh
- Burrowed pond sediments

**Shark Bay**
- Intraclast breccia and sand
- Irregular fenestral structures (pustular mat) in pelleted lime mud
- Planar-bedded coquina and microcoquina
- Laminoid fenestral structures (smooth mat) in pelleted lime mud
- Burrowed skeletal packstone and wackestone

**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

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

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)
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...
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 6** Key biota of the tidal flats

<table>
<thead>
<tr>
<th>Biota</th>
<th>Occurrence and function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangroves</td>
<td>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)</td>
</tr>
<tr>
<td>Salt marsh – (comprising chenopod vegetation and/or Spartina)</td>
<td>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)</td>
</tr>
<tr>
<td>Algal mats and stromatolites</td>
<td>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.</td>
</tr>
<tr>
<td>Molluscs, polychaetes, crustacea</td>
<td>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).</td>
</tr>
<tr>
<td>Fish and avifauna</td>
<td>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)</td>
</tr>
</tbody>
</table>
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*
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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 harborage, 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 harborsages.

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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