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BACK DUNE

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Synonyms

Coastal strand; Rear dune; Secondary dune

Definition

Back dune is a generic term for established dunes in a coastal setting that lie detached from the shoreline by other dunes referred to as foredunes (Salm et al., 2000; Hansen et al., 2002; Hansen et al., 2010; West, 2004). The location of the back dunes behind the foredunes generally offers them protection from the direct effects of onshore winds such that the deposition of new sediment or erosion by wind is often minimal (Timmons et al., 2007). As a result, soils may develop on the surface of the back dunes and vegetal communities usually flourish. Blowouts may develop on back dunes if the vegetation on the dunes is disrupted naturally or by human activity.

Origin: The term back dune has no morphogenetic connotations. Hence, any dune shape formed by any process could be described as a back dune. In many cases back dunes are former foredunes and parabolic dunes that become stable. Thus, the term back dune is more of a descriptive term for an environment of occurrence than a genetic term.

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BACKBARRIER

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Definition

The backbarrier complex lies between the landward side of a barrier island and the mainland. It encompasses a suite of subaerial, intertidal, and subaqueous depositional environments. The preservation potential for some segments of the backbarrier complex, specifically inlet and flood-tidal delta deposits, is high. Such sediments comprise a large portion of ancient clastic coastal deposits.

Introduction

The backbarrier is a sedimentary environment dominated by fine sand and mud, although significant amounts of coarser sediment may occur locally (Howard and Frey, 1985). Large-scale planar and trough cross-bedding is common, along with graded beds and sand-mud interbedding.

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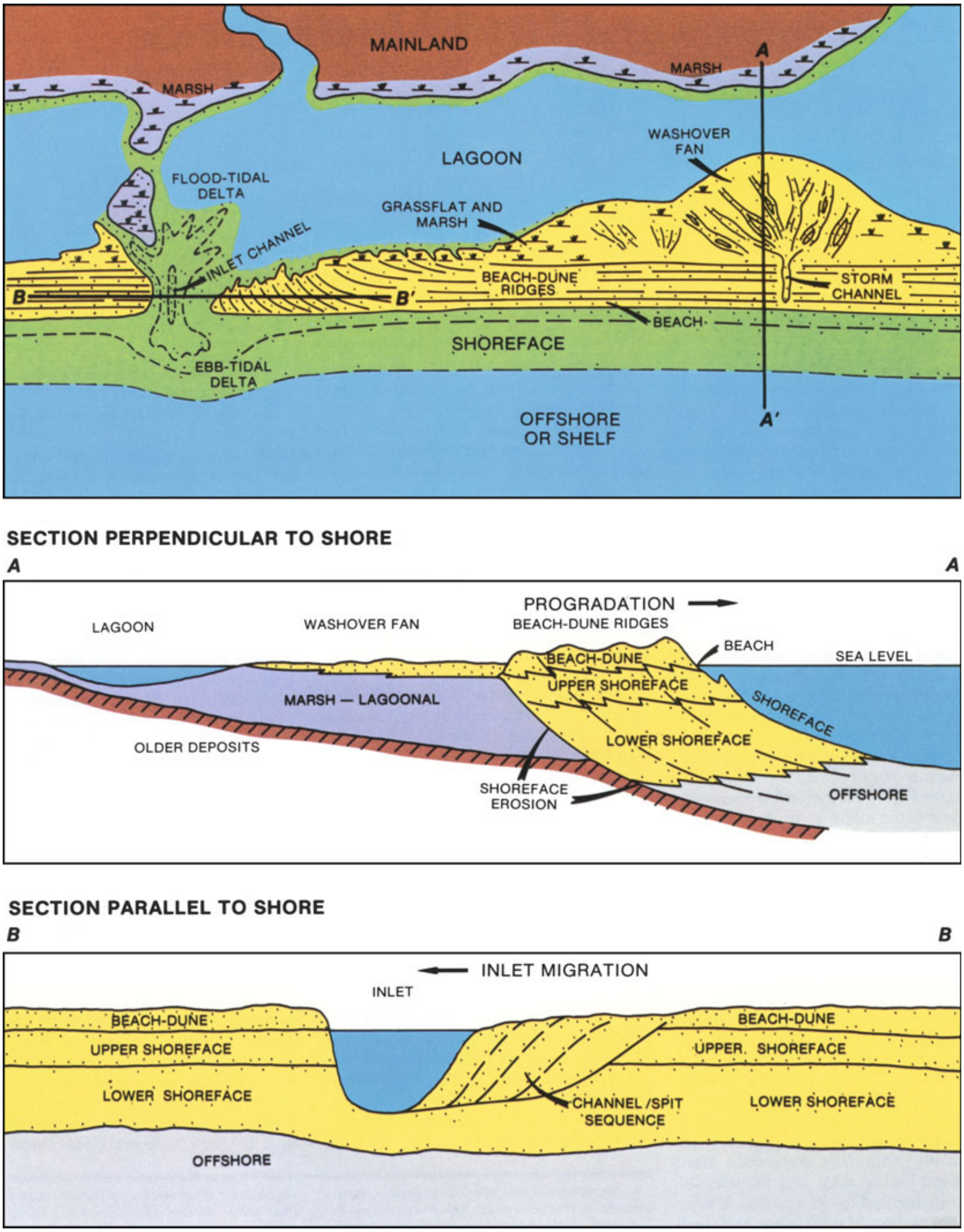

Backbarrier, Figure 1 Barrier island complex, showing the subenvironments of the backbarrier system (McCubbin, 1982).

Bioturbation is common, along with burrows. The components of a backbarrier complex (Figure 1) may include *coastal lagoons*, which are shallow basins lying between the mainland coast and the landward side of a barrier island; *flood-tidal deltas*, which are formed through deposition on the lagoon floor by flood-tidal currents flowing through a coastal inlet; *washover fans*, which are represented by subaerial sheets of coarse sediment which have been carried landward through storm-created gaps in the barrier front; *intertidal flats*, which are the segments of the backbarrier complex lying within mean tide range; and *intertidal marshes*, consisting of the portion of the intertidal region on which salt marsh vegetation is able to grow (McCubbin, 1982; Howard and Frey, 1985; Friedman et al., 1992; Davis and Fitzgerald, 2004).

Coastal lagoons

Lagoons comprise the open-water areas between the barrier proper and the mainland beach. The occurrence of overwash builds out the barrier platform, reducing the tidal prism and altering circulation within the lagoon (Cooper, 1994). Howard and Frey (1985) characterized lagoons as salt marsh estuaries, driven by tidal circulation, as opposed to riverine estuaries, which have a freshwater river source at their head. They noted that the sedimentary characteristics of the two environments were similar and therefore difficult to distinguish in the rock record. Coastal lagoon sediments are composed of silt and clay and are extensively bioturbated (Oertel (1985). Lagoons can be characterized as open-water lagoons or expandable lagoons. Open-water lagoons have a relatively constant water surface area. The surface area of expandable lagoons may vary by as much as 50 % between spring low and high tides. The latter can evolve into the former, provided that the rate of submergence due to sea-level rise exceeds the rate of sediment accretion (Oertel, 1985).

Flood-tidal deltas

Flood-tidal deltas are formed by tidal sediments deposited landward of an inlet mouth. As inlet channels fill and inlets migrate, flood-tidal deltas become inactive and eventually become part of the barrier (Carrasco et al., 2008). This process is one of the principal means by which the backbarrier environment builds outward (Godfrey and Godfrey, 1974). One of the most common backbarrier sedimentary sequences fines upward from coarser inlet deposits to fine-grained flood-tidal delta sands to salt marsh. These sequences comprise a major part of the barrier facies and account for up to half of the Holocene barrier sediment (Moslow and Tye, 1985).

Washover fans

Washover fans are the accumulated product of short-term depositional events during storms that breach the barrier front. Overwash, which affects both the width and height of the barrier platform, is a major control on backbarrier development. When a storm event causes marine water to reach the lagoon, lenticular washover fans are deposited on the backbarrier margin (Carter, 1988). The washover sediments are the result of erosion of barrier dune and beach environments and overlie former salt marsh (Schwartz, 1981). The importance of overwash as part of the barrier lithesome depends on the bathymetry of the foreshore (Ritchie and Penland, 1988), wave conditions (Fisher et al., 1974), and elevation of backbarrier beaches (Morton and Sallenger, 2003). Overwash can have either a positive or negative effect on backbarrier evolution, depending on the frequency and intensity of overwash events (Godfrey and Godfrey, 1974).

Sedgwick and Davis (2003) described the characteristics of washover facies. Washover beds are typically landward-dipping plane beds of well-sorted sand. Shell beds and heavy mineral laminae are often interbedded with sand layers. Bioturbation and reworking by later events can overprint the record. Washover deposits are often difficult to distinguish from flood-tidal delta sediments. Washover deposits in the stratigraphic record are characterized by (1) landward thinning, (2) occurrence of clean sand deposits within the find-grained backbarrier sediments, and (3) presence of shoreface and backbarrier mollusk shells (Sedgwick and Davis, 2003).

Intertidal flats

Intertidal flats lie at elevations between mean high and mean low tide. They may be thought of as salt marshes lacking in vegetation and provide the substrate upon which salt marshes build. The sediments of intertidal flats consist of interbedded mud and sand, representing cyclic changes in tidal current velocities (Howard and Frey, 1985). Bedding varies from flaser to wavy to lenticular, depending on the relative proportion of sand and mud (Reineck and Wunderlich, 1968).

Intertidal marshes

The backbarrier marsh environment includes grass beds and tidal channels lying within the range of mean tides. Backbarrier marshes generally evolve on tidal flats situated between the tidal channels of an abandoned inlet system (Kraft et al., 1979). Tidal current velocities flowing over tidal marsh surfaces are typically an order of magnitude lower than those observed in tidal channels (Howard and Frey, 1985). Bartholdy et al. (2010) reported that the backbarrier marsh is highly sensitive to the rate of sea-level rise. Continued deposition in the marsh environment requires a positive and constant rate of sea-level change. Sea-level stasis, or an increase in the long-term rate of rise, leads to loss of the marsh. Godfrey and Godfrey (1974) noted that excessive overwash can overcome the ability of the marshes to recover and lead to destruction of the marsh environment. The higher elevations in the salt marsh, however, are dependent on overwash events to supply sediment for accretion (French and Spencer, 1993).

Carrasco et al. (2008) developed an evolutionary model for the backbarrier environment, based on the linear extent of salt marsh development along the backbarrier shoreline versus the length of non-vegetated backbarrier beach. The ratio of salt marsh to beach was found to be related to changes in local hydrodynamic conditions. A decrease in hydrodynamic intensity results in a higher ratio of marsh length to beach length. An increase in hydrodynamic intensity, such as the creation of new overwash pathways, results in a lower ratio. The model can be employed to project future changes in the backbarrier environment.

Summary

Backbarrier sediments are a complex of various interfingering subenvironments. Facies models of the several subenvironments can be useful in identifying barrier facies in the rock record. Delineation of individual backbarrier facies is often difficult due to bioturbation, reactivation, and reworking.

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Cross-references

Back Dune
Barrier Island
Barrier Spits
Beach Processes
Coastal Barriers
Coastal Lagoons
Coastal Landforms
Estuarine Beaches
Estuarine Geomorphology
Intertidal Zonation
Overwash
Saltmarshes
Washover Fans
Washovers

BAR

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Synonyms

Sand bank; Sand bar

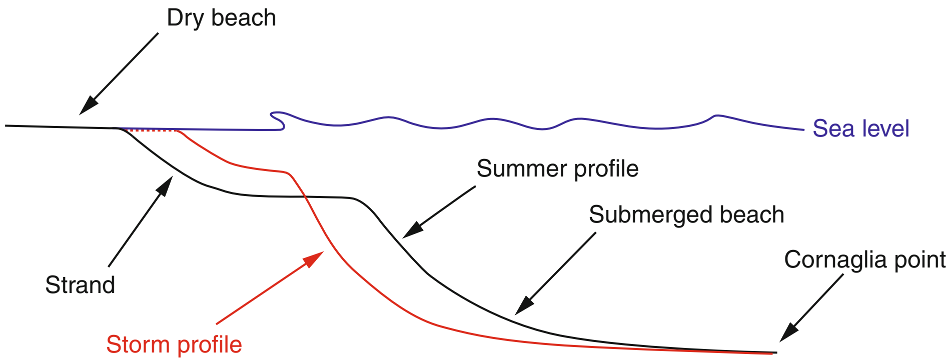
Definition

The term *bar* refers to a step or projection in the cross profile of a beach. While a bar may have slightly different meanings when used by different authors (King, 1972; Finkl, 2004), in all cases the term can be linked to the transformative action of waves when they approach the coastline over a sea bottom that consists of non-cohesive granular sediment.

The concept of a bar is relevant for interpreting data and gaining knowledge of almost all sedimentary coastal formations such as cordons, barrier (sedimentary) islands, hooks, spits, cuspate forelands, and tombolos. For detailed analyses of such formations (Williams, 1982), the Genetic Classification of Simple Coastal Forms (Bores, 1978) is a valuable resource.

Genesis

Water depth gradually decreases as a wave approaches the coast, and mass transport is accentuated because of the asymmetry of the open wave orbital motion. Thus, sea bottom sediments are dragged up toward the breaker line, which generates an increasingly stepped slope toward the shore and carves out a concave profile. Wave motion stops at the breaker line in a tide-free sea, and the cross profile exhibits a geometric discontinuity in that location. This discontinuity is the bar.



Bar, Figure 1 Variability of the beach cross profile and its bar.

As each wave breaks, the orbital energy is converted into kinetic energy over the strand (see Figure 1), where it generates maximum turbulence and stirs up sediments. Then, this energy turns into potential energy on the berm. Finally, the energy is transformed into kinetic energy once again by the falling water, which drags sediments in the offshore direction. Sediments are moved by gravity in the offshore direction from the berm at an increasing speed.

The profile resulting from a monochromatic wave would be a double concave curve with a slope that increases coastward and with the point of discontinuity (bar) at the breaker line. However, wind-generated waves over the sea are irregular, and the associated bars that form are spread out over a wide area. If a sea state lasts long enough, it can carve out a convex-shaped bar in the breaker area that separates the other two concave curves of the cross profile.

Changes over time constantly wash away and carve out new bars. The bars change in size and location depending on the energy and duration of wave action. Hence, bars only consolidate following a certain amount of climate stability and constant wave action. This typically occurs (1) after periods of calm or gentle swells in the summer, where the bar and wave profile prevails, and the berm is more advanced toward the water, and (2) after winter storms, where the bar and storm profile prevails and the berm is more withdrawn landward. The latter bar is then wider, deeper, and farther from the shoreline. The profile of a beach in equilibrium generally displays these two extreme conditions, which vary from 1 year to the next. Additionally, there are coasts where the climate or continuous increases in sediment (hyperstability) lead to profiles with more than one bar (e.g., off the Dutch North Sea islands).

Each sea state requires a volume of sediment over and above a threshold level for bars to form. The absence of a bar on a coast with sediments along the entirety of its cross profile is therefore indicative of instability or erosion.

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Cross-references

Barrier Island
Beach Management
Littoral Cordon
Spit

BARRIER ISLAND

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Synonyms

Barrier

Definition

A barrier island is a coastal landform consisting of an elongated narrow strip of unconsolidated sediment (primarily sand) lying parallel to the mainland coast and being separated from the mainland by a lagoon, salt marsh, or bay.

Introduction

Barrier islands are found worldwide. However, there exist different opinions on the definition of a barrier island. Descriptive definitions of barrier islands, such as the one adopted in this entry, are generally more widely accepted than genetic definitions which consist of quantitative limitations (e.g., Berryhill et al., 1969; Cromwell, 1971). Some researchers define barrier islands as features composed of several major depositional units due to the strong links among these units that are required for their existence.

Barrier Island, Figure 1 Examples of barrier islands in open-ocean (*left*) and fetch-limited (*right*) environments. *Left*, the Dutch Wadden Sea coast; *Right*, the Smith Island in the Chesapeake Bay, USA (Image source: Google Earth 2013).

One example of a systemic definition is given by Oertel (1985) who suggested that a barrier island should be considered as the focal element of a much larger barrier island system, consisting of six major elements: (1) mainland, (2) back-barrier lagoon, (3) inlet and inlet deltas, (4) barrier island, (5) barrier platform, and (6) shoreface. A lack of any one of these elements would result in misuse of the term barrier island.

According to the criteria from Oertel (1985), a recent survey by Stutz and Pilkey (2011) based on global satellite data combined with topographic and navigational charts identified 2,149 individual barrier islands totaling 20,783 km in length, taking up about 10 % of all continental shorelines. In this case only open-ocean barrier islands are taken into account in the survey due to the limitations of the criteria. However, if the criteria are not restricted to the systemic definition but include other islands that meet the descriptive definition as given in this article, another category of barrier islands characterized by sheltered, low-wave energy coastal environments (so-called fetch-limited) would be applicable. Pilkey et al. (2009) reported the existence of more than 15,000 fetch-limited barrier islands developed in the sheltered waters of fjords, bays, lagoons, and behind coral reefs. Due to the absence of driving forces under fair-weather conditions and low sediment availability, development of fetch-limited barrier islands is strongly dependent upon stochastic extreme events (e.g., storms, floods). Fetch-limited barrier islands have a much smaller size than open-ocean barrier islands. They are typically short (~1 km), narrow (some tens of meters), and low lying (mostly less than 3 m above the mean sea level), while open-ocean barrier islands have an average length of 8.8 km and a width of 0.7 km, according to Stutz and Pilkey (2011). Dune ridges higher than 10 m can also develop on some open-ocean barrier islands if aeolian onshore transport is strong and sediment source is abundant (e.g., the Algarve barrier island chains along the south coast of Portugal). Figure 1 shows examples of open-ocean and fetch-limited barrier islands.

Origin of barrier islands

As shown in Figure 1, barrier islands normally occur in chains, which can be found in quite different climatic environments (e.g., from Arctic to tropical zones), suggesting that they are relatively flexible and can form and sustain in a variety of environmental settings. For more than 150 years, coastal researchers have investigated the origin of barrier islands. Numerous theories have been developed to explain their formation and development. By the end of the nineteenth century, three original hypotheses were available. De Beaumont (1845) suggested that barrier islands, such as those found in the North Sea and the Gulf of Mexico, were formed by the emergence of submarine bars. On a low-gradient coast, waves tend to break away from the shoreline enabling the buildup of submerged bars away from the coast, which then gradually grow in size and emerge due to the impacts of waves and aeolian transport. Gilbert (1885) suggested that barrier islands can form from a spit generated by longshore drift. During storms, the spit is breached, creating inlets that divide the spit into a series of islands. McGee (1890) proposed that barrier islands are produced by drowning of coastal ridges during sea-level rise or tectonic subsidence. Since then, there has been considerable debate (e.g., Hoyt, 1967; Fisher, 1968; Otvos, 1981) over these three hypotheses. Until recent decades (e.g., Schwartz, 1973), it has been determined that these three hypotheses can explain the formation of different types of barrier islands, but no single one can fully explain the development of all barriers distributed worldwide. More and more studies (e.g., Schwartz, 1971; Hayes, 1979; Leatherman, 1979; Leatherman, 1985) have shown that the formation and development of barrier islands are a result of multiple processes.

Boundary constraints

Although the environmental conditions required for formation of barrier islands are relatively flexible, there still exist some boundary constraints. According to the statistics from Stutz and Pilkey (2011), barrier islands are most abundant (~63 % of the total) on tectonically stable, trailing edge continental margins as such environments provide favorable boundary conditions (e.g., abundant sediment supply, small ratio of tidal range to mean wave height) for the formation of barrier islands. Of the remaining barrier islands, ~21 % are located on marginal seas, and only ~16 % are found on collision margins. Most (~58 %) of the barrier islands existing on collision margins are developed on delta lobes favored by a low-gradient shoreface produced by abundant riverine sediment input; the rest are located on wide coastal plains. Barrier islands rarely form on narrow continental shelves with an upper shoreface slope larger than 0.8°, in which sediment tends to move offshore rather than accumulating onshore.

Another significant boundary factor influencing the formation and development of barrier islands is sea-level change. A stable sea level is a prerequisite for the formation of barrier islands. Most barrier islands are quite young, being formed during the last ~6,000 years when the global sea level became relatively stable with only minor fluctuations. A stable sea level with small rates of change (within millimeters per year) in the mid- to late Holocene restricts tides and wave actions to a small-range coastal area (i.e., hydrodynamically active zone). Sediment transport within this area became increasingly important to shape the modern coastline. Driven by wave and aeolian processes, an excess of sediment supply to a local accommodation zone would eventually build up new land above the water surface. Holocene barrier spits and islands present such examples. Holocene barrier islands are low-lying structures made of unconsolidated sediment, with the highest part at the dune crests, which is normally only meters above the water level. Thus they are quite vulnerable to high water-stand impacts induced by storms or floods. Without sufficient sediment supply to compensate the increased accommodation zone, continuous sea-level rise would cause a barrier island to shrink and migrate landward.

Besides a sufficient sediment supply to feed the formation of a barrier island, the "quality" of the sediment supply is also critical for the fate of the island. Sediment supply with a larger proportion of sand and coarse material is able to sustain stronger hydrodynamic impacts than fine sediment such as mud and clay. Thus, sandy substrate and shoreface are more durable than a muddy one to maintain a barrier island. The wave-tide regime is also an important factor influencing the morphogenesis of barrier islands. Beaches and barrier islands are products of wave action. They develop most easily on wave-dominated coasts with small to moderate tidal range. Only ~12 % of barrier islands develop in tide-dominated regions (with the ratio of mean tidal amplitude to mean annual wave height generally larger than three according to Davis and Hayes, 1984), and they are rarely found in areas with a tidal range larger than 4 m.

Barrier island morphodynamics

Among different types of coastal landforms, barrier islands have the most variable morphology. They are constantly shaped by winds, tides, and waves and, on a longer time scale, can shift landward or seaward due to oscillations of sea level and variations in the sediment supply (Masetti et al., 2008).

Depending on the relative importance of waves to tides in determining the coastal morphology, three types of coastal environments can be classified: wave dominated, tide dominated, and mixed energy. In wave-dominated coasts, barrier islands are elongate and narrow due to the impact of longshore drift. Inlets produced by tides or storm breaching migrate fast for the same reason. Washover features are prominent, and flood deltas are well developed but ebb deltas are small or nonexistent (Hayes, 1979). Along with an increase of tidal effect, inlets play a more significant role in shaping the barrier island morphology. Substantial ebb deltas can develop, and barrier islands become shorter and wider as a result. As tidal range increases, these features become more prominent. When the tidal range is high enough and overwhelms the wave effects, barrier islands cannot develop and inlet deltas are confined to elongated stringers oriented with the dominant tidal currents.

In addition to tide and wave actions, development of barrier islands is also affected by other processes (e.g., stochastic extreme events, sea-level change, tectonic movements, and fluvial input). Barrier islands evolve and migrate parallel or normal to the mainland in response to these processes. The shore-normal evolution of barrier islands corresponds to two types of behavior: namely, regression and transgression, respectively. Barrier transgression refers to an onshore migration of the landform and an overlapping of deeper water sediment over shallower lagoon deposits. Leatherman (1979) summarized three main processes controlling barrier island transgression, which, in the order of importance, are inlet dynamics, overwash, and aeolian transport. In some areas with a thick and compressible substrate (e.g., the Virginia barrier coast), auto-compaction also contributes to the barrier island transgression (Leatherman, 1985). In response to the increased impacts of these processes induced by an eustatic sea-level rise, three modes have been proposed to describe a subsequent evolution of a barrier island: (1) a continuous landward migration across the underlying substrate to higher elevations; (2) a disintegration of the island due to insufficient sediment supply and backshore relief to sustain inundation during stochastic extreme events; and (3) an in-place drowning which turns the island into a submarine deposit body. Although there exist some cases to support the latter two modes, the most common mode of barrier island transgression is the continuous landward migration through the combined effects of shoreface erosion, overwash, and inlet floods (including storm breaching). Through a continuous "rolling over" itself, the barrier island eventually merges with the mainland, with its upper layers of sediment eroded and recycled.

Barrier regression refers to an offshore expansion of the landform and shoaling growth. It is a result of an excess of sediment supply to the island. Sediment supply mainly comes from three sources: river input, longshore drift, and onshore migration of submarine sandbars. In the process of barrier island regression, the outer (ocean-ward) shoreline progrades seaward, while the inner (lagoon-ward) shoreline remains relatively stable, forming a wide low-lying plain characterized by multiple dune ridges, normally with the most seaward foredune ridges possessing the highest elevation. Such high foredune ridges may prevent overwash and thus help to protect the island from storm erosion; however, meanwhile they also block the transport of sediment to the backshore and may accelerate the erosion on the inner shoreline during eustatic sea-level rise over the long term. Accompanied by a decreased sediment supply, this may lead to a switch of the barrier evolution to a transgression phase.

Numerical modeling

Due to high sensitivity to boundary conditions, natural barrier islands serve as an ideal laboratory for numerical studies of multi-scale physical processes on the coastal morphological evolution. They can also be studied as proxies of long-term climate change (Zhang et al., 2014).

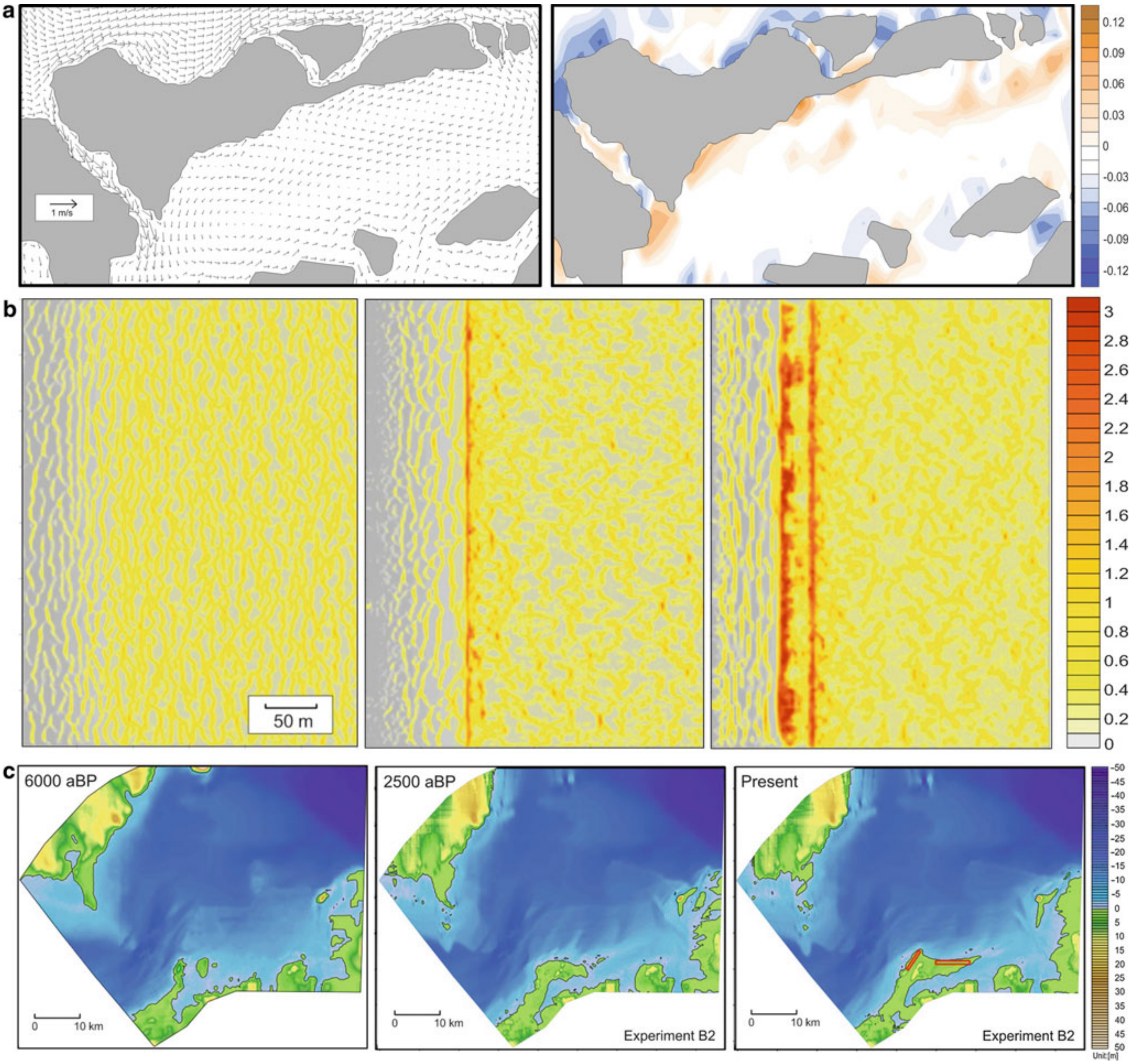
Morphogenesis and evolution of barrier islands are complicated due to the influence of many processes occurring at different temporal and spatial scales as discussed previously. Due to difficulties resolving all relevant processes and their interplay in an integrated numerical model, simplifications are usually used in mathematical descriptions of these processes and their corresponding scales.

The most common numerical models available for study of barrier island evolution are 2-dimensional vertical (2DV) cross-shore profile models. In these models, morphological response of a cross-shore coastal profile to actions of several key processes is used to represent the evolution of the whole barrier island. The coastal profile is selected in such a way that it should be able to represent typical characteristics of the barrier island and its adjacent environments. The profile starts from a high terrestrial point at the mainland and extends seaward to an offshore closure point. Outer areas beyond these two points are presumed unchanged and do not impose any effect on the barrier island system during the time span of interest. After a setup of the initial profile shape and other parameters (e.g., sediment composition, grain size, substrate lithology), response of the profile shape and underlying stratigraphy to influences of different processes is calculated through a set of equations. Depending on the equations adopted, 2DV cross-shore profile models can be further classified into two different types: process based and behavior oriented. Process-based models apply a set of differential equations to describe the wave transformation, sediment transport, and subsequent bed elevation change on the profile. Impacts of storm surge, eustatic sea-level change, and tectonic movement are implemented in the equations through a parameterization of boundary conditions (i.e., incoming wave properties and water level). Examples of process-based 2DV models can be found in Masetti et al. (2008), Rosati et al. (2010), and Zhang et al. (2013). On the contrary, behavior-oriented models (e.g., Roy et al., 1994; Cowell et al., 1995; Storms et al., 2002; Stolper et al., 2005; Moore et al., 2010) describe the profile change by a set of empirical functions of changes of sediment supply, sea level, and shoreface geometry, without simulating the detailed processes involved in sediment transport.

The validity of 2DV cross-shore profile models is based on three pre-assumptions: (1) a zero net sediment exchange at the boundary (thus sediment is conserved in the profile); (2) evolution of the shoreface part of the profile evolves toward a predefined shape (the so-called equilibrium), which is determined by the grain size of the shoreface sediment and the mean wave climate (e.g., Bruun, 1962; Dean, 1991; Dean, 1997); and (3) alongshore uniformity of offshore wave parameters and nearshore isobaths along the coastline (thus the gradient of longshore sediment transport rate is zero and does not affect the profile change).

2DV cross-shore profile models have proven to be more useful in providing detailed insights into the fundamental driving mechanisms of barrier island development than conceptual models. However, one should always keep in mind the limitations of validity which may hinder application of a 2DV model to a real case. Another factor affecting the reliability of a 2DV model is an exclusion of inlet effects, which are most critical in controlling barrier island morphodynamics according to Leatherman (1979). An extension of an individual profile to an area might overcome these limitations; however, this requires much greater effort in bridging the different scales that are involved in barrier island morphodynamics. Development of such models is still at an early stage. An example of such models is presented by Zhang et al. (2012, 2014).

A hybrid and parallel coupling of process-based and behavior-oriented modules provides a way to resolve the relevant processes at their corresponding scales with an affordable computational expense. In the model, wave processes (propagation, transformation, refraction, and breaking), currents, and subaqueous suspended sediment transport are solved in process-based modules, while subaerial aeolian transport, bed-load transport, and land-sea transition processes (e.g., cliff erosion) are simulated either in behavior-oriented manners or by cellular automata approach. The model was applied to investigate the morphogenesis and evolution of a Holocene barrier island



Barrier Island, Figure 2 Processes and morphological change at different scales during the development of a barrier island (Darss-Zingst) at the southern Baltic Sea. (**a**) Storm breaching (*Left*) at the barrier spit and subsequent bed elevation change (*Right*); (**b**) development of foredunes at the back-beach area; (**c**) simulated morphological evolution of the barrier island at different stages. The foredune planes developed on the island are indicated by frames (Images are modified from Zhang et al. (2014). Unit is meter in all images).

(Darss-Zingst) at the southern Baltic Sea. Although the gap between the simulated morphology and the real situation as seen today is remarkable, the model proved to be able to reproduce the main morphological features of the barrier island system, e.g., the development of two barrier spits, foredune plains and the inner lagoon, and major driving mechanisms (storms, inlet erosion and deposition, aeolian transport, littoral drifts, and cliff erosion) for the island formation. Figure 2 shows some simulation results.

Summary

Morphogenesis and evolution of barrier islands are complicated processes. It is clear that the formation of a barrier island is the result of multiple processes and no simple hierarchical relationship can be deduced among the processes in influencing barrier island development. Among different processes that may affect the morphological development of a barrier island, some are found to be of critical importance and act as universal boundary constraints. The history of tectonics and eustatic sea-level change seems largely to determine whether a barrier island can be formed. With favorable tectonics and sea-level change for barrier island formation, a combination of shoreface slope, wave-tide regime, and sediment source determines how a barrier island is formed. Wind-wave climate, as well as the rate and composition of sediment supply, subsequently affects the migration and development of the island. In most areas, vegetation properties (e.g., species, coverage) are important in shaping the island morphology. In areas with a thick and compressible substrate, local consolidation through self-loading of underlying substrate also plays a role in barrier island evolution.

Numerical modeling provides a way to quantify the effects of different processes on barrier island morphogenesis and evolution. However, one should always be aware of the limitations when constructing a model for a specific research object, and simulation results should be carefully interpreted. Much progress is still needed to develop robust models for better understanding of the origin and development of barrier islands.

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Cross-references

Barrier Spits
Spit

BARRIER SPITS

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Synonyms

Barrier; Spits

Definition

Barrier spits are long narrow strips of depositional bodies emerging from water (Evans, 1942), with one end attached to a coast that serves as the source of sediment supply (proximal end) and the other end jutting into open water (distal end), forming a shelter for its inner water.

Introduction

Offshore waves normally approach the surf zone of a coast in an oblique angle. A combination of shore-oblique swash caused by the incoming waves and shore-normal backwash caused by gravity creates a longshore drift, which is further strengthened by longshore currents generated by wave breaking. Sediment is entrained by strong turbulence induced by wave breaking and transported down-drift along the coastline by longshore currents. Longshore sediment transport rate remains constant if there exists a uniformity of waves and nearshore isobaths along the coastline (USACE, 1984). Net deposition occurs where the longshore uniformity is broken by a decrease of the wave energy. This is normally caused by a deepening of the bathymetry or a change of the coastline orientation. In the latter case, the boundary constraint of the longshore currents by the coastline no longer exists, and the currents are veered by a barotropic pressure induced by the wave radiation stress. On the side to which the currents are veered, turbulence is dissipated by free calm water and no longer able to entrain the full load. Much of the sediment is deposited as a result, forming a submerged bar. This submerged bar subsequently acts to maintain the original direction of the longshore currents and on the other hand serves as a reservoir for sediment deposit. Deposition on the submerged bar will not stop until a uniformity of waves and nearshore isobaths is again built up. Eventually an above-water spit is developed and elongated by this process. Terrestrial onshore aeolian transport, which builds up foredunes on the berm of the newly formed beach, plays a key role in stabilizing the spit and allows a further development of the spit. The spit becomes a barrier spit when it is long enough to provide a shelter for its inner water. As foredunes are a common feature on a barrier spit, they serve as useful records for historical environmental change (Tamura, 2012).

Three basic preconditions have to be fulfilled for the formation of a barrier spit:

1. A littoral drift to provide continuous sediment supply
2. A change in the coastline orientation (i.e., a turning point) that is significant enough to remove the boundary constraint of the longshore currents
3. A weak offshore transport at the turning point to enable a major part of the deposited sediment remaining on-site.

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BEACH MANAGEMENT

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Definition

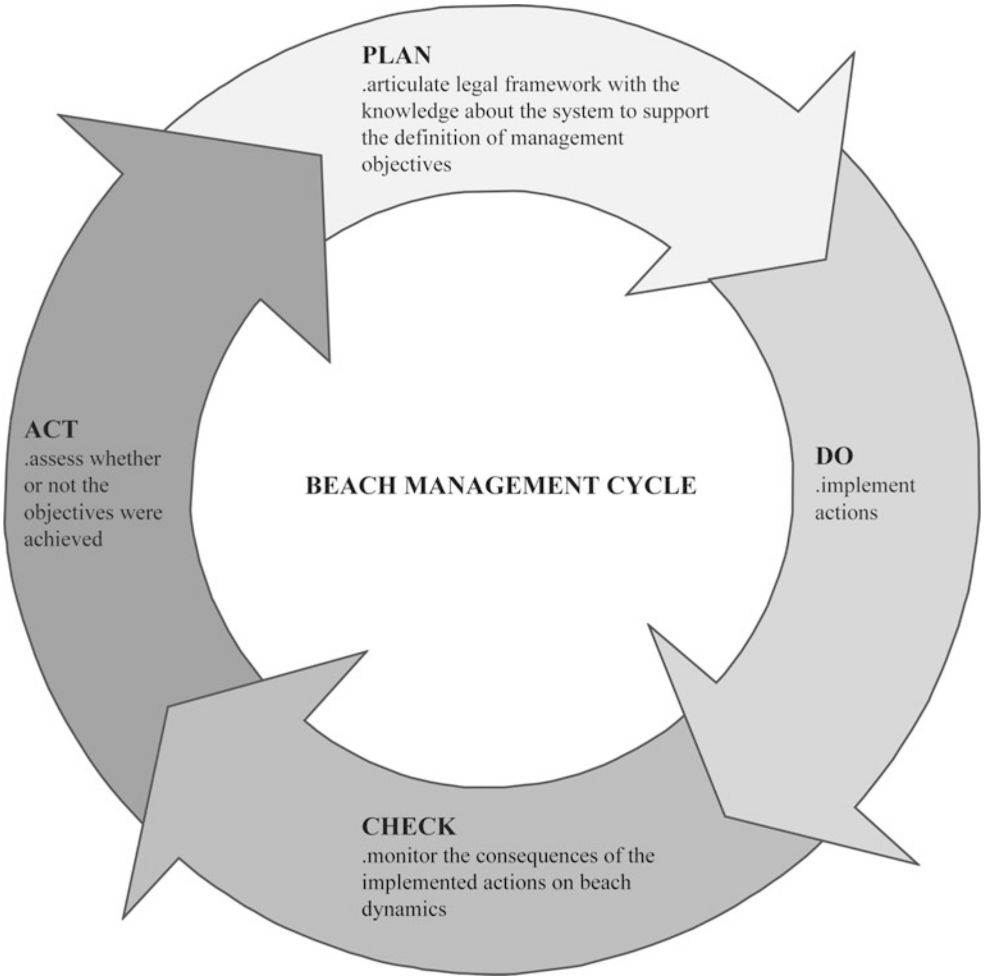
Beach management is the act of organizing and coordinating efforts to identify and implement the optimal use of means to accomplish an end for a specific beach.

Introduction

The process of managing implies the existence of objectives and is used as a technique for achieving an end. Managing also implies knowing the system being investigated, and this constitutes a tremendous challenge in highly dynamic systems, such as a beach, one of the most mutable environments in the world, where morphologic variations can occur on time scales from a few seconds to thousands of years and more and on space scales from meters – or even less – to thousands of kilometers.

In any management activity, four steps are mandatory: plan, do, check, and act (approach known as the PDCA or Deming cycle). *Plan* implies the establishment of management objectives, *do* corresponds to the implementation of the objectives, *check* implies to the objectives implemented and compare them against the expected results (targets or goals from the *plan*) to ascertain the differences, and *act* may imply corrective actions on differences between actual and planned results.

In beach management, the same approach should be considered with the necessary adaptations due to the particularities of the beach environment. In fact, the beach management approaches described in the literature are, in general, implicit deviations of the PDCA cycle (e.g., Micallef and Williams, 2002; Drake, 2010).



Beach Management, Figure 1 Beach management cycle.

Beach management cycle

The beach management cycle is a graphical way, based on the PDCA approach, of synthesizing the key elements in beach management (Figure 1).

First, it is necessary to plan and to establish a management strategy and actions. This step implies to articulate the legal framework, the knowledge of beach managers, and the scientific community concerning beach processes and response, with the strategic and operational management objectives for a specific beach. While strategic objectives provide the long-term context for management and are based on a vision of the natural and the socioeconomic systems (e.g., sustainable development of the beach area), the operational objectives implement the strategic objective (e.g., determine the ecological beach carrying capacity) (van Koningsveld, 2003).

After the actions are established, they should be implemented according to previously established guidelines elaborated in the planning phase.

Monitoring the beach dynamics and response to the implemented actions is the next step. Did things happen according to the plan? Did the system respond as expected? Indicators (quantitative/qualitative statements or measured/observed parameters) should be used in order to support beach monitoring since their main functions are to simplify the information, quantify the target system, and facilitate the communication process between different beach stakeholders (e.g., beach managers and scientific community) (UNESCO, 2006).

The beach management cycle is then completed by evaluating whether the initial objectives were achieved and eventually acknowledging the need to review the original objectives in the context of changing pressures (e.g., climate change) to reflect changes in legislation or good practice (Drake, 2010).

The beach management cycle should be rooted in the integrated coastal zone management philosophy (Cicin-Sain and Knecht, 1998), thus being a dynamic, multidisciplinary, and iterative process aiming to promote sustainable management of the beach area. It seeks over the long term to balance environmental, economic, social, and cultural objectives while acknowledging the specificities of this environment.

Estuarine beaches

Although the beach management cycle is a conceptual approach and therefore applies to all types of beaches, estuarine beaches constitute a singular feature that should be highlighted. Usually, these beaches are subsumed under existing policies to manage ocean beaches, and their specific physical and biological processes and intrinsic values are not always attended in management (Nordstrom, 1992). Estuarine beaches differ from their ocean counterparts in terms of physical structure, social perception, intrinsic values, human use levels, and types of development pressure (Nordstrom, 1992). For this reason, estuarine beach management should be conducted with a thorough understanding of their peculiar dynamics.

Conclusions

Beach management can be described as the act of organizing and coordinating efforts to archive a desired goal for a specific beach. In beach management, four key elements are identified based on the PDCA cycle approach: plan (establish a management strategy and actions), do (implement management actions), check (monitor), and act (assess the degree of achievement of the previous objectives and eventually rethink the initial strategy). For proper beach management, all of these steps should be integrated with scientific knowledge of beach dynamics.

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Cross-references

Beach Processes
Coastal Indicators
Estuarine Beaches

BEACH PROCESSES

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Definition

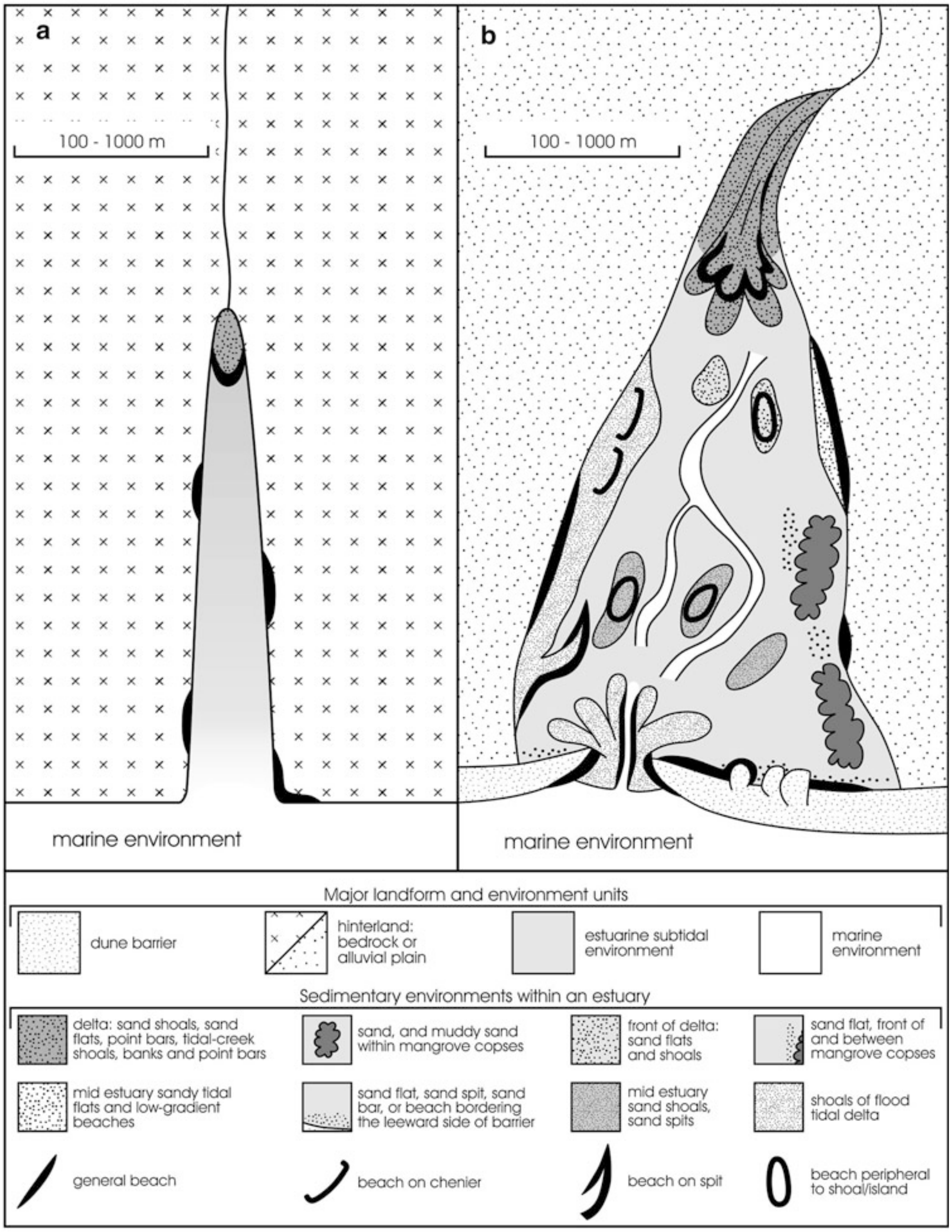
The physical, biological, and chemical processes operating on the surface and shallow subsurface of a beach, resulting in stratigraphic, granulometric, and sediment compositional variations, construction of physical sedimentary structures and biogenic structures, authigenic/diagenetic mineral responses, and biogenic mineral products.

Introduction

A beach can be described as a shoreline that has formed and has been reworked by waves or tides, and that is usually underlain by sand or gravel, and lacking a bare rocky surface (modified from Bates and Jackson, 1987). Beaches largely encompass the tidal interval, but can extend to a limited distance inland, either to a definite change in material or physiographic form (such as a cliff) or to the line of permanent vegetation (usually the effective limit of the highest storm waves). Beaches form in many shore environments, e.g., along mainland coasts fronting an open ocean, small seas, embayments, bays, estuaries peripheral to coral reef islands and volcanic islands, and lakes. This contribution focuses only on the beaches occurring within estuaries and extends, to a limited extent, to the open marine coast (Figure 1).

In tropical regions, some sandy beaches may be inhabited by mangroves, but not to the extent that the beach is fully covered by mangroves. Mangroves, if they inhabit sandy beaches, are generally in the mid-tidal areas, and the high-tidal part of the beach is vegetation-free.

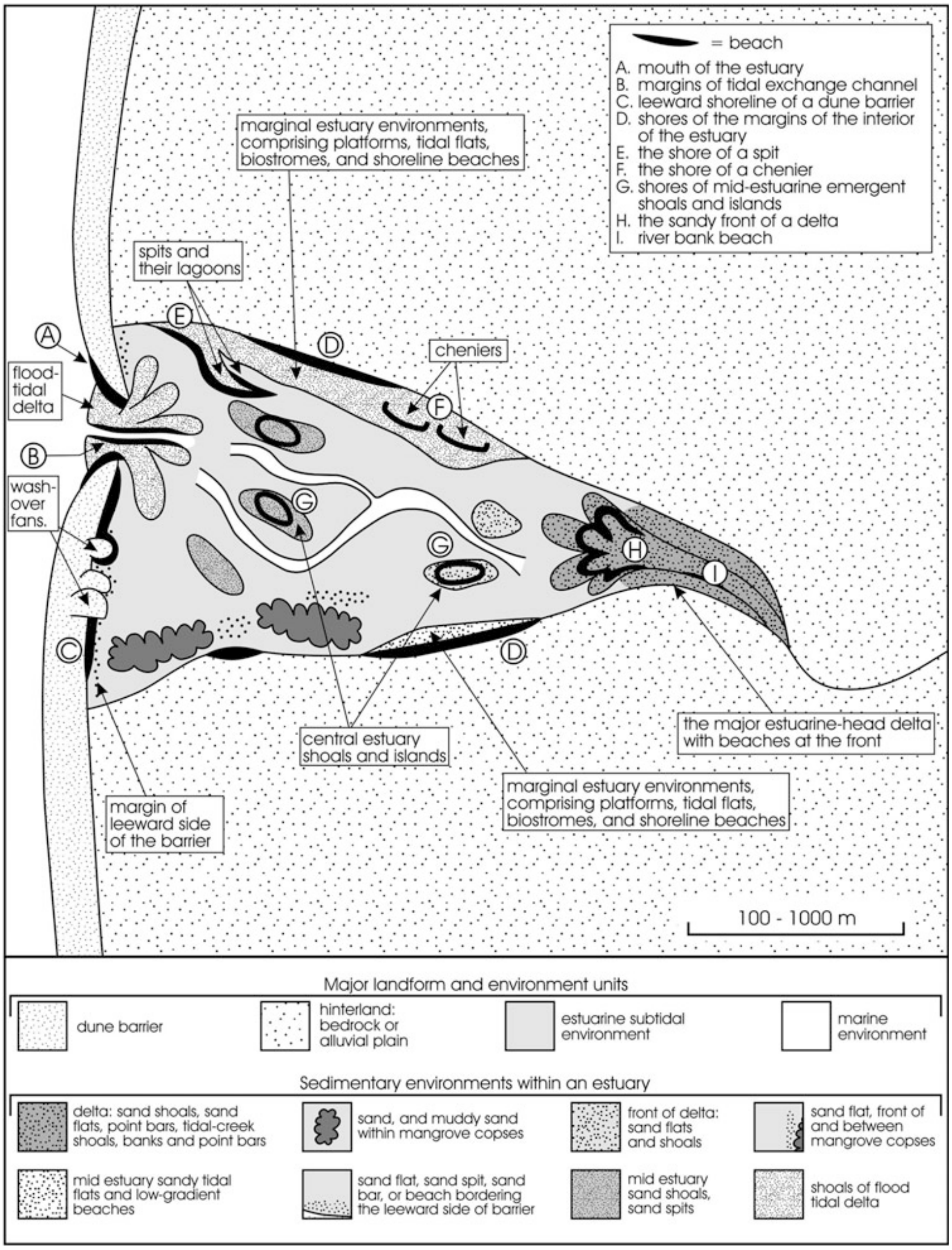
There are a number of locations within an estuary where beaches can form, in general order, from seaward to river; these are (Figure 2; labeled A-I in Figure 2) (1) mouth of the estuary, (2) margins of tidal exchange channel, (3) leeward shoreline of a dune barrier, (4) shores of the margins of the interior of the estuary, (5) shore of a spit, (6) shore of a chenier, (7) shores of mid-estuarine emergent shoals and islands, (8) sandy front of a delta, and (9) sandy sloping bank of a river (a riverbank beach). These shores are locations where sand and/or gravel (that either are preexisting or have been transported to the site by riverine, estuarine, marine, or aeolian processes) is reworked and sculptured by estuarine prevailing wave, storm, tidal, and aeolian processes. These beaches may be small and localized “pocket” beaches varying to large, laterally extensive stretches of shore. The size, slope, and extent of development of a beach in an estuary, and whether it is sandy or gravelly, is a function of a number of factors including the exposure of the shore to wave



Beach Processes, Figure 1 Idealized diagram showing estuaries of the narrow valley-tract type and the wide semi-enclosed type and occurrence of beaches therein. The more complicated, wide, semi-enclosed type of estuary has a larger variety of beaches.

action and storms, the type of sediment that comprises the uplands, the amount of sediment that is delivered to the shore from the estuary or from erosion of the uplands, and the tidal range. A brief description of estuarine beaches in terms of setting, environmental processes, and substrate types is provided later. A selection of beaches in estuaries is shown in Figures 3 and 4.

From seaward to the river along the length of an estuary, the different parts of an estuary vary in relation to the prevailing hydrodynamic conditions. Beaches, for example, are subject to varying oceanic waves, intra-estuarine waves, tides, river currents, floods, and wind, depending on their location. This concept, expressed sedimentologically in facies and stratigraphy along the marine-to-river transition in an estuary, is described by Dalrymple et al. (1992) and is, in principle, also applicable to categorizing and comparing processes and products of estuarine beaches in their locations along, and within, an estuary. Located at the seaward end of an estuary, the hydrodynamic processes are more tide and ocean-wave dominated; located in the central parts of the estuary, the processes are tide influenced, estuarine-wave dominated, and less

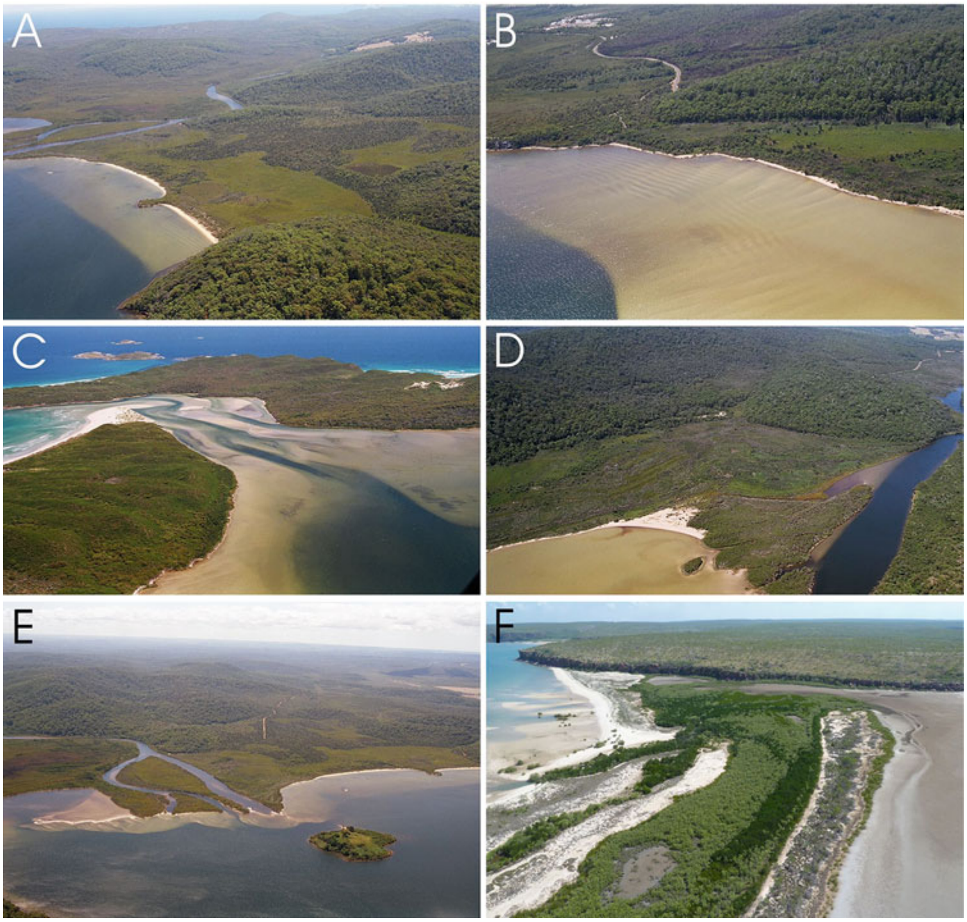


Beach Processes, Figure 2 Using the more complicated, wide, semi-enclosed type of estuary, an idealized annotated diagram showing the various environments of the estuary and where beaches occur. The beaches are labeled A-I.

ocean-wave influenced; and located at the river end, the processes are river-current influenced, estuarine-wave dominated, and less tide influenced.

The shape of an estuary and its relationship to its marine entrance and its relationship to prevailing wind and wind-wave trains also influence the hydrodynamic factors of beaches that affect their shape and sedimentology and the extent that beaches are backed by beach ridges or dunes.

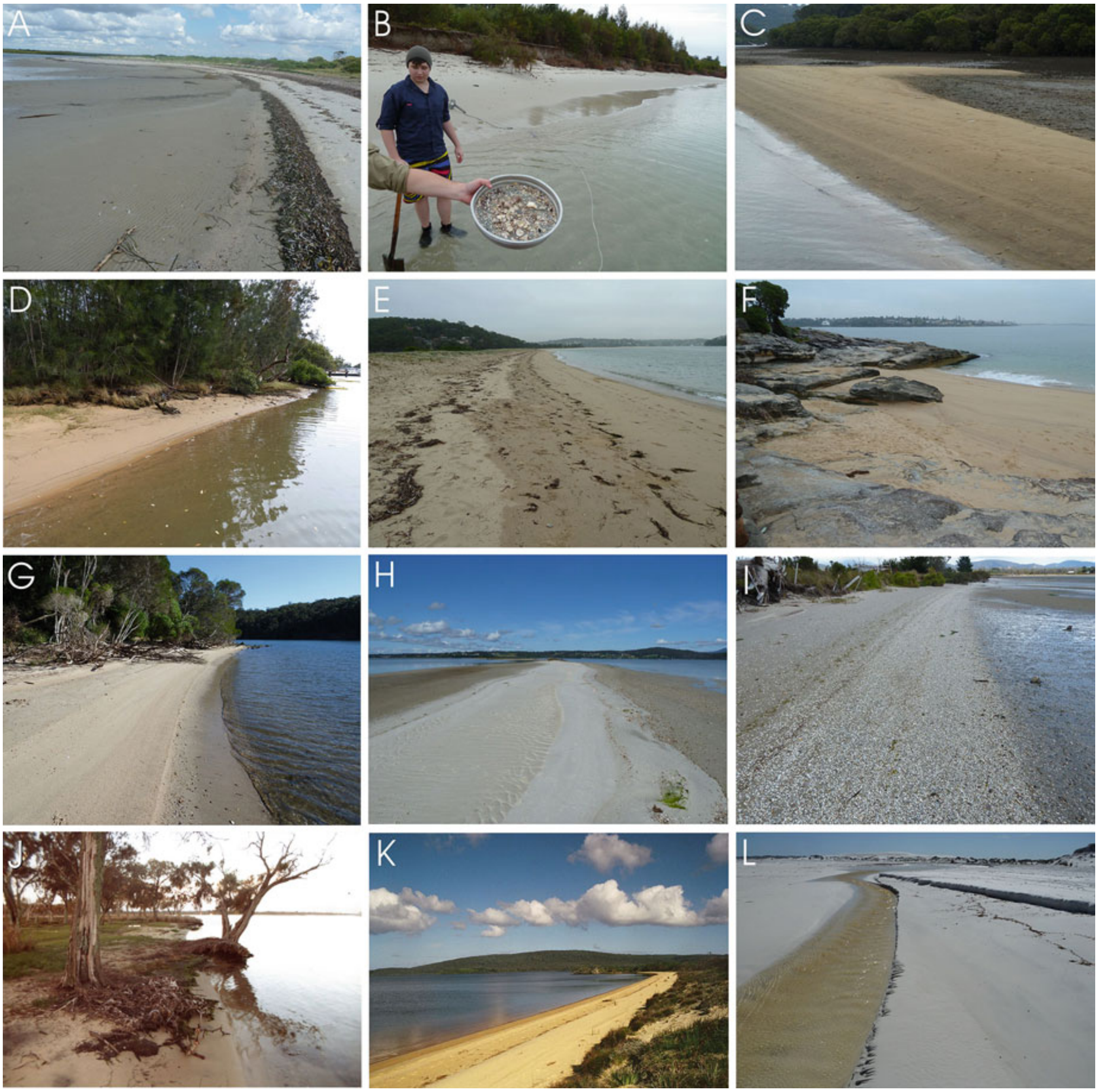
The processes of waves and tides result in different slopes and heights to beaches. Commonly, a beach within an estuary, as a sloping sandy surface, may involve the whole tidal zone of a shore, or only the mid-tidal to high-tidal part of the shore, with the low-tidal part being a low-tidal sand flat, low-tidal muddy sand flat, or low-tidal mud flat. With stronger wave action, beaches within an estuary may have a slope from low- to high-tidal level. Slopes of beaches vary from relatively steep, to moderately sloping, and to low-gradient slopes, and spatially, beaches vary from narrow to wide. Where beaches are exposed to onshore wind, during low tide



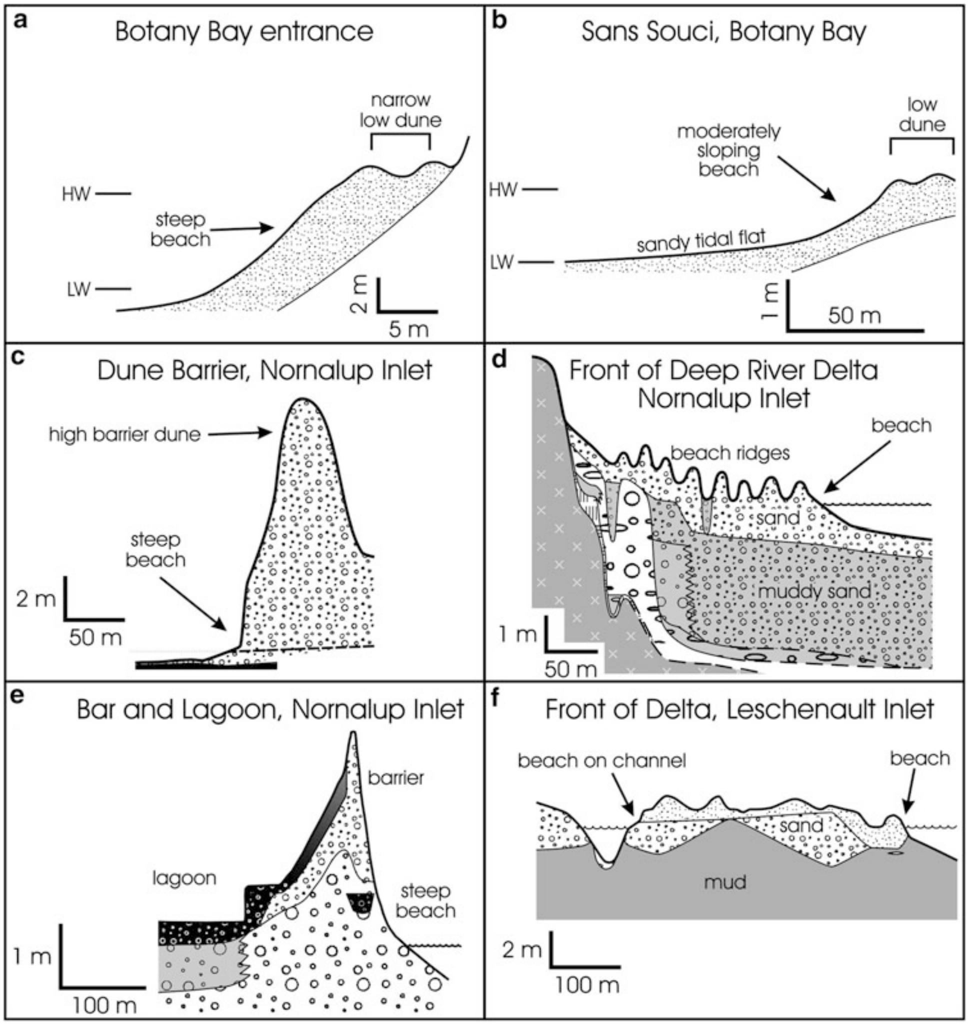
Beach Processes, Figure 3 Aerial photographs of beaches in estuaries in Australia. (**a**) Beach in front of a barrier-and-lagoon complex in Nornalup Inlet estuary, southern Western Australia (Semeniuk et al., 2011). (**b**) Beach in front of a beach ridge system, northern Frankland River Delta, in Nornalup Inlet estuary, southern Western Australia. (**c**) Beaches developed (a) leeward of a dune barrier, (b) at mouth of the estuary, and (c) around shoals in a tidal delta; Nornalup Inlet estuary, southern Western Australia. (**d**) Beach developed at the front of a delta, central Frankland River Delta, in Nornalup Inlet estuary, southern Western Australia. (**e**) Beaches developed along (a) spit at western front of Deep River Delta (to *left*), (b) along sandy central front of the Deep River Delta, and (c) along eastern front of the Deep River Delta (to *right*), in Nornalup Inlet estuary, southern Western Australia. (**f**) Beaches along estuarine-mouth barrier spits, with wave-generated sand ridges, macrotidal Berkeley River Delta estuary, Kimberley Coast, northwestern Australia (Brocx and Semeniuk, 2011); some sand spits and barriers are mangrove vegetated along their lower slope.

(and particularly during low spring tide), aeolian transport sweeps up fine and medium sand from the dry part of the beach to construct a landward low beach ridge above the storm water level. With accretion, the beach ridges may become low dunes. As such, some beaches in estuarine environments are backed by beach ridges and/or dunes. Some profiles of beaches from different estuaries, and ranging from those concavely sloping from high tide to low tide and relatively steep (Botany Bay entrance) to those bordered by a low-tidal flat (Sans Souci, Botany Bay), those bordered by beach ridges/dunes (Deep River Delta, Nornalup Inlet), and those fronting a barrier that shelters a peat-filled lagoon (bar-and-lagoon complex, Nornalup Inlet), are shown in Figure 5.

Wave fields, whether deriving from the open ocean and propagating through the estuary entrance or as wind waves generated within the estuary, in crossing an estuary and impinging on its shores can transport, rework, and winnow sediment to leave a sandy to gravelly deposit, as well as recurringly sorting sediment granulometrically to leave stratigraphically distinctive layers and packages. Storm waves, similarly deriving from open ocean areas or generated within the estuary can transport, rework, and winnow sediment and, additionally, can emplace sediments above the level of the highest tide, often leaving a distinctive stratigraphic, lithologic, and granulometric signature. Combined with wind and wind-induced currents, storms deriving from the ocean can deliver floating debris such as marine algae, seagrass, and shells, as well as chunks of wood, branches, leaves, logs, and the mollusks *Spirula* and cuttlefish skeletons that accumulate on the beach to form a distinctive sedimentary deposit at the



Beach Processes, Figure 4 Examples of beaches in estuaries in Australia showing range of settings, sizes, sediments, geomorphology, slopes, and wrack. (**a**) Narrow sandy moderately sloping mid-tidal to high-tidal microtidal beach with wrack at the *upper* and *lower* limit of slope, bordering a sandy tidal flat; beach is cut into a sandy upland; Botany Bay, Georges River estuary, southeastern Australia. (**b**) Steep sandy microtidal beach extending from low-tidal to high-tidal, and backed by low dune; shells retrieved from the low-tidal part of the beach are shown on the sieve; Botany Bay, Georges River estuary, southeastern Australia. (**c**) Sandy microtidal beach developed on a low-tidal chenier in the mid-tract of the Georges River estuary, southeastern Australia; muddy tidal flats and mangroves occur to leeward of the chenier. (**d**) Microtidal sandy steeply sloping beach developed on the river bank in the mid-tract of the Georges River estuary, southeastern Australia. (**e**) Laterally extensive sandy microtidal low-gradient beach in the central part of the Hacking River estuary (Port Hacking), southeastern Australia; scattered wrack showing high-water levels; beach backed by low dunes. (**f**) Small pocket sandy microtidal beach along the estuarine margin, Hacking River estuary (Port Hacking), southeastern Australia; the beach is interspersed with rocky outcrops. (**g**) Microtidal sandy moderately sloping beach developed along river bank in the estuary of Mallacoota Inlet, southeastern Australia. (**h**) Microtidal sandy beach developed along a spit that emanates from a mid-estuary island in Mallacoota Inlet, southeastern Australia; the beach is bordered by a sandy tidal flat. (**i**) Narrow sandy mid-tidal to high-tidal microtidal low-gradient beach, with lines of scattered wrack, bordering a slightly muddy sand tidal flat; lower part of the beach is cut into a sandy upland; southeastern Tasmania. (**j**) Eroding coast of middle Peel-Harvey Estuary, southwestern Australia (Semeniuk and Semeniuk, 1990) showing cliff cut into peripheral vegetation formations; pocket beaches are developed between the micro-peninsulae. (**k**) Linear extensive microtidal sandy beach, the beach being part of the barrier-and-lagoon system of the northern Nornalup Inlet estuary, southern Western Australia (Semeniuk et al., 2011). (**l**) Exit channel with tannin-stained water at the mouth of an estuary, southern Western Australia; beach shows cliffing.



Beach Processes, Figure 5 Some profiles of beaches in estuaries. (**a**) Microtidal, steep beach backed by rock, at Botany Bay entrance, southeastern Australia. (**b**) Microtidal, moderately sloping beach fronted by wide, sandy tidal flat and backed by low dunes, Sans Souci, Botany Bay, southeastern Australia. (**c**) Narrow, microtidal beach in front of a dune barrier, Nornalup Inlet estuary, southern Western Australia (From Semeniuk et al., 2011). (**d**) Narrow, microtidal, steep beach in the front of beach ridges of the Deep River Delta, Nornalup Inlet estuary, southern Western Australia (From Semeniuk et al., 2011). (**e**) Narrow, microtidal, steep beach in the front of a bar-and-lagoon complex, with a peat-filled lagoon to leeward, Nornalup Inlet estuary, southern Western Australia (From Semeniuk et al., 2011). (**f**) Narrow, microtidal beach in front of the Collie River Delta, Leschenault Inlet estuary (From Semeniuk, 2000).

storm level or high-tide level (Semeniuk and Johnson, 1982; Semeniuk, 1997). Tidal currents perform the same functions of transporting, reworking, and winnowing sediment, creating distinctive lithologic and stratigraphic suites.

Because the provenance of shoreline sediment is variable (reworked from barrier dunes or flood-tidal deltas, and hence marine-derived, reworked as fans, shoestrings, or ribbons from the uplands bordering the estuary, riverine, or generated biogenically), clearly, the sediment type underlying an estuarine beach will vary compositionally and granulometrically (fine sand to coarse sand to gravel and with variable shell content) and, depending on the short-term history of prevailing wave action, storm waves, and tides, will carry a distinctive small-scale stratigraphic signature such as shell gravel lenses interlayered with laminated sand, or coarse sand interlayered with medium/fine sand, or pebble layers in laminated sand, among others.

During a high tide, the beach slope is inundated and the beach sands are saturated. During the ensuing low tide when the beach is subaerially exposed, there are two sub-environments where water resides under a beach: (1) shallow groundwater (that is contiguous with the open waters) whose water table falls and rises with the tide; this water can be referred to as the phreatic zone, where it resides in the pore spaces of the sediments; and (2) water films circumferential to sand particles in the wetted but undersaturated sediment above the water table during low tide; this wet zone can be referred to as the temporary vadose zone and is tidal-flat pellicular water. The surface of the phreatic zone is the groundwater table during low tides. This groundwater table rises and falls with the tides. The phreatic zone determines many of the biological and chemical processes operating under the beach, and the vadose zone during a low tide determines many of the other biological and chemical processes operating under the beach. Depending on the depth to the water table during the period of low tide, the beach may be wet (where the water table is near the surface) or moistened by water rising by capillary action, or may be relatively dry (where the water table is decimeters below the surface).

Location of estuarine beaches

As mentioned earlier, there are nine different environments within an estuary where beaches can form. Therefore, location will determine the suite of processes that combine to form a beach in the first place, the type of sediments that comprise the beaches, and the types of processes that operate postdepositionally on beach sediments.

The most common locations for beaches are the shores of the margins of the interior of an estuary and generally in the central parts of estuaries (i.e., not deltas, spits, cheniers, shoals, and the estuarine mouth). Here, the shores are usually sandy, with sand derived from alongshore, washed up from subtidal zones, reworked from the uplands, or delivered from the marine environment. In microtidal and mesotidal settings, the beach is fronted by low-tidal sand flats. Gravel sources and any eroding rock in estuarine shore environments result in gravelly beaches. Where beaches are bordered by sandy tidal flats and skeletons of shelly benthos are transported onto the beach by waves and storms to form shelly sand, or shell gravel lags, or shell gravel lenses.

The next most common site for beach development is the leeward margin of barrier dunes. Here again, the shores are usually sandy with sand eroded from the dunes, or derived from alongshore, or washed up from subtidal zones. In microtidal and mesotidal settings, such beaches are fronted by low-tidal sand flats which supply shell gravel and shell grit to the beach to form shelly sand, or shell gravel lags, or shell gravel lenses.

The shores of mid-estuarine-emergent shoals and islands also are common sites for the development of beaches. Because shoals and islands present differing aspects to prevailing wind-wave fields, and to wind, there is asymmetry in the suite of processes and in the products developed. Beaches directly facing prevailing waves will have different profiles to those on leeward sides of shoals and islands, and similarly, the sediment response within a beach in terms of lithology, granulometry, and stratigraphic organization will differ from windward side to leeward side of the shoal or island. Beaches peripheral to shoals and sand islands are commonly sandy, while those peripheral to an island of rock can have sandy, gravelly sand, and gravelly beaches.

Beaches can be developed at the mouth of an estuary and along the margins of tidal exchange channels. Beaches at the mouth of an estuary are subject to processes similar to that of open coastal beaches, though the former are more protected; these processes include oceanic wave action, wind-wave action, tides, and wind. These beaches may be backed by low beach ridges built by the prevailing onshore winds. The sediment responses within such beaches in terms of lithology, granulometry, and stratigraphic organization are similar to open coastal beaches and include a larger proportion of floating debris derived from marine sources. Beaches along the margins (banks) of tidal exchange channels are also subject to processes of oceanic wave action, wind-wave action, tides, and wind. Orientation of the channel to the ocean wave field determines how much wave action is involved in shaping the beach morphology and lithology, and, in this context, ebb and flood-tidal currents are more important in that their effects are magnified in (relatively) narrow channels. These shorelines also may be backed by low beach ridges built by the prevailing winds. Beaches at the mouth of estuaries and along the margins of tidal exchange channels are most commonly sandy.

Beaches developed along the shores of spits and cheniers are similar, though these coastal landforms develop in different locations within an estuary, and for spits, there often is a leeward basin. Spits, as linear emergent sandy bars and recurved emergent sandy bars, with one end anchored to a shore, a shoal, or a promontory, are developed along the margins of estuaries in mid-estuarine locations, at the mouths of estuaries, peripheral to shoals and islands, and at the tips of promontories of riverine deltas. Cheniers, as linear emergent sandy bars and recurved emergent sandy bars that are isolated as a sand body, are developed on tidal flats and at the tips of promontories of riverine deltas. The shores of spits and cheniers are developed by prevailing wave action or by storms. Their beach slope is further shaped by tidal currents. For spits, as they are often recurved sand bodies with a leeward lagoon or sheltered area and are subject to hydrodynamic processes on both sides of the sand body, there is a windward beach and leeward beach. Beaches developed along the shores of spits and cheniers are most commonly sandy. For both spits and cheniers, in tropical regions, their sandy leeward (protected) slope often is inhabited by mangroves.

The prograding front of a sandy delta is another location for the development of beaches. In this situation, the beach-constructing agencies are mainly estuarine wind waves, with lesser effect from tidal currents. These beaches are mainly sandy and are peripheral to the delta plain.

The sloping sandy bank of a river is also a location for the development of a beach. Here, the beach-constructing agencies are mainly river current, estuarine wind waves, with lesser effect from tidal currents. These beaches are mainly sandy and locally gravelly. Since these sandy banks are usually protected, in tropical regions, they often support stands of mangroves.

An important aspect of some estuaries is the occurrence of a peat-filled lagoon leeward of a shore-parallel barrier (such as a prograded ribbon of sand or a prograded narrow beach ridge system). With high freshwater levels in the lagoon after rain or floods, freshwater from the peat-filled lagoon may discharge from under the beach slope of the most seaward beach ridge.

Sediment sources

There are four sources of sediment particles that comprise estuarine beaches; these are (1) rivers, (2) estuarine biota, (3) margins of the estuary, (4) preexisting estuarine (relict) estuarine sediment, and (5) marine sources. These sedimentary particles form the "raw material" (viz., the sediment) upon which the physical, biological, and chemical processes in the estuary in the beach environment will act and imprint various structures and products.

River sediment, sediment from the margins of an estuary, and marine sediment are exogenic, deriving from outside the estuarine basin and being delivered to the estuary. Estuarine biota generates endogenic sediment.

Rivers deliver sand, some gravel, and mud, with sand and mud being the dominant particle types. The margins of the estuary through erosion by waves, tidal currents, wind, and (rain) sheetwash provide sand, mud, and gravel. Depending on the type of upland, i.e., whether it is rocky, sandy, or muddy, the sediment eroded into the margin of the estuary by waves, tides, rain, and storms varies from coarse, medium, and fine sand to gravel, mud, or mixtures of these. Preexisting estuarine (relict) sediment is sediment within the estuary relict from an earlier depositional phase that is remobilized by waves, tides, and storms and transported onto the beach. Though it may comprise a range of grain sizes such as sand, mud, and (rock and/or shell) gravel, only sand, rock, gravel, and shell are of relevance to estuarine beaches. Delivery of marine sediment to the estuary (and specifically to estuarine beaches) can be complicated and occurs in three pathways: (1) through the entrance or mouth of the estuary by tidal currents, wind-induced currents, and waves; this sediment is coarse, medium-to-fine sand, rock gravel, and shell; and this source also includes the floating mollusks such as *Spirula* and cuttlefish; (2) initially accumulating from the marine environment as a dune barrier which, on its leeward margin, is then eroded by estuarine processes of waves, tides, and sheetwash into the estuarine shore zone; this sediment usually is medium and fine sand; and (3) aeolian transport from the dune barrier into the estuarine environment; this sediment is usually fine sand.

Endogenic biogenic sediment in an estuary is variable depending on biogeography, climate, and salinity of the environment. At macrofaunal scale, it ranges from molluskan shell and their fragments (deriving from benthic infaunal bivalves, epifaunal gastropods, and oysters that colonize rocks or form biostromes, mussels that also colonize rocks or form biostromes), crustacean fragments, ostracods, and minor components such as bryozoans, echinoderms, hydrozoans, and sponges. Shelly fauna that contributes shell to the sediment in an estuary varies in composition according to their location in terms of salinity and the variability of salinity (Day, 1981): (1) near the estuary mouth where the environment is marine, organisms are stenohaline marine in character; (2) in mid-estuarine environments, biota is truly estuarine or euryhaline marine in composition (the latter are species represented in the marine environment but which tolerate salinities of 5–50 ‰); (3) in the river mouth and river channel where it is freshwater, biota is euryhaline freshwater (i.e., species primarily are freshwater types, but some tolerate salinities greater than 5 ‰) or stenohaline freshwater. At microbiota scale, biota that contributes to estuarine sediment includes foraminifera and diatoms. Some of these biotas inhabit beach environments and so directly contribute to skeletal accumulation in situ, but a majority live externally to the beach and are transported to the beach site.

Seagrass; algal beds; algal mats; saltmarsh; mangroves logs, stumps, and branches; mangrove leaves; and terrestrial wood and logs washed into the estuary from rivers also contribute to beach sediment. Seagrass and algal beds such as *Heterozostera*, *Halophila*, *Ruppia*, *Zostera*, *Chaetomorpha*, *Fucus*, *Gracilaria*, and *Ulva* occur in the intertidal or shallow subtidal zone and are delivered to beaches by waves, tidal currents, and storms. Leaves of saltmarsh species and mangroves and wood are washed onto the beach from alongshore (and, for saltmarsh, also from behind the beach), particularly during storms. Although not growing on the beach, estuarine plants from these various intertidal and subtidal environments are transported from their habitat to accumulate on the beach as "flotsam and jetsam" (also termed "wrack"), as scattered plant fragments or as organic beds (incipient peat) of plant matter some 10–50 cm thick. Most typically, plant material from their respective habitats occurs as scattered fragments and detritus on the beach slope to be buried later in the beach sediment.

The physical, biological, and chemical processes operating on an estuarine beach

Processes operating on a beach can be categorized as physical, biological, or chemical. Many of the processes on beaches are ubiquitous within beaches throughout an estuary, but there is a distinct suite of processes in different parts of the estuary, depending on the extent of wave action, tidal currents and river currents, wind, the nearshore or low-tidal biota (and what is delivered to the beach as shell and plant matter), the type of macrobiota resident under and on the beach, the type of microbiota resident under and on the beach, the amount of sediment sheetwash delivered onto the beach from the adjoining upland, the amount of freshwater seepage onto the beach face, salinity of the estuarine waters, the chemistry of the groundwater and pore waters under the beach (dependent on estuarine setting), and the hydrological (groundwater) through-flow.

These physical processes, biological processes, and chemical processes and their products are described below. Which process(es) on or under the beach is/are dominant is determined by where the beach is located in the estuary, how active are the hydrodynamic processes, the extent of mobility of the sediments (and therefore to what extent the organic matter is turned over), the amount of influx of organic matter, and the extent of oxidation of the sediments.

Sandy beaches commonly exhibit gradients normal to their shore, e.g., a gradient in inundation and evaporation, with attendant gradients in wave energy and tidal energy, and hence a graded expression of the processes of sedimentation, erosion, and hydrochemical effects (Brocx and Semeniuk, 2009). This results in variable, complex, and diverse physical, biological, and geochemical products across the shore and variation in fine- to small-scale stratigraphic sequences.

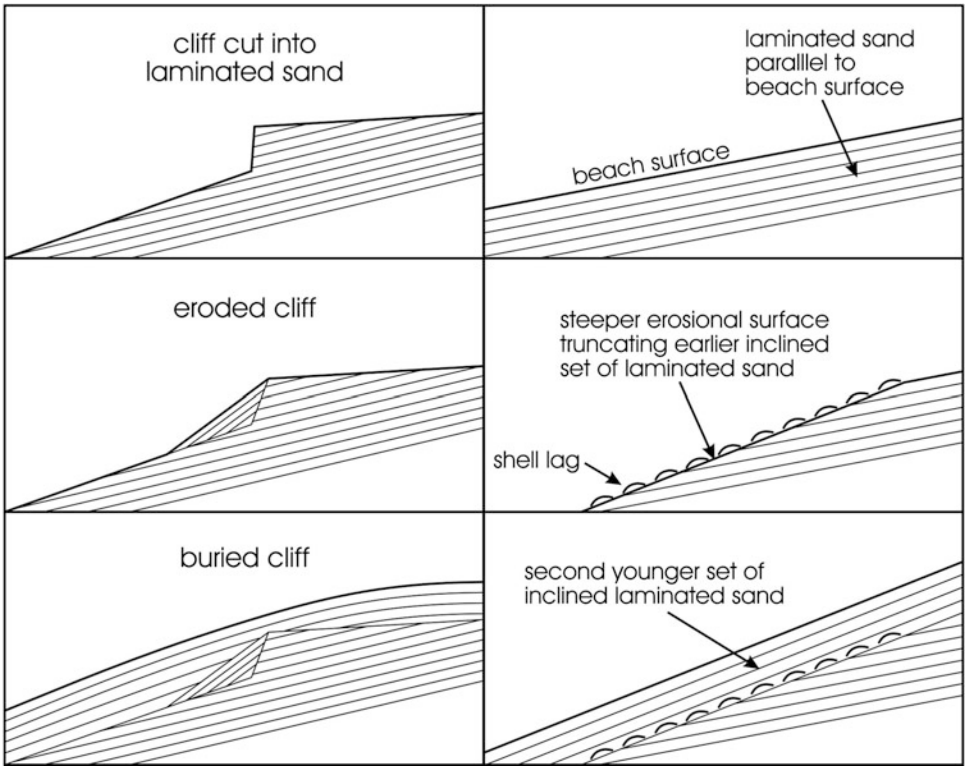
The physical processes on beaches are wave action by prevailing wind waves and by oceanic waves propagating through the estuary mouth, wind-generated currents, tidal currents with maximum currents during spring tides and lower-velocity currents during neap tides, formation of cliffs and cusps, wind activity acting on dry beach surfaces and on wet beach surface, storms resulting in chaotic wave trains and waves often with elevated water levels, evaporation, freshwater seepage into the beach and freshwater upwelling from under the beach, gas upwelling from under the beach, rainfall effects (such as rain infiltration), and wave-swash infiltration.

Wave action, tidal currents, and storms are involved in sedimentation processes to develop beach sand lamination. Wave action, tidal currents, and storms transport sediment, and, depending on the wave energy, tidal-current velocity, and degree of storm activity, they sort and separate sediments into grain-sized suites of sand with grains of similar specific gravity (a monomineralic sand, siliciclastic sand of quartz and feldspar grains, or siliciclastic sand and carbonate sand) or hydraulically equivalent suites (e.g., fine sand-sized grains of magnetite as spheres with specific gravity of 5.2 are hydraulically equivalent to medium sand-sized quartz and feldspar grains as spheres with specific gravity of 2.6, and 2.6–2.7, respectively; Tourtelout, 1968; Selley, 2000). Wave action, tidal currents, and storms also transport and sort shells into size-graded and oriented accumulations (Behrens and Watson, 1969; Reineck and Singh, 1980).

With run-up and backflow during wave action on a beach slope, sediments, once sorted, are deposited as granulometrically distinct and/or compositionally distinct laminae that, with accretion, result in laminated beach sand with laminae alternating in grain sizes, grain-sized suites, or in composition (e.g., quartz fine sand laminae alternating with quartz medium sand laminae, or with mixed quartz fine to medium sand laminae, or with grain-thick micro-laminae of rutile very fine sand or silt). Wave action and tidal currents, during the high tide when the beach slope is inundated, winnow the sand of the beach slope leaving a lamination-scale lag of quartz medium sand and coarse sand and laminae of opaque (heavy) minerals such as rutile, tourmaline, and magnetite. Where there is shell, or shell fragments, the action of waves, tides, and storm waves can concentrate these particles leaving laminae of shell, shell fragments, and shell grit within the sand laminae. As such, with accretion, the beach is underlain by laminated sand, with lamination defined by grain-sized variation, shell layers, shell grit and fragments, and laminae of opaque minerals (heavy minerals). Lamination that is formed by waves, tides, and storms under the beach slope is parallel to the sloping surface so that, with beach-slope accretion, the laminations of the sand in the beach environment are inclined towards the estuary.

With a change of season and change in wave dynamics, or in the change from spring tide to neap tide, or with storms where water levels are higher than normal and wave action is intense, chaotic, and short-term repetitive, the beach slope (with erosion or accretion) can change its inclination. Where such erosion is followed by accretion, the erosional surface is marked as a horizon of truncation of the underlying inclined lamination and accretion of the additional laminated sediment takes place parallel to the horizon of truncation. These horizons of truncation are preserved as bedding discontinuities in the small-scale stratigraphic record. Where there are small channels or basins eroded into the sloping beach (scour is effected by wave run-off, formation of beach cusps, tidal drainage run-off, low-tidal seepage from the beach slope, and freshwater seepage channels), followed by filling and accretion of these channels and scours by later laminated sand, there is the development of small-scale (10–50 cm wide and 5–20 cm deep) cut-and-fill structures.

During storms, or periods of intense and sustained wave action that may be atypical of prevailing conditions, or during the change in water level from spring to neap tide, or a change in the wave climate inter-seasonally, the beach may erode to form a steeper beach slope or to form a cliff (Figure 6). For such beaches, the steeper beach slope is reflected in a change in dip of layering and lamination with a pre-erosion set of lamination less inclined than the post-erosion set of lamination. The interface between the sets of lamination can be marked by a lag deposit of shells or pebbles (Figure 6). Where a cliff has



Beach Processes, Figure 6 Cross sections of beaches showing macroscopic internal structures produced by erosion followed by accretion with the beach changing its slope, and internal structure, where a cliff is cut into a beach, is cliffed, and then later buried by accretion.

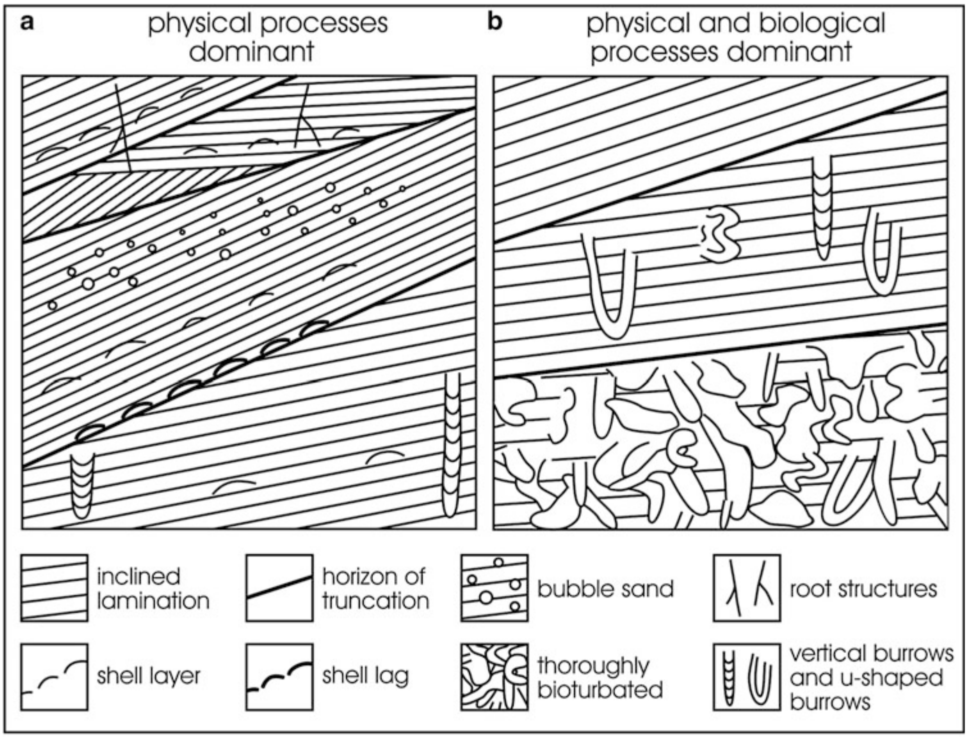
formed, it may be eroded to a more gentle slope and buried such that it is marked by a prominent discontinuity in the stratigraphic profile.

Beach cusps or rhythmic shoreline features are regular triangular, temporary-constructed accumulations of sand and/or gravel projecting from the shore (Komar, 1976). The positive cusps (or horns) alternate with depressions (or embayments). Generally, they are a few to several meters in size and spacing. Usually, the cusps are comprised of sediment that is of coarser materials than that comprising the adjoining embayments, e.g., the cusps may be comprised of coarse sand or shell gravel, while the embayment is comprised of medium sand. Cusps and their embayments manifest a stratigraphically diagnostic internal geometry and sedimentary structures (Reineck and Singh, 1980). If there is a marked grain-sized difference between the horns, this is also evident stratigraphically. The origin of beach cusps is still being debated (Rasch et al., 1993). Originally, it was thought that standing edge waves (waves perpendicular to the shore) interacting with incoming wave trains created the conditions for development of a cusp-and-embayment morphology (Guza and Inman, 1975; Guza and Bowen, 1981). However, Werner and Fink (1993) and Coco et al. (2000) provide an alternative model, i.e., the self-organization theory, wherein feedback processes between currents and sediment response result in a self-organized pattern to develop cusp and embayment on a regular spacing.

The wind has several effects on the beach. It can transport fine sand and medium sand from the dry parts of the beach leaving a lag of coarser grain sizes. In the extreme, the deflation of the beach and removal of finer grain sizes leaves a lag of coarse sand or of shell and shell fragments that form an “armored” surface of platy grains on the beach (van der Wal, 1998). Wind also dries the sediment, ripples the sediment, and constructs adhesion ripples.

The beach surface, particularly if low-gradient, may be rippled. Ripples are formed subaqueously by low-energy wave action and by tidal currents. Ripples are formed subaerially by wind on dry parts of the beach. On wet beaches, subject to strong wind where the wind is delivering dry sand from elsewhere, adhesion ripples are formed (Reineck and Singh, 1980). Adhesion ripples are oriented, linear accumulations of sand that adhere to the wet surface by surface tension and microscopically accrete forming small sand ribbons internally comprised of undulating convex-upward laminae.

With the rising and falling of the tide and concomitant rising and falling of the water table of the phreatic zone under the beach, together with the swash run-up, air is



Beach Processes, Figure 7 (**a**) Structures produced in beach sediment where physical processes are dominant. (**b**) Structures produced in beach sediment where physical processes and biological processes are co-dominant.

forced out of the aerated zone but trapped by descending swash water. As such, air is trapped in bubbles in the sand in the upper tidal level. In areas with low wave action but large tidal range (mesotidal and macrotidal), with a rapidly rising water table, air is also trapped in the sand to form air bubbles. Where air is entrapped in the beach sand, the structure is termed "bubble sand" and is a distinctive structure of sand in tidal zone (Emery, 1945; De Boer, 1979; Reineck and Singh, 1980). In estuaries, it occurs in all beaches with a tidal fluctuation (viz., mouth of the estuary and margins of tidal exchange channels, leeward shoreline of a dune barrier, beaches along the margins of the interior of the estuary, the shores of spits and cheniers, and of mid-estuarine emergent shoals and islands); it is less developed to absent on beaches that comprise the sandy front of deltas.

As noted earlier, storms and wave action during times of elevated water levels are also instrumental in developing lithologically distinct sedimentary deposits (Semeniuk and Johnson, 1982; Semeniuk, 1997). These may be marked by the concentrated occurrence of marine and estuarine plant wrack, wood and log debris, shell deposits, and accumulations of floating mollusks such as *Spirula* and cuttlefish. The marine-derived accumulations of floating mollusks are more common on beaches near estuarine mouths or within estuaries that are widemouthed and have a strong marine influence at their seaward parts.

A summary of the products of the physical processes acting on beach sediments is shown in Figure 7a.

Freshwater through-flow from the uplands bordering an estuarine beach, or from water ponded by a beach barrier, can discharge over or through a beach. With a beach barrier that bars/ponds a freshwater lagoon to leeward, or where the uplands provide general sheet flow of freshwater, the seepage across and through the beach can be a broad front (a seepage front, or interface). Such seepage may not be perennial but linked to the wettest time of the year. On the other hand, due to drainage channels and buried drainage channels from the uplands, or because of hydrological conduits, the freshwater through-flow may be channeled and restricted in its passage in corridors across and in the subsurface through the beach. The through-flow of freshwater across and through a beach will have biological, hydrochemical, and geochemical effects (see later). In particular, it may affect the composition of macrobiota and microbiota that are ecologically linked to a specific salinity.

Freshwater discharging under a beach, because of its buoyancy in relation to denser marine or brackish water, can escape to the beach surface in a discharge "pipe." This water escape, or freshwater upwelling from under the beach, results in physical disruption of the lamination of beach sediment. The upflow can entrain sand and bring it to the surface. The lamination within and in an aureole around the discharge "pipe" is contorted, and the surface of discharge is often marked by a small sand mound ("sand volcano") some 30–50 cm in diameter and up to 10 cm in height.

Methane, hydrogen sulfide, and ammonia gases generated by decomposition of organic matter buried under the beach can upwell along a preferred conduit, escaping to the surface of the beach. Such gas upwelling also causes physical disruption of lamination of beach sediment.

Evaporation, caused by solar radiation or by wind, results in the loss of moisture. Depending on the depth to the water table under a beach, evaporation can induce an increase in salinity by moisture loss and in precipitation of salt (halite).

During rainfall, meteoric water effects three processes: dilution of surface water and pellicular water salinity, dissolution of any halite that has precipitated on the surface, and vadose water-induced infiltration. For the latter, rain washing onto a beach during its exposure at low tide can deliver dust or any fine-grained sediment on the beach to levels lower down the sediment profile. If the beach is not reworked later by waves and tides, this material can be preserved as meniscus sediment. Waves and tides washing over a beach slope on a rising tide can also infiltrate the beach sand vertically and deliver fine-grained sediment (that was in suspension in the water) into the beach-sand pore spaces.

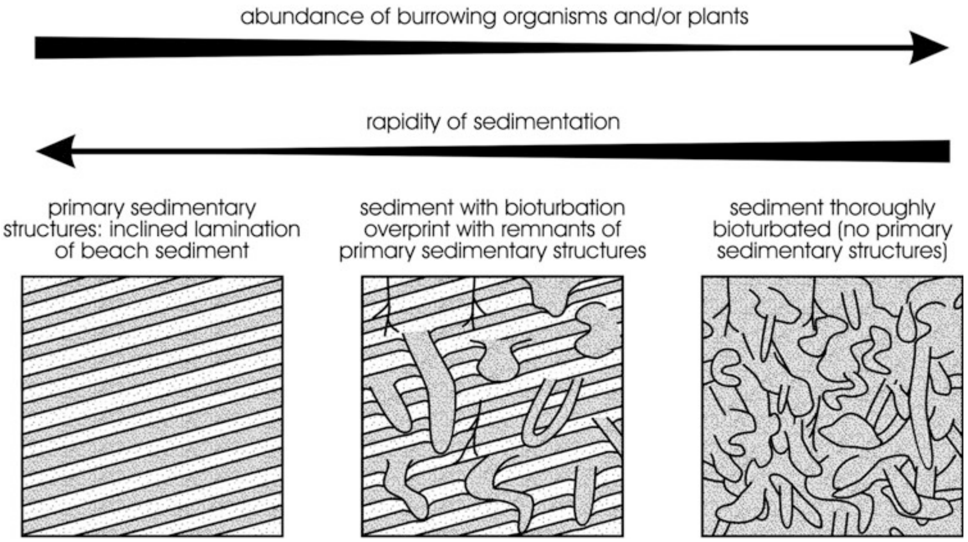
In terms of the horizontal sequence of small-scale landforms, sedimentary structures, and processes, sandy beaches provide excellent examples of the products of wave and tidal energy intersecting a sloping shore and illustrate the range of sedimentary products that are developed across the slope gradient from shallow subtidal to supratidal, in response to the graded effect of waves, tides, wind, and freshwater seepage (Clifton, 1969; Clifton et al., 1971; Reineck and Singh, 1980; Semeniuk and Johnson, 1982; Semeniuk, 1997; Brocx and Semeniuk, 2009). For instance, wave action intersecting a sloping shore is translated from a lower flow regime (varying progressively upslope) to an upper flow regime, and the resultant upslope progressive development of rippled beds and perhaps megarippled bedforms further upslope, and plane beds. Hourly, daily, weekly, and seasonal variation in wave patterns, coupled with storm effects, tide fluctuation, and onshore winds, generate lamination, shell layers, cut-and-fill structures, discontinuities (Mii, 1958), variation in grain size across laminations, and bubble sand. While the literature cited above on beach processes and products is derived mainly from beaches on oceanic shores, the principles of sedimentation and stratigraphic evolution apply equally to estuarine beaches. Moreover, the beaches closer to the estuary mouth, particularly in wide valley-tract, ocean-facing estuaries, have many features in common with oceanic beaches.

The biological processes on beaches are macrobiota shell production; microbiota test production; burrow construction; root structuring; general bioturbation; fragmentation; macrofaunal and meiofaunal breakdown of seagrass, algae, and other plant materials on the beach face; microbial decomposition; sediment pigmentation by sulfides; and hydrochemical changes in pH, Eh, and ionic chemistry effected by microbiota. The conspicuous products of biological activity result in shell layers, burrows, bioturbation, and pigmentation of sediments.

Shell production results in articulated bivalve shells being preserved in situ in the sediment (e.g., pipis and tellinids) or, where shells are disarticulated and locally transported after death, in shells being scattered in the sediment parallel to lamination usually in a convex-up orientation, though concave-up orientations are possible (Nagle, 1967; Reineck and Singh, 1980; Savarese, 1994). Gastropods are often predators of bivalves in the shore environment and are responsible for their death (the evidence being drill holes in the disarticulated bivalves; Carriker and van Zandt, 1972; Kabat, 1990), after which follows disarticulation. Gastropods also scavenge for decaying organic material on beaches. Gastropods contribute shell to beach sediments after their own death. Often bivalve and gastropod shells form laminae of shell concentrates in the beach sediment, with the bivalve shells specifically also forming a platy shell pavement on the surface due to wind deflation or current winnowing. Microbiota, such as foraminifera and diatoms, contribute tests as fine sand-sized particles that accumulate as fine-grained calcareous and siliceous particulates in the sediment.

Some of the major products of biogenic processes on beaches include burrow construction, general bioturbation, and root-structuring (McCall and Tevesz, 1982). Fauna that live in permanent burrows on the beach slope create distinct biogenic structures. Bivalves and beach worms are examples of such fauna (Reineck and Singh, 1980; Brown and McLachlan, 1990). The burrows may be diffuse, vertical structures penetrating the beach lamination (formed as the animal migrated vertically in response to changing groundwater levels), or may be a simple single tube open burrow that the animal has lined with organic matter or mud to prevent collapse, or may be a u-shaped open burrow. With the open burrows, remaining open because of their lining, later sand infiltration into abandoned burrows brought in by wave swash or tidal currents results in a sand-filled tube that is penetrative through the beach lamination. Bioturbation of the sediment is produced by other animals that burrow in the beach sediment but do not produce permanent tube dwellings.

Depending on whether physical processes that produce beach lamination are dominant over biological processes that produce burrow and bioturbation structures, the beach sediments can grade from laminated sand and shelly sand with occasional burrows (i.e., physical processes are dominant), to laminated sand and shelly sand with abundant burrows and bioturbation structures but within which the beach lamination is relict and still evident, to thoroughly bioturbated sand and shelly sand with some sand-filled vertical burrows evident (i.e., biological processes are dominant). Figure 8 illustrates this gradation in laminated sediment to bioturbated sediment.



Beach Processes, Figure 8 The progressive obliteration of primary sedimentary structures in beach sediments reflecting the relative balance between biota abundance and the rapidity of sedimentation. The primary sedimentary structures, once diagnostic of an environment, are reduced to root-structured or burrow-structured sediments and then finally to a thoroughly bioturbated sediment.

Beaches, of course, are commonly shaped and internally structured by physical processes, but macroscopic biological processes can become important enough to co-dominate in the development of the beach sediment structure. Figure 7b illustrates structures produced in beach sediment where physical processes and biological processes are co-dominant.

Burrow structures and bioturbation affect sediment macrobiologically, microbiologically, hydrologically, and geochemically through aeration, providing conduits for micro-hydrological through-flow, altering composition of meiofauna, nutrient recycling (such as nitrogen fluxes), and diagenetic mineral overturning (e.g., pyrite in deeper anoxic sediment oxidized at the sediment surface), among other processes (McCall and Tevesz, 1982; Alongi, 1985; Aller, 1988; Dittmann, 1993; Sadao, 2002; Webb and Eyre, 2004).

The higher parts of a beach, storm levels of a beach, and/or the low beach ridge immediately leeward of the beach slope often are colonized by halophytes and other strand vegetation. Such plants result in root structuring of sediments.

Animal predation, bioturbation, and foraging result in shell fragmentation and shell comminution. Crabs, fish, stingrays, octopus, and shorebirds hunt and feed on various invertebrate fauna of sandy shores, resulting in the invertebrate exoskeleton fragmentation. Animal bioturbation and sediment ingestion also results in shell fragmentation.

After storms, or after some active wave action that might disrupt the seagrass beds and algal beds in the nearby subtidal environments, the plants living on nearby rocky shores, or the saltmarsh and mangroves from high-tidal environments, plant material is transported to the sandy shore and the beach may be littered at the high-tide mark by varying plant debris (flotsam and jetsam, or wrack). A range of macrofauna, such as crabs, or gastropods, or avifauna, forages among this material digesting it, or feeding on the organisms that inhabit it (Griffiths et al., 1983; McLachlan, 1985; Dugan et al., 2003; Lewis et al., 2007). This results in the breakdown of the plant material on the beach. Smaller organisms specialized for this wrack environment, such as amphipods, isopods, and meiofauna, also consume the finer-grained plant material, adding to the biological breakdown of plant and other organic matter stranded on the beach slope (Hayes, 1974; Poulin and Latham, 2002; Mews et al., 2006; Pelletier et al., 2011). In addition, particularly on wet beaches, there is microbial decomposition of organic matter on the beach and of organic matter shallowly buried at or below the water table of the beach (Jørgensen, 1982; Lovley and Phillips, 1986; Henriksen and Kemp, 1988).

Organic matter on and under beaches can also be broken down microbially (decayed). Some of this microbial decay is related to, fixed on, or mediated by structures and larger organisms in the environment (e.g., where microbes, meiofauna, and bacterial productivity are associated with tubes constructed by a polychaete; Alongi, 1985). Microbial decay involves the conversion of organic molecules to inorganic molecules and ions. This biotransformation is often subsumed under the term "mineralization." It is the process by which organic matter is "mineralized" (transformed to inorganic compounds, radicals, or elements) by fermenting, denitrifying, sulfate-reducing, and methane-producing bacteria (Jørgensen, 1982), some under anaerobic conditions and some under aerobic conditions. In estuarine beach environments, this takes place below an anaerobic water table or in the aerated vadose zone of the sandy beach. One major pathway of microbial decay, for instance, involves the breakdown of organic molecules and their oxidation by sulfate-reducing bacteria, which utilize the sulfate exogenically in the environment as the energy source for the decomposition, and in the process, organic matter is removed from the sandy beach environment.

Bacterial reduction of sulfate to sulfide is responsible for the oxidation of organic matter buried in sediments (Lovley and Phillips, 1986; Machel, 2001) that concomitantly results in pigmentation of light-colored sediments to grey or black. The sulfate ion is common in seawater, sediment, or in waters rich with decaying organic material, and sulfate-reducing bacteria are common in anaerobic environments where they utilize the sulfate ion as an electron donor, aiding in the degradation of organic materials. Sulfate reduction is the dominant terminal step in the biomediated mineralization processes of sulfate-rich sediments where the sulfate reducers inhibit the methanogens by competing for common substrates. This sulfate reduction is quantitatively important in the overall oxidation of organic matter (Barton and Fauque, 2009).

Various minerals can be precipitated by biomediation, the best known being iron sulfide (pyrite) and calcite. If Mn, Cu, and Zn are present in the environment, they also can produce sulfides. Generally, Fe is the most common transition metal cation in natural environments, so Fe sulfide (as pyrite) is the most common mineral. Precipitates of pyrite are commonly framboidal (framboids being small clusters of pyrite crystals resembling a raspberry <1 μm in size, but ranging from 0.5 to 40 μm in size; Wilkin et al., 1996; Sawlowlicz, 1993; Schieber, 2002). While organic-matter-rich sediments inherently tend to be black or dark grey, the fine-grained precipitated iron sulfide disseminated throughout the sediment as a result of bacterial decay of organic material similarly renders sediments to various shades of grey to black. Calcite can be precipitated in association with microbial activity, particularly in wet parts of a beach (e.g., that associated with cyanobacterial mats; Kremer et al., 2008).

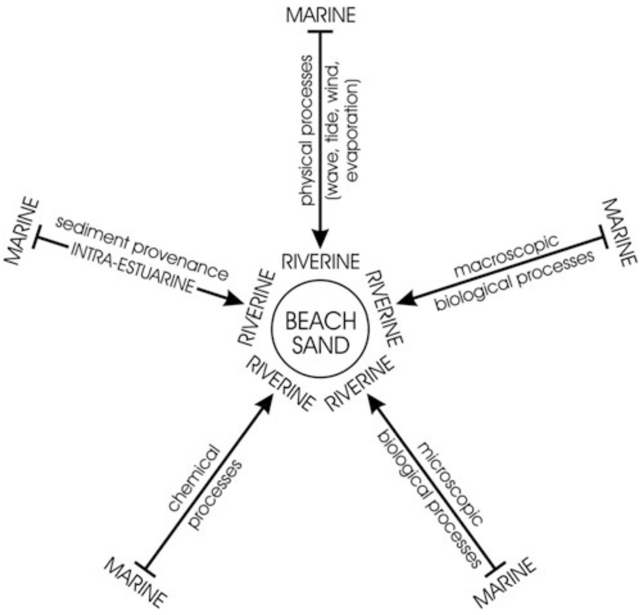
Microbial changes in the sediments leading to pyrite precipitation and sediment pigmentation carry with them hydrochemical changes in pH and redox conditions (i.e., Eh). Groundwaters under beaches often are anoxic and with the biomediated transformation taking place that result in the formation of sulfides; the groundwaters can become acidic and markedly oxygen depleted. From a generally alkaline state for seawater, the pH may decrease to 6.5 or 6.0 in the pore water of beach sediments. The Eh may be negative, with any decrease in Eh generally being related to the decrease in the dissolved oxygen in pore waters (Zobell, 1946; Haraguchi, 2012). Weakly acidic groundwater dissolves shell that is buried in beach sand such that shells lose their luster, appear corroded, or may be completely dissolved away. (In this context, the microbial activities that have been subsumed under "biological processes" grade into "chemical processes" in that the acidity of the groundwaters has increased as a result of biological activity, and this affects carbonate mineral solubility).

Ionic chemistry is also affected by microbial activity. The extent that sulfate and phosphate are microbially utilized in the environment, determining the depletion of sulfate ion and affecting phosphate concentrations, is an example of how biological (microbiological) processes affect ionic concentrations (e.g., Jansson, 1987; Lovley, 1991) and, vice versa, how the resulting ionic chemistry dictates development of precipitates (Berner and Raiswell, 1984). Such microbial activity also changes sulfide concentrations and, with precipitation of sulfide, changes the (transition) metal concentration in waters of species such as Fe and Mn.

In terms of chemical processes, estuaries in general, with their variety of environments ranging from deltas, shallow water sand platforms, tidal mud flats and sand flats, saltmarsh and mangroves, subaqueous shoals to deep water mud beds, among others, manifest a diversity of chemical processes and a variety of authigenic and diagenetic minerals, particularly where there is interaction between microbiota, anoxic sediments, muddy sediments, and different hydrochemical fields (cf., Cook, 1973; Cook and Mayo, 1980; Pye, 1984; Pye et al., 1990; Rasmussen et al., 1998; Hedges and Keil, 1999; Pirrie et al., 2000; Aller, 2004; Bush et al., 2004; Michalopoulos and Aller, 2004; Byrne et al., 2011). Sandy beaches and gravelly beaches, with their well-drained and more aerobic conditions and limited grain composition, however, represent the relatively low diversity end of the spectrum of chemical processes that occur in estuaries and present a more limited range of possible chemical processes and products.

The chemical processes on estuarine beaches are dissolution, precipitation of minerals (authigenesis), biomediated mineral precipitation, diagenesis of minerals, diagenetic structure development, sediment pigmentation (e.g., pyrite mottling), the effects of freshwater throughflow, and the oxidation of organic matter. The products of precipitation, often resulting in color mottling, in cemented laminae, or in development of nodules, commonly occur as diagenetic overprints on a primary sediment (i.e., either laminated, burrowed, or thoroughly bioturbated).

Note that in the context of precipitation of minerals, the concepts of authigenetic minerals and diagenetic minerals can overlap. The broad definition of authigenesis is of a mineral generated in situ. These would include mineral precipitates deposited on the estuary floor. At the mineral level for the process of mineral precipitation and/or alteration, the broad definition of diagenesis is the mineralogical alteration of one mineral to another. At the larger scale, e.g., at the sediment level where minerals are crystallizing in the sediment pore spaces lithifying the sediment, the cementing agents are considered by many authors to be diagenetic, but since they are crystallizing in situ, they are also considered by other authors to be authigenic. In this contribution, minerals precipitated from estuarine waters, regardless of whether they are open



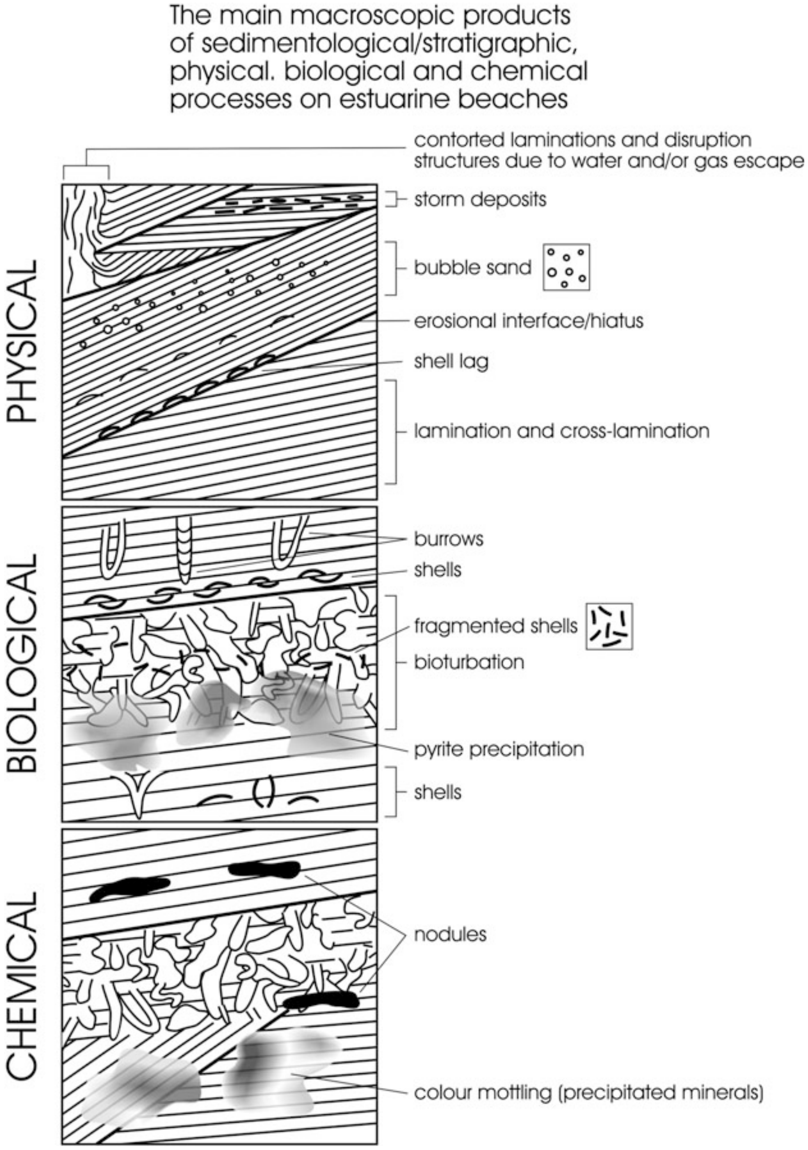
Beach Processes, Figure 9 The core of the diagram shows beach sediment. The influences and imprints on this beach sediment to generate variety in the lithology, structures, and products from physical, chemical, and biological processes are illustrated along five separate axes: (1) the provenance of the beach sediment with origin from river sources, marine sources, and intra-estuarine that influences primary lithology; (2) the gradient of physical processes operating on the beach (i.e., the gradient of hydrodynamic and aerodynamic conditions), grading from marine dominated near the estuary mouth to river dominated at/near the river mouth, to the effects of wind; (3) macro-biological processes, such as shell production, burrowing and bioturbation, environment-diagnostic shell assemblages, and shell fragmentation, grading from marine-dominated biotic effects near the estuary mouth to river-dominated biotic effects at/near the river mouth; (4) microbiological processes, such as biomediated mineralization, decay, and pyrite formation, grading from marine-dominated effects near the estuary mouth to river-dominated effects at/near the river mouth; and (5) chemical processes, such as solution, mineral precipitation, and diagenesis, specific to sites that are marine dominated near the estuary mouth grading to river dominated at/near the river mouth.

estuarine waters or intra-sediment pore waters, are authigenic minerals, and those formed by alteration of preexisting authigenic minerals or of sand grains are diagenetic minerals.

Dissolution of carbonates and precipitation of pyrite are the main chemical process on and under beaches. Dissolution of carbonates is a feature of chemical processes in estuaries (Abril et al., 2003). Under beaches, with acidic groundwaters, carbonate shells (composed of calcite, Mg calcite, or aragonite, or mixtures of these minerals) are corroded. They pass through various stages of corrosion (from lustrous shell, to shells lacking luster, to pitted shells) to ultimately dissolve away. The changing chemistry of the phreatic zone and vadose zone during high and low tides can result in the precipitation of minerals. In highly evaporative climates, with evaporation effected by solar radiation and/or winds, the surface of the beach wetted with saline pellicular water can evaporate to precipitate halite which forms a surface crust, termed salcrete (Yasso, 1966). Under a beach, particularly in tropical estuaries, depending on ionic concentrations, minerals such as aragonite, Mg calcite, and calcite may precipitate interstitially and cement the sand to varying degrees (cf., Bathurst, 1975), though carbonates can also precipitate in beach sand of temperate climates (Arrieta et al., 2011). In environments with alternating pH and with an appropriate Fe content and Eh in the groundwaters, Fe minerals can precipitate (Boyle et al., 1977). Authigenic minerals in freshwater environments in beaches under deltas and headwaters of estuaries include iron minerals and carbonate minerals, while those under beaches in marine salinities towards the ocean part of the estuary can be carbonate minerals. Mineral precipitation is manifest in beach sediments as lithification, color changes, mottling, or nodule development. Some of the biogeochemistry of estuaries and their sediments are described by Bianchi (2007).

Authigenic mineral precipitation can result from organic matter decomposition (Berner, 1981), with the mineral species related to sedimentary setting and location in the estuary. The main minerals precipitated are carbonates, sulfides, phosphates, and amorphous silica (Suess, 1979). The precipitation of minerals in the beach sand can result in the local development of diagenetic structures such as color mottling due to pyrite or to iron oxides, thin ferricrete sheets, ferricrete nodules, and carbonate nodules.

Freshwater through-flow on a beach changes the groundwater salinity from the prevailing marine or brackish salinity to lower salinity concentrations. This affects macrobiota



Beach Processes, Figure 10 Environment-specific processes and products as preserved geohistorically in the evolving stratigraphy under the beach. Three sections are diagrammatically illustrated: lithology and stratigraphy produced by physical processes, lithology and stratigraphy produced by biological processes, and lithology, stratigraphy, and overprints produced by chemical processes.

assemblages that are infaunal under the beach, the composition of microbiota, and some of the geochemical interactions. As described earlier, freshwater through-flow can occur along a broad interface or can be channelized. If freshwater seepage is in a broad front, its chemical effects will be along the interface of beach and upland, and will be shore-parallel. If channelized, the effects will be in specific locations along the beach. If the freshwater derives from upslope peat beds (as described earlier), the seepage will be more acidic than prevailing beach groundwaters and will result in dissolution of the more susceptible shells, alteration of macrofauna composition, and alteration of microbiota composition. These alteration effects will be along a broad front along the upper part of the beach or, if seepage is channelized, in local patches.

Freshwater may also flow over the beach and, by this process, the freshwater affects the hydrochemistry and geochemistry at the sites of entry onto the beach and sites of infiltration into the beach sand. Under the beach, organic matter can vary in content from scattered detritus to peat beds but, under aerial conditions and/or through-flow of freshwater, can oxidize. In time, in such situations, organic matter in upper parts of the beach is depleted by oxidation.

Summary

What may be viewed as a relatively simple system, the beach, underlain mainly by sand, can in fact frequently manifest a variable and spatially complex system. In an estuary, the beach, as a shoreline deposit, spans the range of environments from the river entrance to the marine estuarine mouth. Estuarine beaches, whether as a long continuous shoreline or as a discontinuous set of pocket beaches, traverse three major environments in terms of hydrodynamic setting, hydrochemistry, macroscopic biological setting, microscopic biological setting, and sediment provenance. As such, the beach in estuaries is subject to five major environmental gradients (Figure 9).

In terms of hydrodynamic setting, there is the part of the estuary located at/near the marine environment that is dominated by ocean waves and, to a lesser extent, by intra-estuarine wind waves, tides, and onshore winds; there is the central estuary dominated by intra-estuarine wind waves, wind, and lesser effects from tides, river current, and floods. There is the riverine part that is dominated by river currents, wind waves, wind, and, to a lesser extent, tides. In terms of hydrochemistry, there is the marine part that is dominated by marine salinities and the attendant effects on biota and their biological processes and marine authigenesis/diagenesis. There is the central estuary dominated by fluctuating salinities or brackish waters, the attendant effects on biota and their biological processes, and estuarine authigenesis/diagenesis. There is the riverine part that is dominated by freshwater and its attendant biological and authigenesis/diagenesis products. In terms of biological setting, there is the marine part that is dominated by marine assemblages. There is the central estuary dominated by euryhaline biota specialized for estuarine conditions. There is the riverine part that is dominated by freshwater biota. In terms of sediment provenance, the tripartite subdivision of estuaries is reflected in the exogenic sedimentary particles (those derived outside of the estuarine basin) in that there is a marine component dominantly towards the estuarine mouth, a mixed component in the central estuary, and a riverine component towards the river mouth. The tripartite subdivision of estuaries also is reflected in the composition of endogenic sedimentary particles and sediment types (those derived inside the estuarine basin) in that peat and bioclasts (shells) are diagnostic of freshwater parts of the estuary (though peat is not within the beach environment; its presence leeward of beaches adds hydrochemical complexity to freshwater seepages). As such, the beaches of the estuary provide a framework to viewing and studying beach processes across the longitudinal range of estuarine environmental variability.

This variability of beach setting within the estuary and the beach processes relative to beach setting is expressed geomorphologically, stratigraphically, lithologically, biologically, and authigenically/diagenetically.

At smaller scales, the physical, biological, and chemical processes operating on beaches result in environment-specific features such as sedimentary structures, specific suites of lithology such as laminated sand, or concentrations of shell and rock gravel, shell lenses, burrow structures, bioturbation, and chemical products. These environment-specific processes and products are preserved geohistorically in the evolving stratigraphy under the estuarine beach (Figure 10).

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Cross-references

Evaporation and Transpiration
Mineralization
Stratigraphy of Estuaries
Tidal Flat Salinity Gradient

BENTHIC ECOLOGY

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Definition

Benthic ecology is a subdiscipline of ecology that focuses on organisms living in or on the bottom of a water body (e.g., an estuary) and the interactions among these organisms and with their surrounding environment.

Expanded definition

E. P. Odum (1971) defined ecology as "the science of interrelations between living organisms and their environment." The word "benthic" is derived from "benthos" defined as the bottom of a water body and/or the organisms living on the bottom of the water body (Websters II New Riverside University Dictionary, 1994). Thus, benthic ecology encompasses the study of the interrelations among organisms living in or on the bottom of a water body (e.g., an estuary) and their interactions with the surrounding environment. Benthic organisms include megafauna (>>>1 mm) such as bottom-oriented fish, crustaceans, and echinoderms living at or just above the sediment surface; macrofauna (>0.5 or 1 mm) such as polychaetes, molluscs, anemones, and arthropods living on top of or within the sediment; meiofauna (0.1 mm to 0.5 or 1 mm) such as nematodes, oligochaetes, and harpacticoid copepods living in sediment interstices (spaces between grains of sediment); and microfauna (<0.1 mm) such as protozoans (Miller, 2004; Levinton, 2009). Benthic organisms also include benthic diatoms, attached algae, kelp, and seagrass, as well as the associated bottom microbial community. In addition to biological and community interactions, benthic ecology includes chemical transformation and physical modifications of the environment as mediated by the benthos and the effect of these transformations and modifications on associated ecological communities (Levinton, 2009; Day et al., 2012). For example, benthic organisms can influence nutrient cycling and hydrodynamics through their activities (e.g., bioturbation, reef building, seagrass bed expansion), while hydrodynamics, depth, and other environmental factors can act to structure benthic communities. Benthic ecology examines a wide variety of organisms and habitats from the intertidal to the deepest bottom of the ocean. The science of benthic ecosystems is as diverse and interconnected as the seafloor itself.

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Cross-references

Biogenic Sedimentary Structures
Infauna
Macrofauna
Meiofauna
Microphytobenthos
Nutrient Dynamics
Oyster Reef
Soft Sediment Communities

BIOACCUMULATION

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Definition

The accumulation of contaminants, pollutants, and/or their metabolites into animal or plant tissues along a period of time which typically represents the degree of exposure of the individual to the chemical element, species, or compound present in the environment where it lives.

Fundamentals

Contaminants, pollutants, and their environmental metabolites (chemical agents) can be found in all the different biogeochemical compartments (air, water, soil/sediment). These agents can be both organic and inorganic. The accumulation of a chemical agent by living organisms depends on the fraction of it that is chemically and physically available to the biota. The chemical form of contaminants and pollutants present in the environment will define the pathway, higher or lower uptake of the chemical agent by the organisms, and consequently its bioaccumulation. Bioaccumulation is therefore a natural phenomenon that becomes even more relevant when the chemical element or compound in question is distributed in the environment in concentrations above its natural level or, in the case of synthetic compounds, is present even in minimum amounts (Clark, 2001).

Contaminants and pollutants are present in the air, soil/sediments, and water of every environment on the surface of the Earth, where they arrive via direct release or short- to long-range transportation. The biota is then inevitably exposed to environmental contaminants and pollutants released by every economic and social activity known. All biological groups present will, in theory, be exposed (Chen et al., 2012; Melwani et al., 2013). However, their susceptibilities vary according to taxonomic group and ecological function. This exposure means that there will be (in)direct contact of the chemical with the individuals and therefore biochemical interaction between them. For an element or chemical compound to be bioaccumulated, it must be first incorporated via one of the biological processes of respiration, feeding/digestion, or skin absorption (Clark, 2001). Through respiration, contaminated water or air enters in contact with tissues specialized in efficient gaseous exchanges (i.e., gills or lungs). This facilitates the passage of the contaminant through cell membranes and vascular walls, from which it gains the circulatory system and is distributed throughout the body. The most common (and efficient) way for an aquatic animal or plant to assimilate and accumulate elements and compounds in their tissues is via feeding and digestion of contaminated food sources (Chen et al., 2012; Melwani et al., 2013). If food is contaminated with toxic/harmful chemicals, it can, during digestion, release then in the digestive tract. Therefore, the pollutant is absorbed through the intestine walls, together with nutrients, and also falls into the circulatory system to be distributed. Accumulation of such elements and chemicals occurs preferentially in the different tissues of plants and animals. Some tissues have functions, structures, and compositions more prone to the accumulation of different elements and compounds. Some examples are the liver, kidney, brain, and fat tissues.

Bioaccumulation is, to a certain extent, reversible. If exposure ceases, metabolism can eventually excrete the accumulated chemical back to the environment. Bioaccumulation is a biological phenomenon related to each individual and can be examined at tissue level when necessary. It is worthy of note that the bioaccumulation concept refers to the tendency of a certain chemical agent to be accumulated by the biota through all sources of ambient, i.e., by water and food. Bioaccumulation differs from bioconcentration since bioconcentration refers to the tendency of a certain chemical agent to be accumulated by biota only from the water.

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Cross-references

Bioavailability
Biomagnification

BIOAVAILABILITY

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Definition

An ecological property presented by chemical elements and compounds in the environment (chemical agents) that determines if they will be more, or less, efficiently assimilated by the biota that enters in contact (is exposed to) with them.

Fundamentals

The bioavailability of a chemical corresponds to the amount of the element that can be absorbed by the living organisms from the environment (Chen et al., 2012). It is a parameter directly associated with the chemical species of this element present in each biogeochemical compartment (Hoffman et al., 2012; Sinoir et al., 2012). This characteristic of chemical agents in the environment can then be time and space dependent as water quality changes along ecological gradients and seasons. Bioavailability is a descriptive property of chemical elements, chemical species, and compounds determined by a relatively complex group of factors, indicating their own chemical characteristics, the chemical and physical characteristics of the medium they are distributed in, metabolism rates, and the type of exposure the biota has (skin, breathing, feeding). Bioavailability can increase or decrease according to the combination of these factors (Chen et al., 2012; Hoffman et al., 2012; Sinoir et al., 2012). The same chemical can have its bioavailability change with the presence and concentration of Cl^- ions, as in seawater, for example, or due to changes in water temperature, organic particulate loads, or dissolved oxygen. In the same way, bioavailability varies if an element changes its oxidative state (e.g., Cr^{+3} vs. Cr^{+6}). Chemical agents must be bioavailable in the environment in order to be assimilated, bioaccumulated, and possibly biomagnified in the biotic compartment. Usually, once a chemical agent enters the trophic web, it becomes readily available for all its subsequent levels. Contaminated food is a common form of bioavailability (Chen et al., 2012).

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Cross-references

Bioaccumulation
Biomagnification

BIOCHEMICAL OXYGEN DEMAND

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Synonyms

Biological oxygen demand

Definition

Biochemical oxygen demand (BOD) is the amount of molecular oxygen required to oxidize organic matter into a stable inorganic form through aerobic microbial decomposition.

Description

The biochemical oxygen demand (BOD) is determined by empirical testing in which standardized laboratory procedures yield the relative oxygen requirements of wastewaters, effluents, and polluted waters (APHA, 1999). Five days at 20 °C is often used to oxidize the carbonaceous organic matter, being referred to as "$BOD_{5,\ 20}$."

Importance: This test is important for pollution control. Heterotrophic microbial metabolism transforms biodegradable organic compounds into stable or mineralized end products, including water, carbon dioxide, sulfates, phosphates, ammonia, and nitrates. The BOD test is widely used to assess the level of domestic or industrial sewage pollution discharged in estuaries. Dissolved oxygen (DO) consumption by bacteria during organic matter regeneration is an indirect indicator of estuarine water quality.

Impacts: This process can consume dissolved oxygen (DO) faster than the atmosphere can supply it through diffusion or the autotrophic community (algae, cyanobacteria, and macrophytes) can produce it. Decomposition of organic matter may fully deplete oxygen from the water (Kennish, 1997). Since less dissolved oxygen is available in the water, fishes and other aquatic organisms may not survive.

Analytical Method: This method of determination is based on dissolved oxygen (DO) measurements. In the first measurement, two or more bottles of water samples are collected. The oxygen is measured in sample 1 on the first day, and 5 days later, it is measured in sample 2. Next, the BOD is calculated by subtracting the results. The BOD may reach 7 mg/l in productive estuaries compared with values higher than 7 mg/l in polluted estuaries (APHA, 1999).

Estuarine Dynamics: Aquatic plant photosynthesis raises the DO during the day, and respiration lowers it at night in estuaries (Day et al., 2013). This leads to a large diurnal variation in the availability of dissolved oxygen. Meteorological variations and estuarine dynamics have a large influence on the dilution and transport of organic matter. During high tide, more oxygenated coastal waters are encountered, increasing the availability of dissolved oxygen. The lower dissolved oxygen levels are generally found in lower-salinity regions in the upper estuary. When the runoff is high, more freshwater enters the estuary often transporting higher loads of organic wastes into the system.

Limitation: BOD measures the pollution potential. It is an indirect quantification of the potential impact, not a direct measurement of such impact. $BOD_{5,\ 20}$ does not detect nonbiodegradable matter. It does not consider toxicity, nor does it inhibit effects from materials on microbial activity because it only measures the oxygen consumed in a standardized test. The BOD is a subset of the chemical oxygen demand (COD).

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Cross-references

Dissolved Oxygen
Eutrophication
Heterotrophic
Nonpoint Source Pollution
Oxygen Depletion

BIOGENIC SEDIMENTARY STRUCTURES

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Synonyms

Ichnofossils; Trace fossils

Definition

Biogenic sedimentary structures are evidence of organism–substrate interactions preserved in rocks and sediments, including those recorded in estuarine environments. Their study is termed "paleoichnology" (from the Greek *palaios* = old, ancient and *ichnos* = a trace, a track), whereas similar studies in modern sediments are referred to as "neoichnology." Markings that do not reflect the behavior of organisms (e.g., marks made by the shells of dead mollusks passively transported on the seafloor by waves and/or currents) are excluded from the trace fossils. In addition, biogenic sedimentary structures do not include body fossils (direct remains, such as shells, bones, teeth, etc.) or molds of organism bodies.

Introduction

Organisms that have adopted endobenthic or epibenthic modes of life produce biogenic sedimentary structures by "disturbing" the substrate. The number of biogenic sedimentary structures is vast, and various authors have proposed subdividing them into component groups to better define their significance (e.g., Frey, 1971, 1973; Frey and Pemberton, 1984; Pemberton et al., 1992; Bromley, 1996). Four major categories of structures produced by the activities of organisms are generally accepted:

- Bioturbation structures, which reflect the disruption by organisms of biogenic and physical stratification features or sediment fabrics, include tracks, trails, burrows, and similar structures.
- Biostratification structures, which consist of stratification features imparted by organism activities, include certain stromatolites, biogenic graded bedding, byssal mats, and similar elements.
- Biodepositional structures, which reflect the production or concentration of sediments, include coprolites, fecal pellets, pseudofeces, and fecal castings.
- Bioerosion structures, which are mechanically or biochemically produced by organisms in rigid substrates, include borings, rasps and scrapes, bites, drill holes, and related traces.

These categories, and others proposed in the literature, are not exhaustive because the divisions among the various categories are vague. For example, plant–arthropod interactions may be revealed by biogenic structures preserved in wood, leaves, and seeds, which are not strictly rigid substrates comparable to rockgrounds or hardgrounds.

Consequently, the appropriate placement of this group in one category or another is unclear. Egg cases are not usually described as trace fossils, but eggs can be preserved within a fossil nest, providing direct evidence of reproductive behavior. In that sense, they fall within the realm of paleoichnology and are often placed under "other evidence of activity."

The conceptual framework

The importance of paleoichnology in traditional fields such as paleontology, paleoecology, sedimentology, and stratigraphy derives from the peculiarities of trace fossils, which reflect both their mode of formation and their taphonomic histories. Unfortunately, the limitations of trace fossil also arise from these basic characteristics ("ichnological principles" of Bromley and Fürsich 1980; Ekdale et al., 1984; Bromley, 1996; Pemberton et al., 2001). The examples are as follows: (1) A long stratigraphic range can limit the use of trace fossils in biostratigraphy. (2) A narrow environmental range may reflect similar responses of tracemakers to a given set of paleoecological parameters, and therefore, biogenic sedimentary structures tend to occur preferentially in certain depositional environments. The combination of (1) and (2) greatly facilitates the comparison of rocks of different ages formed in similar depositional settings. (3) The rarity of secondary displacement means that trace fossils are very rarely transported and therefore represent the original environmental position of the tracemakers (i.e., they are in situ fossils). This characteristic reveals the strength of ichnofossils in paleoecological reconstruction. (4) Non-preservable soft-bodied trace producers must be considered since many biogenic sedimentary structures record the activities of soft-bodied organisms that are usually not preserved because they lack hard parts. This fact highlights once again the difference between trace and body fossils. (5) Peculiar occurrences in otherwise nonfossiliferous sediments are very often the result of diagenetic processes that, on the one hand, enhance the potential preservation of trace fossils and, on the other, may obliterate the tests and shells of body fossils. (6) The same individual or species of organism may produce different structures corresponding to different behavior patterns; this characteristic can produce compound traces, where intergradational forms reflect the transition from one behavior to another. (7) The same individual may produce different biogenic structures, reflecting the same behavior on different substrates; this peculiarity is attributable to variability in the substrate conditions in terms of the degree of consistency, grain size, and stratal position. (8) Conversely, identical (or very similar) structures can be produced by systematically different organisms, where their behavior is similar; this peculiarity makes it impossible to establish a one-to-one relationship between tracemakers and biogenic structures. (9) A single structure may reflect the activity of two or more organisms, living together or in successive times, within the substrate (the "composite" traces of Pickerill, 1994). Paleoenvironmental research based on these characteristics represents the majority of contemporary ichnological studies and applications.

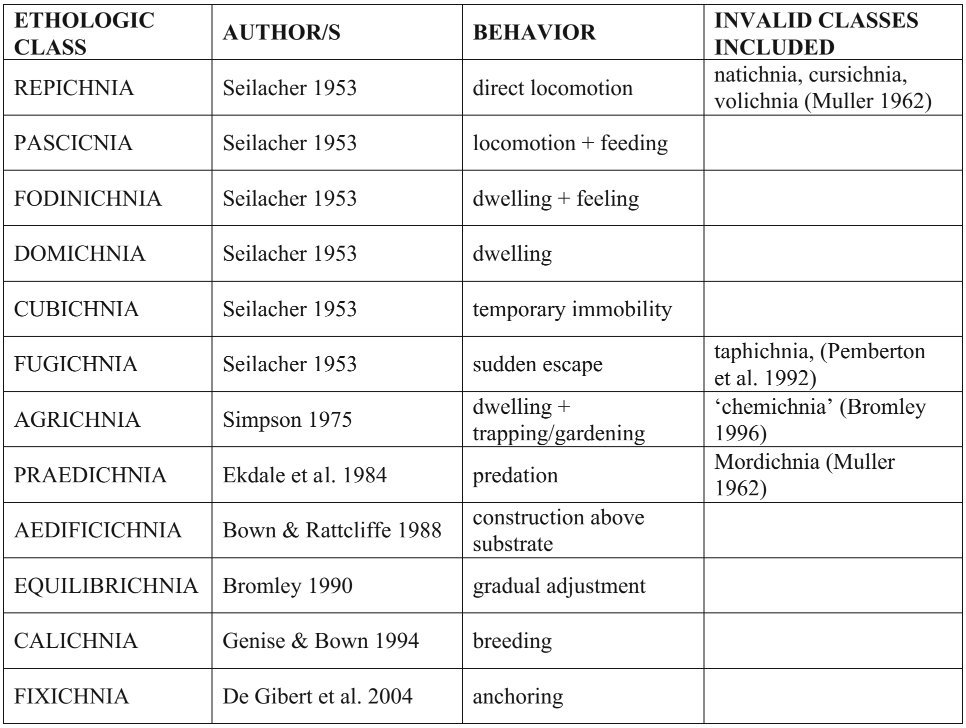
Naming biogenic sedimentary structures

The use a formal taxonomy by ichnologists must accommodate the many difficulties that arise from both the historical background and the intrinsic nature of ichnofossils. In the early years of paleoichnology, a large number of invertebrate trace fossils were named and described as the remains of algae or other organisms (Age of Fucoids by Osgood, 1975). However, based on the priority law, many of these names are taxonomically valid, such as *Cruziana*, *Zoophycos*, and *Chondrites* erected as algae and *Nereites* as worms.

The 1964 edition of the International Code of Zoological Nomenclature (ICZN) ruled that trace fossil names erected after 1930 were to be accompanied by a statement on the identification of the tracemakers. Because fulfilling that requirement is essentially impossible, all post-1930 trace fossil names (ichnotaxa) were formally unavailable, whereas the pre-1930 taxa retained their valid names but were treated on the same basis as body fossils. This is considered the beginning of the Dark Age of Ichnotaxonomy (Bromley, 1996). Thanks to the long-lasting and determined activities of ichnologists and exhaustive scientific debate, ichnofossils have finally been bounded by the ICZN in 1985. The 4th edition of the ICZN (1999) includes in the "work of animals" all trace fossils. This means that animal, protistan, plant, and fungal trace fossils are considered in exactly the same way as zoological taxa in terms of the availability and validity of their names. However, they are called "ichnotaxa" ("ichnogenera" and "ichnospecies") to distinguish them clearly from true biotaxa. The significant departures with respect to body fossils (see also the previous section) further complicate trace fossil taxonomy. For example, according to the ICZN, only fossil specimens should be named, which prevents ichnologists erecting ichnotaxa based on recent biogenic structures that might be assigned very often to their producers on a case-by-case basis. Under these circumstances, some authors prefer to name the tracemaker associated with the recent structure, whereas others opt to use the prefix "incipient" before the ichnotaxon (e.g., incipient *Thalassinoides*) (Bromley and Fürsich, 1980). A separate code for naming trace fossils, as proposed by Sarjeant and Kennedy (1973), might be a possible alternative to circumvent the aforementioned difficulties, but this prospect has never gained legal standing.

Classification of trace fossils

Although the recent ICZN explicitly encompasses ichnofamilies, there is no true ichnotaxonomic superstructure above the rank of ichnogenus, and trace fossils can be grouped together in several ways. Traditionally, the most



ETHOLOGIC CLASS	AUTHOR/S	BEHAVIOR	INVALID CLASSES INCLUDED
REPICHNIA	Seilacher 1953	direct locomotion	natichnia, cursichnia, volichnia (Muller 1962)
PASCICNIA	Seilacher 1953	locomotion + feeding	
FODINICHNIA	Seilacher 1953	dwelling + feeling	
DOMICHNIA	Seilacher 1953	dwelling	
CUBICHNIA	Seilacher 1953	temporary immobility	
FUGICHNIA	Seilacher 1953	sudden escape	taphichnia, (Pemberton et al. 1992)
AGRICHNIA	Simpson 1975	dwelling + trapping/gardening	'chemichnia' (Bromley 1996)
PRAEDICHNIA	Ekdale et al. 1984	predation	Mordichnia (Muller 1962)
AEDIFICICHNIA	Bown & Rattcliffe 1988	construction above substrate	
EQUILIBRICHNIA	Bromley 1990	gradual adjustment	
CALICHNIA	Genise & Bown 1994	breeding	
FIXICHNIA	De Gibert et al. 2004	anchoring	

Biogenic Sedimentary Structures, Figure 1 List of acceptable ethological classes according to De Gibert et al. (2004) (Modified).

important classifications include preservational, phylogenetic, and behavioral schemes, although virtually all classifications are to some extent genetic because they presuppose that the structures were produced biogenically.

The preservational aspect takes into account two main facets: (1) the physiochemical processes of preservation and alteration and (2) the toponomy (or stratinomy). The former facet falls within the realm of diagenesis, which is of paramount importance in trace fossil preservation; nevertheless, no classification based on diagenetic features is yet available. The latter focuses on the description and classification of biogenic structures in terms of their mode of preservation and occurrence. Toponomic schemes have been devised by various authors (e.g., Simpson, 1957; Seilacher, 1964; Martinsson, 1970), and most of these relate to the position of a trace fossil to the main casting medium. The schemes of Martinsson (1970) and Seilacher (1964) have a lot in common and have gained the greatest acceptance.

Phylogenetic classification attempts to establish a correspondence between a trace fossil and the potential producer, a fascinating target but very difficult to reach. This is because ichnofossils usually reflect animal behavior and reflect their anatomy or morphology to a much smaller extent. As stated in the previous section, a single taxon may construct different biogenic structures, and conversely, identical (or very similar) structures may be made by different taxa. It is sometimes possible to match tracemaker and trace fossil, but this problem must be approached with caution, bearing in mind that generalizations should be avoided and each occurrence of a given ichnofossil must be treated on an individual basis.

Above all, trace fossils are good indicators of the behavior of animals, and it is therefore not surprising that ethological classification has been extremely successful. The original scheme proposed by Seilacher (1953), based on five categories, has been progressively modified and enlarged by various authors; among them are Frey (1973), Ekdale et al. (1984), Ekdale (1985), and Bromley (1996). Frey and Pemberton (1985) suggested that categories be restricted in number and that new proposals are only justified if they are well founded on new behaviors. Today, a dozen categories are generally accepted (Figure 1), although it must be emphasized that the overlap among groupings is unavoidable, reflecting the intergradation inherent in nature.

Ichnofacies model

According to the concept proposed by Seilacher (1964, 1967), ichnofacies are trace fossil assemblages that recur through long intervals of time and are typical of a given set of environmental conditions (Frey and Pemberton, 1985). Ichnofacies are named after a characteristic ichnogenus and may be recognized even if the namesake form is absent. The classic marine ichnofacies, those named for *Nereites*, *Zoophycos*, *Cruziana*, and *Skolithos* by Seilacher (1967), were originally based on the fact that many of the parameters controlling the distributions of the tracemakers tend to change progressively with increasing depth. Because these bathymetrical relationships are potentially very valuable for paleoenvironmental reconstruction, the ichnofacies sequence has long been regarded as a relative paleobathymeter. Today, it is well known that ichnofacies are essential for the reconstruction of depositional settings, but paleobathymetry constitutes only one aspect because the distribution of tracemakers is controlled by a number of interrelated ecological/sedimentological parameters, including the sedimentation rate, substrate grain size, salinity, oxygen level, turbidity, light, temperature, and water energy (Pemberton et al., 1992). Because these parameters may occur at specific water depths, it should not be surprising to find nearshore assemblages in offshore sediments, and vice versa. For example, the *Skolithos* ichnofacies, which is typical of nearshore settings, may occur in offshore tempestites or deep-marine turbidites, and the *Cruziana* ichnofacies, which is typical of lower shoreface to offshore deposits, may also be present in shallower settings, such as intertidal flats on tide-influenced shorelines (Miller, 2007).

In recent decades, ichnologists have proposed many new ichnofacies from continental and marine environments, some of which are considered well founded, some are retained as mutually equivalent, and still others are considered invalid categories (see Buatois and Mangano, 2011 for a detailed discussion). In a recent paper, Knaust and Bromley (2012) recognized 14 formally defined ichnofacies among those that conform to Seilacher's paradigm. Five of them encompass the marine to marginal-marine softground substrates: *Psilonichnus*, *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites*. Three are regarded as substrate-controlled (omission) ichnofacies and are very useful for delineating surfaces, with sequence-stratigraphic implications: *Glossifungites*, *Trypanites*, and *Teredolites*. Six ichnofacies encompass the continental realm: *Scoyenia*, *Mermia*, *Coprinisphaera*, *Termitichnus*, *Celliforma*, and *Octopodichnus–Entradichnus*.

Ichnology and estuarine systems

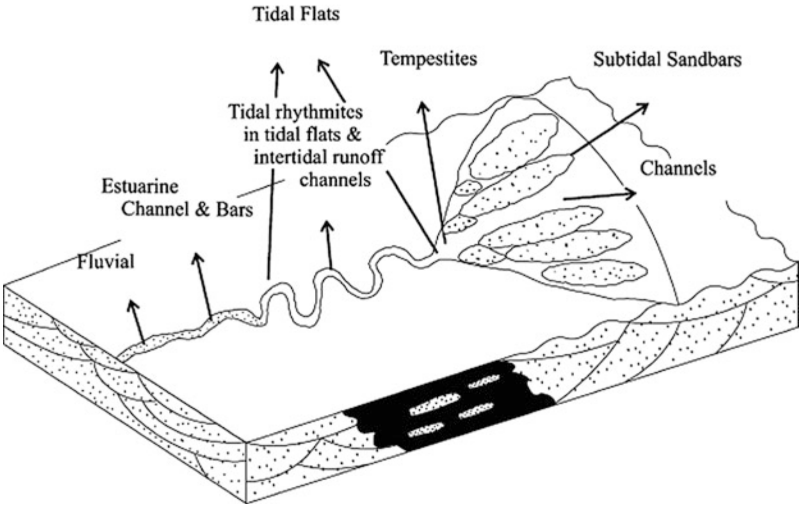
According to Dalrymple et al. (1992), an estuary is "the seaward portion of a drowned valley system which receives sediments from both fluvial and marine sources and which contains facies influenced by tide, wave, and fluvial processes. The estuary is considered to extend from the landward limit of the tidal facies at its head to the seaward limit of the coastal facies at its head." All of these environments are characterized by rapid perturbations and typically by salinity changes, but also other ecological controls may generate stressful conditions that strongly affect the benthic biota. Ichnology has provided a powerful tool with which to identify these depositional settings by recognizing anomalous ichnofaunas (typical of marginal-marine brackish conditions), which display less variety and a lower abundance of forms than are found in fully marine environments (Buatois and Mangano, 2011).

Dalrymple et al. (1992) also classified estuaries into two main groups: wave-dominated and tide-dominated systems. In the former, there is a well-structured spatial distribution of energy. Three main zones are recognized: (1) the bay-head delta, a high-energy inner zone dominated by river processes; (2) the central basin, characterized by the mixing of marine energy and fluvial currents; and (3) the estuary mouth, dominated by marine processes.

Bay-head deltas are strongly stressful environments with unbioturbated or sparsely bioturbated deposits showing very low ichnodiversity, which is dominated by the dwelling structures of suspension feeders. In terms of ichnofacies, this zone mainly contains the *Skolithos* ichnofacies, followed by an impoverished *Cruziana* ichnofacies. Central basin settings show a combination of stress agents (brackish water, water turbidity, and oxygen depletion) associated with a low degree of bioturbation, although bioturbation may be moderate in some beds. The ichnofauna reflects the dominance of unspecialized deposit feeders and is characterized by the depauperate *Cruziana* ichnofacies, with minor contributions from the *Skolithos* ichnofacies. Although the estuary-mouth complex is highly variable, in terms of both trace concentrations and depositional settings, the bioturbation intensity and ichnodiversity generally range from moderate to intense (higher than in the previous zones), reflecting near-normal marine salinities; mixed depauperate *Cruziana* and *Skolithos* ichnofacies are present. In summary, trace fossil distributions along wave-dominated estuaries are mainly controlled by the salinity gradient, varying from the brackish waters of the inner zone to the near-open-marine salinity of the outer estuary.

Tide-dominated estuaries are characterized by a less pronounced distribution of energy along the estuarine valley because of the migration of intertidal runoff channels. Nevertheless, the following zones are recognized: (1) the upper estuary, a fluvio-estuarine transition zone characterized by freshwater conditions; (2) the middle estuary, meandering to straight tidal channels, tidal flats, and salt marshes; and (3) the lower estuary, comprising the outer zone with elongate subtidal sandbars, channels, and tidal flats (Figure 2).

Arthropods are the dominant tracemakers in the typical freshwater/terrestrial biotas of upper estuaries, and their activities are recorded in tidal rhythmites, which display a mixture of the elements of continental depauperate *Scoyenia* and *Mermia* ichnofacies. Farther towards the sea, the middle estuary commonly has brackish-water conditions. To different degrees in a number of settings, tidal flat deposits are dissected by a network of meandering tidal channels and creeks that migrate across the intertidal zone, producing lateral accretions in point bars (Dalrymple, 1992); the substrate-controlled *Glossifungites* ichnofacies may occur, corresponding to coplanar surfaces (incision during a sea-level fall and subsequent transgressive erosion), whereas mixed impoverished *Cruziana* and *Skolithos* ichnofacies record



Biogenic Sedimentary Structures, Figure 2 Reconstruction of a tide-dominated estuary from Santa Rosita Formation (Cambriano, Argentina) (From Buatois and Mangano, 2003, modified).

the activities of opportunistic communities that developed understressed conditions (brackish waters) in transgressive sediments overlying coplanar surfaces. The outer zone of the estuary displays fully or almost fully marine conditions, and the possible trace assemblages reflect the activities of organisms that include deposit feeders, predators, and suspension feeders in intertidal to subtidal settings. However, high-energy and rapidly migrating bedforms generally preclude the establishment of a mobile epifaunal and/or shallow infaunal biota (Buatois and Mangano, 2003).

Summary

Trace fossils can be retained as both paleontological and sedimentological entities because they represent not only the morphology and ethology of the tracemakers but also the physical characteristics of the substrate on which the tracemakers lived. In this sense, biogenic sedimentary structures can make meaningful contributions to numerous research fields in the earth sciences, with an integrated approach that articulates ichnological information with other sources of data. This is a good approach to reconstruct ancient depositional settings, which notably takes advantage of the integration of both sedimentological/stratigraphic and ichnological data. In marginal-marine environments (including estuaries), trace fossil assemblages play a major role in distinguishing open-marine, brackish-water, and freshwater/terrestrial deposits.

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Cross-references

Deltas
Estuarine Geomorphology
River-dominated Estuary
Sandflat
Soft Sediment Communities
Tidal Flat

BIOGENOUS SEDIMENT

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Synonyms

Biogenic sediments; Shelly sediments

Definition

Biogenous sediments are broadly defined as sediments consisting of large amounts of skeletal remains of macroscopic and microscopic organisms or remains of organic production.

Description

Estuarine sediments are derived from a number of sources including the watershed, continental shelf, atmosphere, erosion of the estuarine margins and bottom, and biotic activity within the estuary. The dominance of one sediment source depends on the interaction between the type and the quantities of available components. Terrigenous sediments such as sand and clay may be linked to riverine contributions, whereas biogenous sediments seem coupled to the lower estuary and the marine estuarine morphodynamic domains (Nichols and Biggs, 1985; Nichols et al., 1991). Biogenous sediments are formed from the insoluble remains of living organisms, such as shells, bones, and teeth (Davis, 1985; Cronin et al., 2003). They can be grouped in three major categories: calcareous biogenous sediments, siliceous biogenous sediments, and phosphatic biogenous sediments. The first group includes calcareous shells or remains of benthic organisms (mainly molluscs, snails, ostracodes, or foraminifera). The second group includes sponge spicules or diatoms and radiolarian remains, and finally, the last group includes fish scales and bones or organic matter formed in situ. These kinds of sediments are often used as a proxy of the human-induced changes in estuarine sedimentation (Colman and Bratton, 2003). Cronin (2007) shows that in estuarine environments such as the Chesapeake Bay diatoms can constitute 5–10 % of dry sediment, whereas calcareous shelly sediments can comprise as much a 5 %.

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Cross-references

Sediment Grain Size
Shell Beds

BIOINDICATORS

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Synonyms

Biomonitors; Ecological indicators; Environmental indicators

Definition

Bioindicators – biological attributes or characters of estuarine-associated organisms that are objectively or subjectively assessed to evaluate the conditions, status, or trends in the estuarine environment.

A broad range of biological attributes have been used as bioindicators in estuaries (Bortone, 2005). These biological attributes or characteristics can be selected from all levels of biological organization (with increasing order of specificity) from the community, population, and individual levels of biological organization at the individual level of organization; these finer aspects of biological organization include bioenergetics, reproductive, pathological, histological, physiological, immunological, genetic, biochemical, and molecular features. Generally, attributes at the higher levels of organization are more ecologically relevant but are of low specificity and sensitivity. Oppositely, attributes from lower levels of biological organization are less relevant ecologically but are of high specificity and sensitivity (Adams, 2002).

When selecting a biological indicator to assess estuaries, it is important to consider the time and space scale of response that would be useful for a particular situation (Bortone, 2008). For example, long-term (decadal), gradual changes in mean salinity within an estuary can be assessed using species distributions, their abundance, or community composition and diversity. Short-term changes in salinity might be better assessed using the physiological response (lethal dose or local movements) of individuals within a species. More specifically, changes to an individual's ability to osmoregulate (blood chemistry) would be a more immediate biological indicator of a situation of altered salinity. It is often preferable to measure several attributes in any given situation to serve as a corroboration and to allow assessment at several time and space units (Bortone et al., 2005).

Bioindicators can be either passive (e.g., observing growth) or active (extraction of tissues for chemical analysis). Not mutually exclusively, bioindicators can be sensitive to direct environmental stress (biochemical, physiological) or indirect stressors such as environmental changes that affect trophic and/or behavioral changes (Adams, 2005).

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BIOMAGNIFICATION

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Definition

Biomagnification is the process where chemical compounds are transferred from food to an organism resulting in higher concentrations compared with the source. It occurs when a chemical element or compound (chemical agent) then presents higher concentrations in the tissues of organisms as they occupy higher levels in the trophic web.

Fundamentals

Biomagnification is a phenomenon that occurs across different levels of the same trophic web and can involve whole populations and communities (Clark, 2001). It was first discovered when California brown pelicans were observed to have poor chick recruitment year to year due to the presence of $\sum$DDT in their tissues which is an endocrine disruptor interferring with Calcium fixation, and consequently egg shell's thickness and hardness. The $\sum$DDT was found to have originated in their main food resource (anchovies) which had fed plankton contaminated with $\sum$DDT from the Columbia River estuary that crossed pesticide-sprinkled agricultural areas. $\sum$DDT increased exponentially up to the female pelicans. Most organochlorines (e.g., PCBs) are now recognized as capable of undergoing biomagnification in aquatic environments. This phenomenon is closely related to polar food webs where large carnivores quickly acquire elevated concentrations of organic pollutants in their tissues that compromise their survival and progeny. Mercury and especially its organic forms also biomagnify in aquatic food webs (Clark, 2001; Costa et al., 2012). It is an ecological and analytical challenge to identify and quantitatively describe the biomagnification process across a given food web (Cardwell et al., 2013). Ideally, the trophic relations among the components of the food web should be well known, and analysis should be made in tissues from linked trophic positions. The study of the trophic transfer process along the food web is a useful tool to assess the biomagnification of trace elements from one trophic link to another (Cardwell et al., 2013). Also, biomagnification should preferably be confirmed by other analyses such as δ^{13}C and δ^{15}N isotopes.

One way to compare biomagnification across food webs is to plot the linear relationships between log chemical compound and δ^{15}N and use the regression slope (β) as a measure of the biomagnification power. The biomagnification power of a chemical compound is assessed using regression slope (β) of the simple linear regression, including all organisms of the food web possible: log[chemical compound] $= \beta^*(\delta^{15}\text{N}) + a$, where a is the y-intercept. For mercury, the regression slope, i.e., biomagnification power, values range from 0.10 to 0.28 for tropical, temperate, and arctic marine and lacustrine ecosystems (Costa et al., 2012). This high range reflects the different composition of the food webs and/or differences in growth rate of organisms. On the other hand, the simple linear regression (log[chemical compound] $= \beta^*(\delta^{15}\text{N}) + a$), including all organisms of the food web, is a useful tool to compare across habitats (pelagic, demersal, benthic) or ecological functions of the trophic web. It also assesses the bioavailability of a chemical compound to each organism. For example, the biomagnification power is higher for pelagic and benthopelagic species than for benthic species. It suggests that the chemical compound is readily available to the base of the benthic food chain but that trophic transfer is more efficient in pelagic and benthopelagic food chains (Costa et al., 2012). As a top consumer, human populations can often be involved in this environmental process when ingesting large predatory fish from both freshwater and marine origins. This constitutes a public health issue and must be seriously addressed by authorities (Costa et al., 2012).

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Cross-references

Bioaccumulation
Bioavailability

BIOMONITORS

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Synonyms

Sentinel organisms

Definition

Biomonitors are organisms that accumulate contaminants in their tissues and can be used to yield a relative measure of the total amount of contaminants in the environment integrated over a period of time. They respond simultaneously to different stressors, providing quantitative information on the quality of the environment.

Applications and characteristics

To observe the impact of anthropogenic activities on ecosystems and their development over a long period or different locations is a large-scale, costly, and time-consuming task. Monitoring such impacts is a challenge, once it involves systematic data acquisition in time and/or space in order to characterize distribution patterns and trends in all possible environmental compartments in which contaminants may accumulate (Chapman et al., 1982).

Biomonitors, by definition, are net accumulators of trace elements (Rainbow, 2002) and can be seen as self-contained, self-powered units that can respond to the presence of contaminants in the environment and are used for monitoring purposes around the world. Concentrations of contaminants in biomonitors are generally high enough to be easily measured with minor risk of contamination during sample collection or pretreatment when comparing to other environmental matrices, such as water samples. Moreover, the contaminants accumulated in biomonitors represent the most direct measure of bioavailable metal to an organism, i.e., the fraction of a contaminant that can be taken up from the environment and therefore with the potential to cause ecotoxicological effects (Rainbow, 2006; Luoma and Rainbow, 2008).

The first large-scale use of biomonitors was through the Mussel Watch Program, which developed monitoring activities using the blue mussel *Mytilus edulis* to quantify and assess spatial and temporal trends in coastal contamination of a suit of trace metals (Goldberg, 1986).

Several groups of organisms are currently used as biomonitors of environmental quality, including crustaceans, fish, corals, macroalgae, and benthic macroinvertebrates. Effectively used biomonitors facilitate comparisons of contaminants over different time and space scales. Across a pollution gradient, some organisms will be more tolerant and may become dominant, whereas the most sensitive groups may become rare. Important intra- and interspecific variation can be observed in the accumulation and tolerance of contaminants (organics or inorganics) in biomonitors, even for species belonging to the same taxonomic group (Amiard-Triquet et al., 2011). Therefore, it is advisable to use more than one biomonitor to increase the comprehension of different sources of contaminants (e.g., dissolved, particulate, sediments, etc.) (Luoma and Rainbow, 2008). It is also important to know the biology of each biomonitoring organism to understand the potential routes of metal uptake available to the organisms (Rainbow, 2006).

The most useful biomonitoring organisms are sedentary, abundant, and tolerant of environmental contamination and natural stressors. They should also be long lived to integrate variation in contaminant availability over a protracted period of time. They should also be large enough for analysis (Rainbow, 2006). Biomonitors must be resistant to handling during sample collection, manipulative experiments, and identification. Additionally, the more widespread the distribution of a biomonitoring organism, the greater its value as a cosmopolitan biomonitor providing cross-reference through large geographical areas (Rainbow and Phillips, 1993; Luoma and Rainbow, 2008).

Summary

Biomonitors are important tools to estimate and monitor the bioavailability of contaminants in the environment integrated over a specific period of time. The net accumulated contaminants may be used to identify ecologically significant pollutants.

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Cross-references

Bioavailability
Bioindicators
Biomagnification
Ecological Monitoring

BIOREMEDIATION

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Synonyms

Biotreatment of pollutants

Definition

Bioremediation refers to the use of an organism's metabolism to remove wastes, hazardous substances, or other pollutants. In general, microorganisms have been used as bioremediators, such as in phytoremediation, bioventing, bioleaching, landfarming, bioreactor, composting, rhizofiltration and biostimulation. However, not all contaminants are easily treated by bioremediation using microorganisms, and thus the elimination of a wide range of pollutants and wastes from the environment requires increased understanding of different pathways for specific bioremediation technologies and biotransformation processes.

Bioremediation options

Bioremediation has emerged as a promising technology, particularly as a secondary treatment option for oil cleanup. It has several potential advantages over conventional technologies, being less costly, less intrusive to the contaminated site, and more environmentally benign in terms of its end products (Zhu et al., 2004).

Bioremediation has been effectively used in estuarine environments as well as other aquatic ecosystems to remediate oils spills. It has proven to be an effective tool for also treating oil-contaminated marine shorelines. Microbes isolated from estuarine (brackish) waters have been of value in detoxification of many metals (Nagvenkar and Ramaiah, 2010).

In addition, bivalves have been utilized to mollify estuarine eutrophication by removing substances from the water column and reducing nitrogen (N) loads to coastal waters (Carmichael et al., 2012). Many molluscan species have the potential to reduce organic and inorganic compounds (nutrients) from aquaculture effluents; filter-feeding bivalves, microalgae, and macroalgae are potentially valuable organisms for reducing nutrient enrichment in estuarine and other coastal water bodies (Martinez-Cordova et al., 2011).

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Cross-references

Anthropogenic Impacts
Eutrophication
Macroalgae
Oil Pollution
Trace Metals in Estuaries

BIVALVE AQUACULTURE

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Definitions

Aquaculture is the farming of aquatic organisms by intervention in rearing to enhance production. It implies individual or corporate ownership of the stock.

Bivalve includes any member of the molluscan class Bivalvia, or Pelecypoda, characterized by having a two-piece (valved) shell.

Carrying capacity is the maximum population size or biomass that can be supported in a given area.

Epifauna are animals living on the surface of the sediments or hard substrate.

Infauna are animals living in the sediments such that the organism is entirely or nearly entirely covered.

Bivalve aquaculture classification

Bivalve aquaculture can be classified in two ways. The first focuses on the intended use of the final product, harvest, or restoration. Most bivalves are cultured for food, but some such as pearl oysters are cultured for jewelry, while others are produced to enhance or restore natural populations. Culture techniques for all uses are generally similar, but restoration stocks are maintained beyond normal harvest size to augment depleted populations. The major difference between harvest and restoration organisms involves the parental stock. Restoration stocks are generally selected to be genetically similar to the native populations to be restored, but, if disease is responsible for low population levels, it may be desirable to utilize stocks selected for disease resistance. Harvested individuals may be bred for genetic sterility, disease resistance, shape, meat yield, and fast growth.

An alternative classification scheme divides bivalves by habitat type: infaunal and epifaunal. Infauna includes those living near the surface (*Mercenaria*, *Cerastoderma*, *Meretrix*, *Ruditapes*), deeper burrowers (*Mya*, *Panope*), and the active burrowers (*Ensis*, *Solen*). Epifauna attach by cementing themselves to solid objects (oysters: *Ostrea*, *Crassostrea*, *Saccostrea*, etc.) or deploying a byssal thread (mussels: *Mytilu* and *Perna*). Others do not attach as adults, but move actively over the bottom (scallops: *Argopecten*, *Patinopecten*). The discussion below utilizes habitat classification because it facilitates discussion of environmental needs and the methods and equipment utilized during culture.

Hatcheries and nurseries

The two methods for obtaining seed for culturing are collection from wild stocks or the use of a hatchery. Culture historically started with species whose seed could easily be collected from the wild such as oysters, mussels, manila clams, soft-shell clams, and some scallop species. Wild-harvested seed is unavailable for some species such as the hard clam (*Mercenaria*) and the geoduck (*Panope*) because seed density is too low to support harvest. For species whose seed can be collected, the harvested seed are cultured in a manner similar to hatchery seed. When wild seed are unavailable, hatchery technology offers a means of obtaining seed. Hatcheries can also provide a more consistent seed supply and the opportunity for breeding and genetic improvement. Larger seed cost more but usually have higher survival. This cost dictates what sized juveniles must be produced to allow a reasonable trade-off between seed cost and survival of the planted crop.

Bivalve hatcheries are typically located on estuaries because waterfront access and reduced wave energy lower the cost of installing piping and pumps needed to provide water (there are exceptions, such as in Hawaii, where deep ocean water is available near shore, is high in nutrients and low in suspended sediments, and has constant temperature and salinity). Water pumped from estuaries has variable physical and chemical characteristics and often requires filtration and/or sterilization before use.

The hatchery process begins with ripening brood stock by warming the water and providing sufficient food, usually cultured microalgae (phytoplankton) although naturally available food can be utilized if water quality can be controlled. Most hatcheries begin the production season as the waters warm but may start earlier than nature so small seed are available to gain a growth advantage as the natural system warms. The early production of seed implies that the hatchery must maintain the newly set animals on cultured food for longer than is typical for seed produced later in the season. The conditioned brood stock is spawned, fertilized eggs collected, and the larvae are raised in tanks supplied with food, usually in the form of cultured microalgae. These larvae are held until they reach a size when they are ready to settle or set. Larval life span is determined by temperature, but for most species, the larval period is 10–20 days. Under optimal culture conditions, cultured species set at the lower end of the time spectrum. There are always exceptions to any generality dealing with bivalve culture. Instead of tanks and cultured algae, at least one commercial operation relies on lined open ponds and natural phytoplankton production for larval and nursery culture.

At setting, epifaunal and infaunal species may be treated differently. Epifauna such as oysters may be transferred to settling tanks and set as single animals or attached as clusters to shell or alternate materials. Scallops may be set on mesh or, as with infauna, allowed to attach by their byssus and then washed from the setting tank and placed in the appropriate containers. For many species, there is an intermediate nursery where late-stage larvae or immediate post-set are placed in a mesh-bottomed container and water, with cultured algae, is recirculated in the top and out of the bottom mesh (a downweller). Once the animals reach an appropriate size (typically about 0.75–1 mm), they are placed either on raceways or into upwellers (a mesh bottom cylinder where water flows up through the mesh, across the animals, and out through a pipe near the top). Scallops may be left in mesh bags and hung in a tank that is supplied with unicellular algae.

Once seed reach several mm in size, it is no longer economically feasible to culture algae for food, and the hatchery/nursery reverts to pumping water and food from the environment. Depending on location and species, these systems can be placed on land, or as floats in the water, but all are characterized by the use of some form of pumping mechanism to force water and food through the container of animals. If protected areas are available near a power source, floating systems can be utilized and pumping cost can be greatly reduced. If land-based systems are used, pumping costs are increased, but system security is improved. Epifauna may be kept in upwellers while infauna may be placed in raceways where sediments accumulate, helping to protect the seed from fouling. Fouling and overset control can also be achieved by coarsely filtering the water to remove potential fouling organisms, treating the tank and animals on a weekly basis with fresh water, air drying, or other methods. The treatment methods work well with species that tightly close (oysters), but cannot be utilized for species that cannot completely close their shells (scallops). As the animals grow, there is a constant need to increase both the space for the animals and the pumping capacity. These requirements mean that there is a trade-off between the maintenance and feeding requirements in the nursery and the potential losses incurred by planting small animals in nature.

To this point, the spatial area required for producing large numbers of animals is relatively modest. Most animals spawned in the spring will be placed in areas for grow-out in the fall. In some instances involving seed that did not reach planting size or when larger sized animals are needed, a nursery system that uses the passive movement of water through a cage (floating or on the bottom) or a nursery plot where animals are maintained at high density is utilized. The nursery plots are typically placed in easily accessed, sheltered locations. Nursery structures and grow-out structures (see below) are typically similar, but animals are usually at higher density and protection devices use finer mesh in the nursery.

Grow-out

Once animals reach a size where they can be planted for growth to market size, there are many methods depending on the needs of the organism, the environmental conditions, regulatory framework, and the value of the final product. Extensive methods (low density over a large area with minimal bed preparation and no predator protection), intensive methods (high-density bottom plantings with some form of predator protection), or "water column" methods (seed placed on long lines, hung from strings, placed in cages/trays or other containment vessels, or attached to stakes placed in the intertidal) are all utilized.

Epifaunal organisms may be placed in the inter- or subtidal directly on bottom beds that usually receive some preparation before planting. This may be rudimentary cleaning during the harvest of the prior crop or elaborate after harvest fallowing, followed by cleaning and resurfacing. In sites with large tidal amplitude, low earthen berms constructed on the tidal flats may be seeded or used to "finish" adults. These berms, topped by the incoming tide, retain water when the tide recedes, allow a longer feeding period, and ameliorate temperature fluctuations.

More intensive methods for epifauna utilize structures in the intertidal areas to contain the animals. These can be poles or stakes driven into the bottom and wrapped with mesh containing seed (bouchot culture for mussels) racks on which oysters are placed in bags arrayed horizontally (rack (or trestle) and bag culture) or seed may be set on stakes and that are placed horizontally (stick culture) in an intertidal area. Alternatively, cables can be stretched over the flats and baskets or cages attached to the lines (intertidal long-line culture). Cages offer both containment and some predator protection but must be maintained to prevent fouling from occluding the mesh. Structures in this zone must withstand storm and ice conditions, and an alternate site, in deeper water, a protected location, or a cool moist environment on shore, may be needed to provide protection. Fouling may be controlled by proper siting, turning the bags to expose the surface to the sun, power washing, other mechanical methods, or antifouling coatings. Rarely, chemical fouling control, such as dipping the containers and the animals in a brine solution, is utilized.

Beyond the intertidal zone, epifaunal species can be grown on line systems attached to rafts or a variety of surface floats (long-line culture) and may extend many meters below the surface. Mussels attach directly to the line systems, with intermediate supports to keep the crop from sliding off. Oysters and scallops may be attached to lines but are more typically placed in cages that are then attached to lines. Fouling control is an important maintenance procedure. Cages maintained on the surface can simply be inverted to allow the top to dry and the fouling organisms to die, while submerged cages must be cleaned or exchanged on a regular basis.

Infaunal species are typically planted in prepared areas (beds) in the intertidal or very shallow subtidal. Bed preparation may be rudimentary or elaborate. In most cases, protective mesh is stretched over the bed and its edges imbedded in the bottom to reduce predation. In areas of low predation, or when large seed are planted, the mesh may be eliminated. Mesh size is based on seed size. The mesh may be placed on the sediment surface and the seed allowed to dig through or the seed planted and the mesh placed over the seed. In the former, the seed must be smaller than the mesh, while in the latter, the seed are larger than the mesh. In both cases, the beds must be in areas of low wave energy or the mesh can be covered by moving sediments. Beds of shallow-burrowing species are typically mesh covered for the duration of the grow-out cycle (2–3 years) except in areas where ice can cause severe damage. In such areas, mesh may be removed from large seed (after the first summer's growth) in late fall and replaced in early spring. In ice-prone areas, meshes are maintained over small seed because of predation from ducks. Some high-value species such as the geoduck may be planted in tubes (PVC) implanted in the intertidal area and covered, individually or en masse, with mesh that may remain for several years. When the clams become larger and are deeply burrowed, the tubes and mesh are removed for final grow-out. In some areas, flats are bisected with low earthen berms being seeded to grow *Solen* without mesh. These berms retain the water for a longer portion of the tidal cycle.

Environmental effects

Environmental impacts of bivalve aquaculture have been shown to be relatively small and isolated because no food is added to the system. Further, bivalves filter the water, increase the biodeposition rate, and increase the rate of nutrient recycling, including denitrification. Exclusive of the potential for the importation of unwanted species, which has been reduced by importation regulations, the environmental impact of bivalve culture can be divided into three major categories: aesthetic, water column, and benthic. Aesthetic effects have caused delays in obtaining permits for farms because property owners do not want to see culture gear or hear noise associated with gear maintenance and harvest. Proper siting and education of nearby property owners and culturist usually result in compromises that satisfy both parties. Water column effects are generally positive because water clarity is improved by removal of inert particles and microalgae. Too many bivalves placed in the water column can reduce growth rates because the local carrying capacity is exceeded. In temperate areas, annual periods of low temperature plus low growth may add substantially to the length of the culture cycle. Studies documenting where ecosystem carrying capacity has been exceeded have recently been reviewed (Burkholder and Shumway, 2011). The culture of infauna and the bottom culture of epifauna typically results in fewer water column effects than the epifaunal culture on long lines or rafts because bottom culture is conducted in a single layer and results in less biomass per square meter than water column methods.

The biggest environmental change caused by bivalve aquaculture is benthic due to the accumulation of biodeposits on the sea floor that in turn can affect the other benthos. For animals cultured in the water column, biodeposits can greatly exceed normal deposition by animals living in or on the bottom. This accumulation and its effects were documented over a half century ago (Ito and Imai, 1955; see also Norkko and Shumway, 2011), and effects can be reduced by proper siting or site rotation. For infaunal and epifaunal benthic culture, the biodeposits are limited by food supply and resuspension/erosion rates. If the food supply is too low, growth decreases and deposition of feces and pseudofeces decreases. If food supplies are not limiting, siting the culture in an area of moderate currents can reduce excessive buildup of biodeposits. This scouring effect is particularly evident in intertidal or shallow subtidal culture areas where both currents and waves serve to clear the bottom. In spite of this natural sediment movement, the increased density of cultured organisms causes an increase in the fine particle content of the sediments. This change plus the physical presence of the cultured species can alter the infaunal community. Protective structures such as mesh increase epibiota and may emulate the structure and function of nearby reef or seagrass areas. In general, except for the increased density of the cultured species and effects associated with harvesting, bottom culture of bivalves has relatively little ecosystem level effect (Dumbauld et al., 2009). Studies on effect of the adding structural components (PVC tubes) for geoduck culture on the US west coast and screening for clam culture on the US east coast have found that these culture operations do not significantly alter the ecosystem processes (Kraeuter et al., 2013; Van Blaricom et al., 2013).

Breeding

Selective breeding has been conducted on a few bivalve species. Oysters have received the most attention because of the need to develop strains that resist diseases. Stocks of *Crassostrea virginica* have been developed that are resistant to MSX (*Haplosporidium nelson*)

(Haskin and Ford, 1979). These stocks have been further bred to provide lines that are better suited for certain regional conditions. In addition, oysters (*Crassostrea gigas* and *C. virginica*) have been subject to ploidy manipulation to provide for animals with reduced or no gonadal development allowing marketing a uniform product on a year-round basis. By developing tetraploid (four sets of chromosomes) stocks (Allen and Guo, 1998), hatcheries are now able to provide triploid (functionally sterile) oysters for the culture market. Some breeding work has been conducted with hard clams (*Mercenaria mercenaria*), but most of this was to develop faster, more uniform growth. There is evidence that some strains of hard clams are better suited for certain environments and have higher resistance to the disease QPX (Quahog Parasite Unknown) (Ragone-Calvo et al., 2007; Kraeuter et al., 2011), but the stocks have not been bred for these characteristics.

Health effects

An important aspect of bivalve culture is the requirement for high water quality. As bivalves filter the water, they concentrate microorganisms. This characteristic, and because many bivalves are eaten without cooking, means they must be cultivated in waters free of organisms that cause human sicknesses. This constrains site selection and means the presence of bivalve culture provides an incentive for water quality managers to maintain or improve bacterial water quality.

Summary

Over 75 % of the bivalves harvested from estuaries are produced by aquaculture which is rapidly increasing (Creswell and McNevin, 2008; Rheault, 2012). Bivalve aquaculture does not rely on adding feed to the environment, and as such is considered to be a form of nutrient extraction. If populations are dense enough, they can become a natural control of eutrophication (Cloern, 1982; Officer et al., 1982). In addition, since bivalves are filter feeders, they remove fine particles from the water and can increase water clarity. Through biodeposition, they enhance nutrient recycling including denitrification (Newell et al., 2005). Lastly, sites culturing bivalves for human consumption require the highest water quality standards and can provide important incentives for increasing or maintaining estuarine water quality.

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Cross-references

Shellfish Production

BIVALVE MOLLUSCS

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Synonyms

Molluscs; Pelecypods

Definition

Bivalves (nearly 20,000 species) are one class in the phylum *Mollusca* (Abbott, 1974; Gosling, 2003; Gofas, 2013). They secrete a relatively hard shell that covers the mantle and gill tissues. The shell grows out from the point of articulation, the hinge, with new layers regularly added from the mantle tissues. Some species live free, singly (clams), or in dense aggregations (scallops); others live attached to each other by either byssal threads (Wilker, 2011) or cement (Burkett et al., 2010; Moeller and Matyjaszewski, 2012). Many serve as economically important wild stock fisheries or aquaculture species (see Gosling, 1992, 2003; Spencer, 2002; Hardy, 2006; Shumway and Parsons, 2006; FAO, 2009, see also FAO and NMFS websites). Most are filter feeders (Dame, 1993, 1996; Wildish and Kristmanson, 1997) or deposit feeders (Rhoads, 1973; Kamermans, 1994), but some species are very specialized (Abbott, 1974), boring into wood, rocks, corals, and even other bivalve species (Families *Teredinidae*, *Pholadidae*, some *Mytilidae*, and *Veneridae*). Clams and mussels (*Mytilus*, Gosling, 1992), for example, are found from full strength salinities, in estuaries to freshwater (perhaps a third of all bivalve species, see Haag, 2012) (Dame, 1996; Levinton, 2013). Many freshwater clams and mussels reside in isolated water bodies, have atypical larval adaptations, and are currently endangered (Haag, 2012).

Characteristics

Estuaries and their component habitats are generally recognized as some of the most productive and important ecosystems, as they provide critical feeding, spawning, and nursery areas for numerous species, including economically important fish, shellfish, and waterfowl, in addition to ecologically valuable invertebrate and vertebrate species (Boesch and Turner, 1984; Beck et al., 2001, 2003; Barbier et al., 2011). They are also one of the most impacted ecosystems on the planet (Lotze et al., 2006; Airoldi and Beck, 2007; Molnar et al., 2008; Beck et al., 2009, 2011). One important and common species lineage is the bivalve molluscs, found both intertidally and subtidally in estuaries. Habitat-forming bivalve species (ASMFC, 2007) might be viewed as those that are (1) "reef-forming" (see DeAlteris, 1988; Waldbusser et al., 2013, Figure 1), (2) "aggregation-forming," or (3) "shell-accumulating." Many species are or were important economically, including clams, scallops, mussels, and oysters (MacKenzie, 1996, 1997a, 1997b, 1997c; Bell et al., 2005). For example, the softshell clam (*Mya arenaria*) once supported a commercial fishery in the Chesapeake Bay that is currently nonexistent (Abraham and Dillon 1986). Restocking or restoring these invertebrates can be very different from conventional finfish approaches (Breitburg et al., 2000; French McCay et al., 2003; Bell et al., 2005; Arnold, 2008; Beck et al., 2009; Coen et al., 2011a).

Many "free-living" (e.g., non-reef-forming or solitary) species occur in coarse sand to "shelly" habitats cobbles or in submerged aquatic vegetation (SAV) which can provide some protection from predators (Sponaugle and Lawton, 1990; Irlandi, 1994; Kraeuter and Castagna, 2001; Grabowski, 2004; Grabowski et al., 2008). Many clam species (e.g., hard clams, *Mercenaria* spp., softshell clams *Mya*, etc.) that occur infaunally are able to "migrate" horizontally, as well as vertically, when conditions are adverse (Newell and Hidu, 1986; Dame, 1996) such as low dissolved oxygen (Diaz and Rosenberg, 1995; Burnett, 1997), whereas cemented species are unable to relocate (Lenihan and Peterson, 1998; Lenihan et al., 1999; Altieri and Witman, 2006; Breitburg et al., 2009; Johnson et al., 2009). Loss of dense populations of bivalves can have significant ecosystem effects (Altieri and Witman, 2006; Beck et al. 2011).

Harvesting (=disturbance) of bivalves and associated faunas in sediment or reefs (Hall et al., 1990; Coen, 1995; Dayton et al., 1995; Thrush et al., 1995; Lenihan and Micheli, 2000; Stokesbury et al., 2011) can have significant effects on their functioning and recovery (Hall, 1994; Coen and Luckenbach, 2000; Jackson et al., 2001; French McCay et al., 2003; Lotze et al., 2006; Grabowski and Peterson, 2007; Grabowski et al. 2012).

Mobile infaunal species are found in a variety of substrates including sand, mud, shell, and mixtures of these (Dame, 1996; Levinton, 2013). For example, razor clams (family *Pharidae*) can move very rapidly in estuarine sediments with a specialized shell and foot. Non-cementing scallop species are relatively mobile as juveniles and adults moving off the bottom for short excursions (Fay et al., 1983; Shumway and Parson, 2006), for example, to flee predators (Pohle et al., 1991; Ambrose and Irlandi, 1992; Arnold, 2009). Some species have siphons that are used for feeding and respiration. These straw-like structures also allow many species to reside deeper in the sediment (soft clams, *Mya arenaria*; see Figure 2) providing some protection from both lethal and sublethal predators (Irlandi, 1994). However, these fleshy tissues are then available to "sublethal" predators whose diets can be

Bivalve Molluscs, Figure 1 Examples of intertidal and subtidal shellfish habitats. (**a** and **b**) Pen shell, *Atrina zelandica*, aggregations in New Zealand (Source: Simon Thrush, University of Auckland, New Zealand); (**c**) *Modiolus modiolus* assemblages in St. Joe Bay, Florida, USA (Source: Brad Peterson, State University of New York, Stony Brook); (**d**) nesting oyster catchers on intertidal shell accumulations (racks) along the Intracoastal Waterway, SC, USA (Source: Phil Wilkinson, South Carolina Department of Natural Resources); (**e**) *Geukensia demissa and Crassostrea virginica* among *Spartina* stems in New Jersey, USA (Source: David Bushek, Rutgers University); (**f**) dense pen shell aggregation in a seagrass bed in the intertidal zone in Dubai (Source: Raymond Grizzle).

Bivalve Molluscs, Figure 2 *Mya arenaria* (soft clams) with extended fleshy siphons extended. The current softshell fishery in the Chesapeake Bay (USA) is nearly extirpated. This is another example of a bivalve species that once supported a commercial fishery that is no more. http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/clams.aspx.

Bivalve Molluscs, Figure 3 *Rangia cuneata* clam shells Texas (USA) coast (Photo by Steve Black. See http://www.texasbeyondhistory.net/coast/prehistory/images/shellfish.html).

dominated by cropped tissues (Peterson and Quammen, 1982; Lindsay et al., 1996; Meyer and Byers, 2005).

Another common estuarine to marine bivalve, pen shells (family *Pinnidae*) are relatively large bivalves that bury themselves partly into the substrate and are anchored by byssal threads. Only the upper portion of the shell is exposed above the sediment (referred to as "emergent shellfish beds"; see ASMFC, 2007), providing additional habitat (Figure 3a, b) for other organisms, when either live or dead (Keough, 1984; Kuhlmann, 1998; Cummings et al. 1998, 2001; Munguia, 2004). In dense numbers, these live and dead pen shells create a critical habitat in many systems (Connell and Keough, 1985; Munguia, 2004). In some areas stranding events point to large nearshore populations such as those near Sanibel Island, Florida, USA (L. Coen personal observations. Perry, 1936). Many bivalve "foundation species" support enhanced diversity quite often and complex communities (Altieri and Witman, 2006).

Many smaller clams such as the estuarine wedge clam, *Rangia cuneata* (Figure 3), form dense filtering aggregations in brackish to estuarine salinities with regular freshwater input. These bivalves, as well as many others, serve as important food sources for fish, crabs, and birds (LaSalle and de la Cruz, 1985; Ruiz, 1987; Ruiz et al., 1989; ASMFC, 2007). Mined deposits of wedge clam shells from Lake Pontchartrain, Louisiana, from 1933 to 1990 (Abadie and Poirrier, 2000) supported the wild stock oyster industry in Louisiana. The shells were planted in estuaries on state and leased grounds until a moratorium stopped the removal of the natural clam shells for their intrinsic functions (ASMFC, 2007). Mined oyster shell has been dredged also from many estuaries throughout the USA for use in replanting leased or state-managed shellfish "grounds" (Hargis and Haven, 1999; Burrell, 2003).

Shell mounds or "middens" from indigenous peoples are found in nearly all coastal areas where bivalves were once common or still are (Ceci, 1984; Beck et al., 2009; Balbo et al., 2011). Along the Gulf of Mexico and Atlantic coasts of the USA, middens primarily consist of *C. virginica*, but also clams (*Mercenaria* spp., *Rangia*), blue (*Mytilus* spp.) and ribbed mussels (*Geukensia* spp.), and slipper snails (*Crepidula* spp.) (Mackenzie et al. 1997a; Saunders and Russo, 2011). For North America, European settlers (Dutch, English, and French) began to harvest these species in the 1600s. In colonial days, bivalves were quite abundant (Kent, 1992; MacKenzie, 1996; Mackenzie et al., 1997a; Kirby, 2004), but through the late nineteenth century on, stocks in North America and many other areas became depleted (Rothschild et al., 1994; Kirby, 2004; Beck et al., 2009; zu Ermgassen et al., 2012).

Even when dead, bivalve shells accumulate (intact or broken as "shell hash," "rakes") in or on the sediment floor often in sufficient quantities to provide significant structure and habitat for a variety of organisms (Anderson et al., 1979; Lehnert and Allen, 2002; Street et al., 2005; Coen et al., 2006, 2011a; ASMFC, 2007; Summerhayes et al., 2009). In some areas, boat wakes have apparently degraded the natural reefs resulting in large accumulations of dead shell along the shorelines (Grizzle et al., 2002; Wall et al., 2005). Oystercatchers and other wading birds use intertidal to supratidal shell accumulations as nesting/feeding sites along dredged areas such as the Intracoastal Waterway (ICW) (Figures 1d and 4a, b, Marsh and Wilkinson, 1991; Goss-Custard, 1996; ASMFC, 2007; Sanders et al., 2008; Thibault et al., 2010). This can even occur when nonnative bivalves (*Mya*) are introduced into novel estuarine habitats (e.g., Dumbauld et al., 1993). Shell of many different bivalve species [mined from seafloor or from middens (see above)

Bivalve Molluscs, Figure 4 (**a**) Washed intertidal shell (racks) in South Carolina, USA along the IWW (see also Anderson et al. 1979, Source: Felicia Sanders, SCDNR, Charleston, South Carolina, USA). (**b**) Oystercatchers feeding in Cape Romain, SC, USA (Source: Felicia Sanders, SCDNR, Charleston, South Carolina, USA).

or accumulated at shucking houses] is used for rehabilitation and restoration of other bivalves (LaSalle and de la Cruz, 1985; Kraeuter et al., 2003; Waldbusser and Salisbury, 2014).

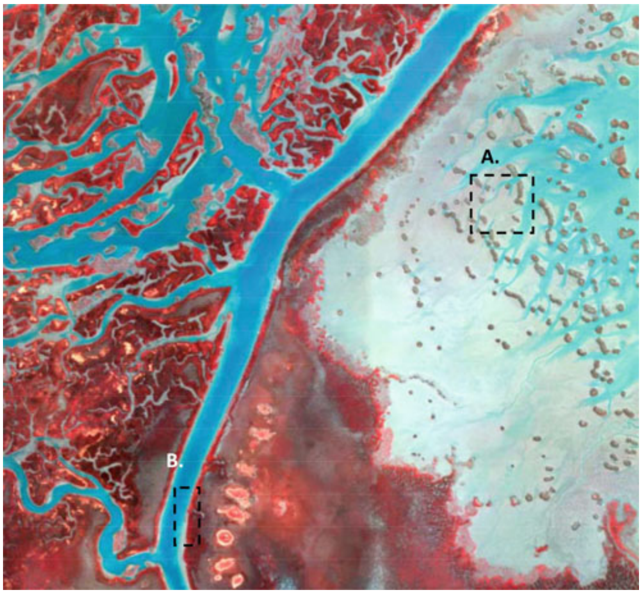
Many bivalve species, especially the reef-forming oysters (e.g., the True Oysters, *Ostreidae*, genus *Crassostrea*; see Carriker and Gaffney, 1996), are under pressure or have already been impacted significantly across the globe (e.g., Rothschild et al., 1994; Lotze et al., 2006; ASMFC, 2007; Beck et al., 2009, 2011, zu Ermgassen et al., 2012). It is these reef-forming species (often called "ecosystem engineers," Gutiérrez et al., 2003; Byers et al., 2006) that have been the focus of recent and current restoration efforts (Beck et al., 2011; Powers and Boyer, 2014), especially for their "ecosystem services" in North America (e.g., Coen et al., 1999a, 2007; Coen and Luckenbach, 2000; ASMFC, 2007; Grabowski and Peterson, 2007; Grabowski et al., 2012; Brown et al., 2014; La Peyre et al., 2014b).

One widely ranging species, the Eastern oyster, *Crassostrea virginica*, forms living subtidal and intertidal biogenic reefs that are a dominant feature of many Atlantic and Gulf US coastal estuaries (Chestnut, 1974; DeAlteris, 1988; ASMFC, 2007; Beck et al., 2011). Because of its extensive range and importance as a major fishery species in the USA dating back to the late eighteenth century (Brooks, 1891), there exists an extensive body of information on the biology of this species and their populations (Marshall, 1954; Galtsoff, 1964; Bahr and Lanier, 1981; Sellers and Stanley, 1984; Stanley and Sellers, 1986; Kennedy et al., 1996). However, its populations have declined significantly in many US estuaries that once had major fisheries (Rothschild et al., 1994; Kirby, 2004; NRC, 2004; Lotze et al., 2006). The causes are numerous and interrelated including overharvesting, pollution and related impacts, habitat destruction, and oyster diseases. Most harvestable oyster populations were primarily subtidal (Figures 5 and 6), such as those in the Chesapeake Bay (Maryland and Virginia), Delaware Bay (Delaware and New Jersey), and the Gulf of Mexico (Florida to Texas) (MacKenzie, 1996; MacKenzie et al., 1997a; zu Ermgassen et al., 2012).

In contrast, many intertidal *C. virginica* reefs (Figures 7 and 8) such as those in the southeastern (Galtsoff, 1964; Bahr and Lanier, 1981; ASMFC, 2007) and southwestern USA develop in locations where salinities is often moderately high, water column and resuspended food are sufficient, and siltation is not excessive, although most oysters can thrive in highly turbid waters (Coen, 1995). In these areas intertidal oysters often grow in isolated patches

Bivalve Molluscs, Figure 5 Image of a shallow subtidal *Crassostrea virginica* restored reef from Chesapeake Bay, MD, USA (Source: K. Paynter, University of Maryland, College Park).

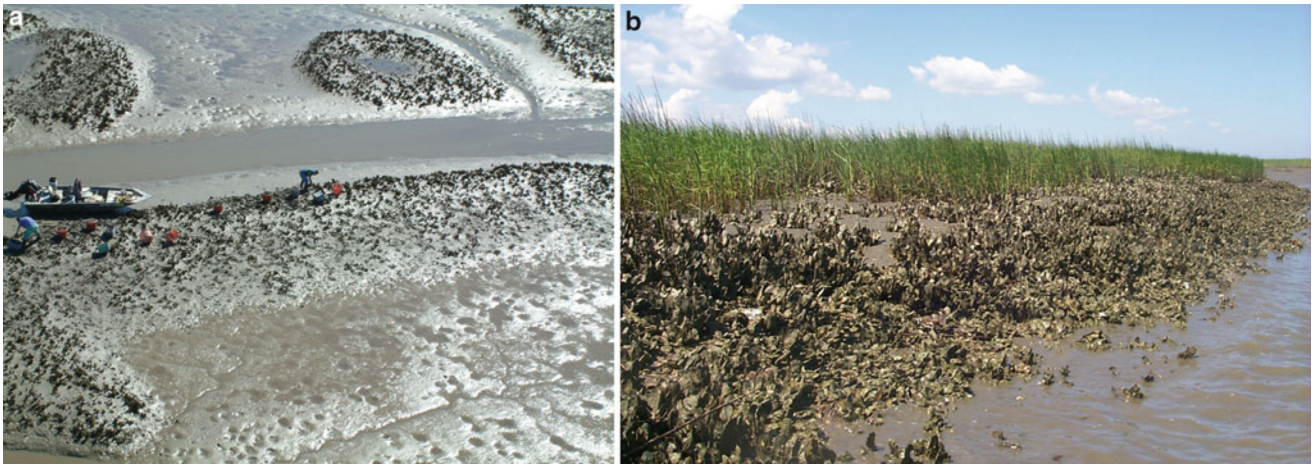
Bivalve Molluscs, Figure 6 Restored oyster reef in the Great Wicomico River on the western shore of lower Chesapeake Bay, USA. The high-relief reef harbored about 1,000 oysters m^{-2} of four age classes (Schulte et al. 2009) and is thought to resemble historical reefs from Colonial times (Source: R.P. Burke and R.N. Lipcius, VIMS, VA, USA, image taken from Remotely operated underwater vehicle or ROV video).



Bivalve Molluscs, Figure 7 Multispectral aerial image of intertidal oyster reef types typical of southeastern USA. The dashed square on the right (see Inset A, Figure 8), "oyster flats" in embayments, and the dashed rectangle (see inset B, Figure 8) represents "fringing oyster reefs" adjacent to salt marsh-lined tidal creeks (see ASMFC 2007 and SCDNR, 2008, for more information; Charleston Co., South Carolina, USA).

away from shore-lines (Figures 7a box and 8 inset a) or along fringing marsh (*Spartina*), on mangroves and around their islands, bordering creeks, rivers, sounds, and embayments (Figures 7b rectangle and Figure 8 inset b, Galtsoff, 1964; Bahr and Lanier, 1981; Burrell, 1986; ASMFC, 2007; Volety, 2013; Baggett et al., 2014). Mussels (e.g., *Geukensia* spp.) also can be quite abundant (Figures 1c, e, and Figure 9) in fringing marshes and intertidal and subtidal natural and restored oyster reefs (Bertness and Grosholz, 1985; Franz, 2001; Luckenbach et al., 2005; Walters and Coen, 2006).

Grabowski and Peterson (2007) and others (Coen et al., 1999a; Coen et al., 2007; Baggett et al., 2014) have delineated ecosystem services provided by oyster reef habitats: (1) oyster production; (2) water filtration/fecal concentration; (3) nutrient sequestration; (4) habitat for fish and invertebrates and augmented production; (5) stabilization of adjacent habitats/shorelines; and (6) enhancement of ecosystem complexity. Recent research has attempted to quantify the contribution of oyster habitats to ecosystem functioning in economic terms (Peterson et al., 2003; Grabowski and Peterson, 2007; Grabowski et al., 2012). For example, oysters create vertical, three-dimensional reef or bed habitats utilized by numerous fishes, crustaceans, other invertebrates, birds, and mammals (reviewed in Coen et al., 1999a; Coen et al., 2007; ASMFC, 2007). The abundances and biomasses can rival SAV, salt marshes, or mangroves in terms of harboring



Bivalve Molluscs, Figure 8 Detail of square, (see Figure 7a) of a typical "oyster flat" area (Source: SCDNR) in southeastern USA. Detail of rectangle, (see Figure 7b) of a typical "fringing oyster" marsh lined tidal creek (Source: Loren Coen) in southeastern USA.

Bivalve Molluscs, Figure 9 Mussels (*Geukensia demissa*) can be quite abundant in fringing marshes and intertidal and subtidal natural and restored oyster reefs (Source: David Bushek, Rutgers University, NJ, USA).

organisms (Glancy et al., 2003; Tolley and Volety, 2005; Coen et al., 1999a; Coen et al., 2006; Hosack et al., 2006; Rodney and Paynter, 2006; ASMFC, 2007; Coen et al., 2007; La Peyre et al., 2014b). Both subtidal (Figures 5 and 6) and intertidal (Figures 7 and 8) oyster habitats can support a diverse suite of sessile and mobile species (over 300 species in North Carolina; Wells, 1961). Natural reefs support greater numbers than the surrounding natural sand, mud, or even marsh habitats (Coen et al., 1999a; Glancy et al., 2003; Plunket and La Peyre, 2005; Coen et al., 2006; Hosack et al., 2006; ASMFC, 2007; Shervette and Gelwick, 2008; Taylor and Bushek, 2008; Stunz et al., 2010; Humphries et al., 2011a; Humphries et al., 2011b; Shervette et al., 2011). Constructed subtidal and intertidal reefs can also support diverse communities throughout *C. virginica*'s range (e.g., 115 macrofaunal species in South Carolina, Coen et al., 2006; see also Harding and Mann, 1999; Rozas and Zimmerman, 2000; Luckenbach et al., 2005; Tolley and Volety, 2005; Rodney and Paynter, 2006; ASMFC, 2007; Taylor and Bushek, 2008; Gregalis et al., 2009; Stunz et al., 2010; Kingsley-Smith et al., 2012; Brown et al., 2014).

Numerous studies have documented positive synergies between bivalves (especially mussels and oysters) and other habitats such as seagrass (Figure 1c) (Valentine and Heck, 1993; Everett et al., 1995; Peterson and Heck 1999; Peterson and Heck 2001a; Peterson and Heck 2001b; Wall et al., 2008, 2011; Booth and Heck, 2009). This largely results from improved water clarity from bivalve feeding activities thereby increasing light. Water flows are also slowed and sediments and seeds fall out around the reefs. Shellfish release ammonia also and other metabolites and nutrients for SAV (Williams and Heck, 2001). Native oysters and bivalve aquaculture may potentially play a parallel role with SAV (Newell, 2004; Erbland and Ozbay, 2008; Dumbauld et al., 2009; NRC, 2010, Coen et al. 2011a), enhancing or protecting other habitats from erosion (Meyer et al, 1997; Coen et al., 2004, 2007; Piazza et al., 2005; Beck et al., 2009). One of the direct and indirect influences of shallow subtidal or intertidal oyster shell (reef) construction is protection or enhancement of fringing marsh habitats (e.g., Meyer et al, 1997; Piazza et al., 2005; Currin et al., 2010; Scyphers et al., 2011). "Living shorelines" are one set of approaches (Figure 10) that may provide an alternative to stabilization with hardened structures (bulkheads, revetments, concrete) which have armored major portions of estuarine shorelines (Douglass and Pickel, 1999; Scyphers, 2012). Their use attempts to minimize the relatively poor habitat quality along developed shorelines (e.g., Seitz et al., 2006). Landscape issues

Bivalve Molluscs, Figure 10 Development of ReefBLK living shoreline reefs constructed of rebar and filled with shell in Texas, USA. Natural recruitment and growth after roughly one year (Source: Jeff DeQuattro, TNC, Mobile, AL, USA). See http://www.reefblk.com/ for more information.

Bivalve Molluscs, Figure 11 Intertidal *Ostrea lurida* beds in Port Eliza, Nootka Sound, Vancouver Island, Canada (Source: B. Kingslett, Deep Bay Field Station, Vancouver Island University, BC, Canada).

are critical to consider since mobile fauna (fishes and invertebrates) use multiple habitats either for feeding, refuge (Micheli and Peterson, 1999; Harwell et al., 2011), or because they must move with tidal exposure (Coen et al., 1999a, 2006; ASMFC, 2007).

Shell alone once planted or aquaculture gear once deployed (Erbland and Ozbay, 2008; Dumbauld et al., 2009; Marenghi and Ozbay, 2010; Coen et al., 2011a) immediately attracts a diverse assemblage of organisms prior to oysters and other sessile organisms recruiting (Luckenbach et al., 2005; Walters and Coen, 2006). Mobile resident and transient species can be found immediately on these "artificial reef" structures (Dumbauld et al., 1993; Wenner et al., 1996; Coen et al., 1999b, 2006; Lehnert and Allen, 2002; Tolley and Volety, 2005; ASMFC, 2007; Gregalis et al., 2009; Humphries et al., 2011a; Humphries et al., 2011b). With time, oysters and mussels and other filter-feeding invertebrates (barnacles, cnidarians, tunicates) (Haven and Morales-Alamo, 1966; Dame et al., 2001; Newell, 2004; Luckenbach et al., 2005; Walters and Coen, 2006; Coen et al., 2007; Kellogg et al., 2013) then settle. Cumulatively, these filter feeders can filter significant quantities of water, potentially improving water clarity/quality locally (Nelson et al., 2004; Newell, 2004; Grizzle et al., 2006; Grizzle et al., 2008a; zu Ermgassen, 2013a, b; La Peyre et al., 2014b) through increased denitrification rates and enhanced nutrient sequestration into the shells themselves (Piehler and Smyth, 2011; Carmichael et al., 2012; Higgins et al., 2011, 2013; Kellogg et al., 2013; Smyth et al., 2013; Hollein and Zarnoch, 2014). They also form a unique association with fringing salt marsh habitats where the two habitats often abut (Meyer et al., 1997; DeBlieu et al., 2005; Piazza et al., 2005; Coen et al., 2006, 2007, 2011b). The other ecosystem services discussed above are just coming into play outside of North America, based on publications and presentations at meetings such as International Conference on Shellfish Restoration (ICSR, Coen pers. obs., http://www.oyster-restoration.org/workshops-meetings-related-to-oyster-restoration/).

Similarly on the west coast of the USA, the native oyster, *Ostrea* spp. (Figures 11 and 12; Polson and Zacherl, 2009; Polson et al., 2009) populations have reached near extirpation (Trimble et al., 2009; Beck et al., 2009, 2011, zu Ermgassen et al., 2012), with perhaps a few examples in Canada of what their beds once resembled (Jacobsen, 2009). This species never probably formed high vertical relief reefs, but rather abundant "beds" both intertidally (see Figures 11, 12) and subtidally (Beck et al., 2009; Polson and Zacherl, 2009; Trimble et al., 2009; Baggett et al., 2014).

Nonnative bivalve species (e.g., *Crassostrea* spp.) introductions, either through direct and accidental introductions, were first penned by Elton (1958) and are having significant and complex impacts on worldwide (Figures 13 and 14) (Wolff and Reise, 2002; Ruesink et al., 2005;

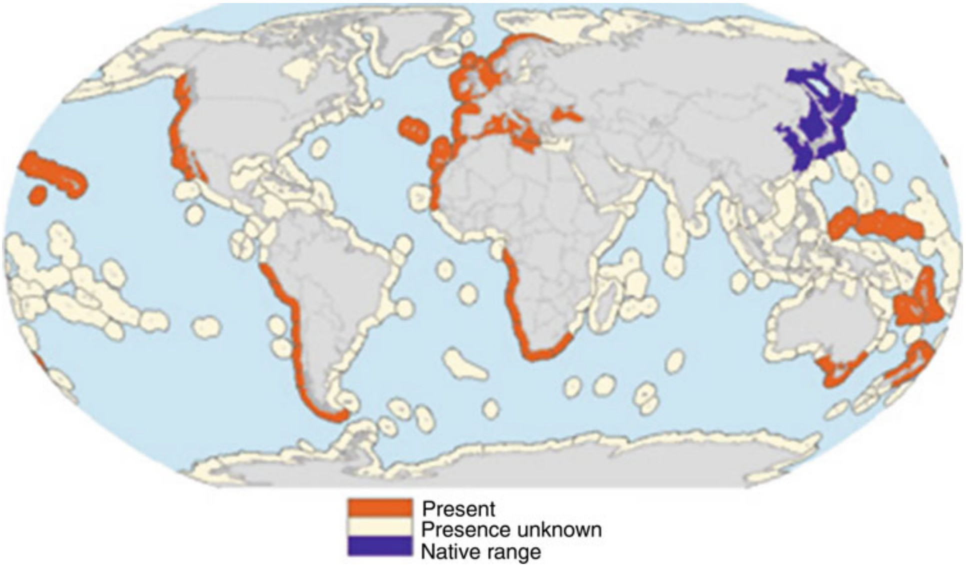
Thieltges et al., 2006; Decottignies et al., 2007; Thomsen et al., 2007; Brandt et al., 2008; Molnar et al., 2008; Kochmann et al., 2008; Wrange et al., 2010; Padilla et al., 2011). In Europe, the native flat oyster, *Ostrea edulis* has been replaced by the introduced Japanese oyster, *Crassostrea gigas* (see Figures 13, 14a, b). The same situation has occurred in many other estuaries throughout the world (Ruesink et al., 2005; Molnar et al., 2008; Kimbro et al., 2009) where native species have declined (Beck et al., 2009) and nonnatives have been introduced to support a commercial fishery (NRC, 2004).

Bivalve Molluscs, Figure 12 *Ostrea lurida* from above beds (see Figure 11) in Vancouver Island, Canada (Source: B. Kingslett, Deep Bay Field Station, Vancouver Island University, BC, Canada).

In many nearshore and estuarine areas, introduced oysters are transforming the landscape in manifest ways (reviewed in Ruesink et al., 2005; Smaal et al., 2005; Molnar et al., 2008; Padilla et al., 2011). In the Wadden Sea, for example (Nehls and Büttger, 2007), the invasion of the Pacific oyster *Crassostrea gigas* is causing major habitat shifts from the formerly dominant native bivalve, the blue mussel, *Mytilus edulis* which formed beds to intertidal oyster reefs (Figures 14a, b). The consequences for native benthic communities, mussel-eating birds and other higher food web consumers, the mussel fisheries, etc. have yet to be resolved. In some cases diseases (MSX) or hitchhikers (slipper shells, *Crepidula* spp.) have had significant impacts (Elton, 1958; Burreson and Ford, 2004; Decottignies et al., 2007).

Restoration

As mentioned already, past oyster restoration efforts have focused on recovering lost or impaired oyster fisheries (MacKenzie, 1996; MacKenzie, 1997a, MacKenzie, 1997b, MacKenzie, 1997c, Beck et al., 2009, 2011). Because of the significant decline of oyster reefs worldwide (e.g., Beck et al., 2009, 2011) and related efforts to reconstitute these species' habitats, numerous attempts (from small to large scale) have been initiated, especially in North America for non-resource-related ecosystem functions (Coen and Luckenbach, 2000; Gutiérrez et al., 2003; Coen et al., 2007; Brumbaugh and Coen, 2009; La Peyre et al. 2014; Powers and Boyer, 2014). As mentioned above, the focus of recent (since 1990s) enhancement and restoration efforts has been for the other "ecosystem services" (Luckenbach et al., 1999; Coen and Luckenbach, 2000; Grabowski and Peterson, 2007; Baggett et al., 2014;



Bivalve Molluscs, Figure 13 Relatively recent distribution of the Pacific oyster, *Crassostrea gigas*. Orange is its "invasive" (nonnative) range, blue is its "native" range (prior to reanalysis by molecular approaches), and white is unknown (potential) occurrence from Molnar et al. (2008, see Figure 4).

Bivalve Molluscs, Figure 14 (**a**, **b**) Pacific oyster, *Crassostrea gigas* replacing mudflats and cockle/mussel areas in the Dutch Wadden Sea. Above – (**a**), mudflats and (**b**) typically what invaded flats look like after five years. Both images taken in 2013 (Source: Carola van Zweeden, Institute for Marine Resources and Ecosystem Studies (IMARES), Centre for Shellfish Research, Netherlands).

Powers and Boyer, 2014) versus stock enhancement (Bell et al., 2005; Luckenbach et al., 2005; Arnold, 2008). As described elsewhere, we define restoration as "The process of establishing or reestablishing a habitat that in time will come to closely resemble a natural condition in terms of structure and function" (see Coen and Luckenbach, 2000; Coen et al., 2004; Baggett et al., 2014). One of the key differences among sites has been either a deficiency of adequate (=appropriate) shell or other hard substrate for settlement (Figure 15a, b) or a limitation of oyster larval recruits ("spat"). Modeling is beginning to get at those sites that have enhanced larval recruitment (e.g., Kim et al., 2013). In areas where larval supply is limited (e.g., Hudson River Estuary; Levinton and Waldman, 2011; Starke et al., 2011; Levinton et al., 2012; Grizzle et al., 2013), spat on shell ("SOS") is one approach. Shell ("cultch") with small set oysters ("spat") either from hatcheries or from field sets can be required (Figures 16a, c) (Coen and Luckenbach, 2000; Coen et al., 2004; Brumbaugh et al., 2006; Baggett et al., 2014). Once the oysters reach a given size (perhaps 25-40 mm shell height) or have a thick enough shell, they can be added to reefs on the shell or if larger, seeded directly onto newly constructed reefs (Figures 16b, d). Connections among oyster reefs and regions (Eggleston, 1999; Eggleston et al., 1999; Mroch et al., 2012; Puckett and Eggleston, 2012) are also key to

Bivalve Molluscs, Figure 15 (**a**) Overharvested fringing intertidal shoreline with clusters of *Crassostrea virginica* at fringe of the *Spartina alterniflora* marsh only (cf. Figures 7b & 8b). Lower down on the bank is mostly loose shell, with intact live oyster clusters closer to the marsh, SC, USA (Source: Loren Coen). (**b**) Restored leased shoreline after shell ("cultch") was planted and allowed to recruit with natural oysters ("spat") after several years without harvesting, SC, USA (Note the oyster clusters with numerous vertical oyster "blades") (Source: SCDNR, Charleston, SC).

future restoration success (Lipcius et al., 2008; Lipcius and Ralph, 2011).

Critical for successful restoration efforts are clear goals, related metrics, and success criteria and designs (Weinstein et al., 1997) that are rigorous with adequate monitoring (Coen and Luckenbach, 2000; Coen et al., 2004; NRC, 2010; Kennedy et al., 2011; Baggett et al., 2014; Powers and Boyer 2014). Monitoring also allows for adaptive management of the restoration process in the event efforts also beyond the initial restoration activities are required (Coen et al., 2004; Kennedy et al., 2011; Baggett et al., 2014). Past efforts also suggest that at least four or more years are required to begin to assess long-term success (reviewed in Baggett et al., 2014).

Shell budgets for subtidal oyster reefs in the northeastern USA have been calculated and used to assess reef shell trajectories and the likelihood of long-term restoration success (Powell et al., 2006, 2012; Waldbusser et al., 2013). Intertidal evaluations of natural oyster reef changes and restoration success metrics can be more easily assessed using a number of approaches (Grizzle et al., 2002; Coen et al., 2004, 2011b; Powers et al., 2009; Baggett et al., 2014). For a large number of restoration footprints in North Carolina, Powers et al. (2009) determined that intertidal success was much greater than that observed for subtidal restoration efforts, but this finding may be confounded by a number of potential methodological problems. More work needs to be done with regard to success of small to large footprints (reviewed in Kennedy et al., 2011; Baggett et al., 2014). The large-scale 2009 American Recovery and Reinvestment Act (ARRA) for oyster reef-related projects across the Gulf of Mexico and eastern USA may provide some of these answers.

One significant result of earlier restoration efforts is that for most subtidal restoration, where dissolved oxygen is a major problem (Baker and Mann, 1992;

Bivalve Molluscs, Figure 16 (**a**–**d**) In cases where recruitment potential ("larval supply") is low or where one needs to jumpstart reefs during enhancement or restoration efforts, "spat on shell" (SOS) or seed oyster additions may be used. (**a**) Shell in tanks with oyster larvae added to recruit in the hatchery (Source: R. Grizzle); (**b**) trays of SOS ready to deploy the field in Soundview Park, Bronx, N.Y. as part of a restoration effort lead by Hudson River Foundation, see http://www.hudsonriver.org/?x=orrp (Source: Rocking the Boat, NY, USA); (**c**) natural oyster "spat" collected on Atlantic surf clam (*Spisula solida*) shell in lower Delaware Bay, USA. Spat collectors (shell in bags) were deployed as part of Rutgers University's (New Jersey, USA) community-based oyster restoration program (or PORTS: Promoting Oyster Restoration Through Schools; Source: Lisa Calvo, Rutgers University, NJ, USA); and (**d**) larger "single" 6-month-old oysters are often used to seed reefs (Source: J. Gatling, Kiwanis Club of Suburban Norfolk, VA, USA).

Diaz and Rosenberg, 1995; Lenihan and Peterson, 1998; Lenihan, 1999; Breitburg et al., 2009), higher-relief reefs prove to be more successful than low-relief or no-relief reefs (discussed in Coen and Luckenbach, 2000) in the Gulf of Mexico (e.g., Gregalis et al., 2009), the southeastern USA (e.g., Lenihan and Peterson, 1998; Lenihan, 1999), as well as the mid-Atlantic USA (e.g., Luckenbach et al., 1999; Woods et al., 2005; Schulte et al., 2009).

Mapping

In many areas, major efforts have taken place with new imagery and related mapping (Figure 7, ASMFC, 2007; SCDNR, 2008; Kennedy et al., 2011; La Peyre et al., 2014a) or will be underway (e.g., RESTORE funding for the Gulf of Mexico) to assess the current status and eventually trends for triaging these recovery efforts that require their mapping (Grizzle et al., 2005, 2008b; Powers et al. 2010) for later detection and, if possible, storage in a GIS geodatabase (see http://www.dnr.sc.gov/GIS/descoysterbed.html; Gambordella et al., 2007; SCDNR, 2008; Ross and Luckenbach, 2009, http://www.oyster-restoration.org/oyster-restoration-research-reports/).

Aquaculture

Aquaculture is playing an ever increasing role in the enhancement or restoration of native and nonnative bivalves and more generally molluscs in North America (see Figure 17) (Manzi and Castagna, 1989; Dumbauld et al., 2009; Shumway, 2011) and of late as a potential tool for other nonconsumptive "ecosystem services" for

Bivalve Molluscs, Figure 17 (**a**) Grow-out (predator-exclusion) cages with small oysters held in the water column in shrimp ponds in South Carolina, USA (Source: Bill Cox, Island Fresh Seafood, Meggett, South Carolina, USA). (**b**) Oyster farming on the west coast of USA (Washington, USA), where significant areas are often leased for growing native and nonnative molluscan shellfish species such as oysters (Source: Bill Dewey, Taylor Shellfish, WA, USA).

shellfish worldwide (French McCay et al., 2003; DeAlteris et al., 2004; Beck et al., 2009, 2011; Coen et al., 2007; Coen et al., 2011a; Grabowski and Peterson, 2007; Brumbaugh and Coen, 2009; NRC, 2010; Allison et al., 2011; Powers and Boyer, 2014). Additionally, there are many parallels in the services rendered by farmed and natural reef restoration approaches (e.g., Dumbauld et al., 2009; Coen et al., 2011a), especially since bivalve aquaculture is unique in many ways from other cultured species' approaches in that it requires exceptional water quality for field grow-out (Figure 17, Leonard and Macfarlane, 2011). The shellfish aquaculture industry has helped to improve water quality standards in areas they utilize (e.g., waste water treatment or septic system upgrades), and some have suggested that mussel aquaculture may provide a mechanism for reducing the eutrophication impacts (reviewed in Lindahl, 2011). However, not all of the impacts are strictly positive (Simenstad and Fresh, 1995; Dumbauld et al., 2009; NRC, 2010; Coen et al. 2011).

River diversions

In many estuaries, large-scale diversions and rediversion ("reengineering") of rivers and also seasonal releases or reserves of freshwater (e.g., Louisiana, South Carolina, Texas, Florida, USA) have led to major controversies and related impacts on oyster resources, as well as many other habitats in the overall landscape (Wilber, 1992; Burrell, 2003; La Peyre et al., 2009, 2013; Volety et al., 2009; Pollack et al., 2011). For example, in the ever so important northern estuaries of the Everglades (the Caloosahatchee, Loxahatchee, Lake Worth Lagoon, and St. Lucie , Florida, USA), seasonal wet/dry rainfall variability and related managed pulses or the absence of freshwater can either raise or lower salinities and other environmental variables increasing predators and parasites (when releases are low) or killing estuarine organisms that cannot relocate (e.g., SAV, clams, and reef-building oysters) given the extended periods of these man-made conditions (Tolley et al., 2005; Volety et al., 2009; Volety, 2013). Climate change (including pH and CO_2 levels), diseases, and sea level rise will cause even greater problems in the future (Lafferty et al., 2004; Allison et al., 2011; Levinton et al., 2011; Waldbusser et al., 2013; Burge et al., 2014; Waldbusser and Salisbury, 2014). Enhancement and restoration efforts will play key roles in the future (Blignaut et al., 2013; Powers and Boyer, 2014). The use of shellfish, especially bivalves for nutrient assimilation in estuaries, may also play an increasing role in the future

(Higgins et al., 2011, 2013; Levinton et al., 2011; Shumway, 2011; Piehler and Smyth, 2011; Kellogg et al., 2013; Smyth et al., 2013).

Summary

Bivalves, especially reef-forming species (see DeAlteris, 1988, and Figure 1 in Waldbusser et al., 2013), are important habitat formers in many estuaries worldwide (Kirby, 2004; Beck et al., 2009). Bivalve populations (e.g., mussels) often have positive synergies with other habitats such as sea grasses (Williams and Heck, 2001; Coen et al., 2011a). Similarly, some oyster species (e.g., *Crassostrea gigas*), through direct and accidental introductions, are having significant negative impacts on many native species (Europe, Smaal et al., 2005; Nehls and Büttger, 2007; Kochmann et al., 2008). Impacting one habitat can often impact another in various ways. Because of their numerous ecosystem services, they are in many places being enhanced or restored from current often depauperate levels. A major effort in assessing their current status and eventually trends for triaging these recovery efforts (e.g., in the Gulf of Mexico, post-Deepwater Horizon) requires that habitats be mapped in advance and put into a GIS geodatabase (SCDNR, 2008; see http://www.dnr.sc.gov/GIS/descoysterbed.html). Approaches for their population assessment entails consistent approaches and good designs for monitoring natural and recovering populations. The importance of population connectivity (metapopulations) needs to also be considered for restoration efforts over larger spatial scales (Lipcius et al. 2008, 2009; Schulte et al., 2009). Goals and related success criteria need to be developed whether they are intertidal, shallow, subtidal, or in deeper estuaries and surrounding waters (see http://www.oyster-restoration.org/). Climate change, shoreline erosion (and related fringing habitat loss), changes in native and nonnative (introduced) diseases, competitors, and predator introductions will impact estuaries and the native and cultured bivalves in these systems. Sea level rise, increased hypoxic zones, and other challenges will create habitat winners and losers in estuaries. Oyster reefs are potentially one of the nine important nearshore habitats that will protect coastal communities and infrastructure (Arkema et al., 2013; Grizzle and Coen, 2013). Aquaculture will have an increasing role in bivalve sustainability (Beck et al., 2009; Brumbaugh and Coen, 2009; Dumbauld et al., 2009; NRC, 2010; Shumway, 2011).

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Cross-references

Bivalve Aquaculture
Coastal Erosion Control
Estuarine Habitat Restoration
Habitat Loss
Intertidal Zonation
Introduced Species
Invasive Species
Oyster Reef
Predator–Prey Relationships
Salt Marsh Accretion
Sea-Level Change and Coastal Wetlands
Shell Beds
Shellfish Production
Shore Protection
Shoreline Changes
Thermal Biology

BLUE CARBON

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Synonyms

Coastal carbon; Vegetated coastal carbon sinks

Definition

The term “blue carbon” refers to the proportion of “green” or biological carbon that is found in the oceans of the world (Nelleman et al., 2009). Three main types of coastal ecosystems contain the majority of this blue carbon. Mangroves are a type of tidal, forested wetland found in the tropics and subtropics. Tidal marshes are tidal wetlands dominated by emergent vegetation including grasses, sedges, and reeds. Seagrass beds or meadows are ecosystems along the coasts from the arctic to the tropics containing submerged aquatic vegetation, which resembles terrestrial grasslands. Because these three types of ecosystems store the majority of this carbon, “blue carbon” has become synonymous with coastal carbon. Altogether, mangroves, tidal marshes, and seagrass beds cover roughly 49 million hectares in area (Pendleton et al., 2012) and account for the burial of approximately 114–131 Tg (1 Tg = 1 × 10^{12} g) C/year (Nelleman et al., 2009). Within these ecosystems, the majority of the blue carbon is stored in soils and sediments; however, in mangrove ecosystems and tidal freshwater swamps, a good proportion of carbon may also be stored in trees.

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Cross-references

Carbon Sequestration
Mangroves
Saltmarshes

BLUE CRABS

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Synonyms

Atlantic blue crabs; Blue claw crabs

Definition

Blue crabs, *Callinectes sapidus*, are an ecologically and economically important crustacean species in estuaries along the east coast of the United States. Their entire range is from Massachusetts to Argentina (Millikin and Williams, 1980).

Summary

Blue crabs are considered estuarine residents with all life history stages, except for the larval stages, occurring in estuarine waters. Adult females release larvae into the water column near the mouths of estuaries (Millikin and Williams, 1980). Larvae are carried offshore where at least 30 days are required to go through seven zoeal stages (Millikin and Williams, 1980; Epifanio, 2007). As a result, blue crab larvae represent one trophic link between estuarine and oceanic food webs. The final planktonic stage (megalopa) returns to the estuary, via wind-driven currents and tides (Epifanio, 2007), where they metamorphose to form the first juvenile stage (<5 mm carapace width) and become benthic. These juveniles grow rapidly, molting on average every 3–4 weeks depending on water temperature (Smith and Chang, 2007), making them important prey for a variety of fish and birds, but they are also important predators on other small invertebrates (Lipcius et al., 2007). Therefore, young juveniles (<20 mm carapace width) occupy shallow, structured habitats that also contain food sources including seagrass beds, macroalgae, and oyster reefs (Lipcius et al., 2007). During the 12–18 months required to reach sexual maturity (at 90–100 mm carapace width), habitat use expands based on size and density-dependent factors (Hines, 2007; Lipcius et al., 2007). Smaller juveniles (20–30 mm carapace width) move to alternative nursery habitats including marsh creeks and marsh-fringed mud flats (Lipcius et al., 2007). Larger juveniles (>20 mm carapace width) begin venturing into unstructured habitats and, as they grow, inhabit deeper areas where they continue to be important predators but are prey to fewer organisms (Hines, 2007).

Unlike females that exhibit a final molt to reach maturity, adult males grow throughout their lives (reaching sizes of >200 mm carapace width), molting every 30–40 days depending on temperature, and they typically return to more protective habitats during molting, as they are particularly vulnerable to predators. As a result of ontogenetic shifts in habitat as well as movement into lower salinity areas, blue crabs can be found in a wide array of habitats, throughout the estuarine-to-ocean salinity gradient (e.g., 5–35 ppt) (Hines, 2007; Lipcius et al., 2007). Because they represent both predator (contrary to popular belief, they are not scavengers) and prey in these habitats, blue crabs are a critical component of the estuarine food web both within and between estuarine habitats.

Blue crabs have been an important food item for humans since the early 1700s and have supported a commercial and recreational fishery since the 1800s (Kennedy et al., 2007). As a result, blue crabs are part of the historic, economic, and social fabric of communities along the Atlantic and Gulf coasts of the United States. Blue crabs are consumed as “hard crabs” (crabs with a hard carapace, typically in the intermolt stage) and as “soft crabs” (crabs with a soft carapace as a result of recent molting) (Kennedy et al., 2007). The predominant fishing techniques vary with the season and with the sex of the harvested crabs. During the warmer seasons (late spring-late fall), blue crabs are typically harvested with a trap or “pot,” and the catch is predominantly males. During the winter, particularly in the mid-Atlantic region, blue crabs are harvested by a dredge, and the catch is predominantly females.

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Cross-references

Soldier Crabs (Mictyridae)

BULKHEADS

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Synonyms

Retaining walls; Revetments; Seawalls

Definition

Vertical structures or partitions that hold or prevent soil from sliding seaward and reduce land erosion. A secondary purpose of these structures is to provide protection to the upland from light-to-moderate wave action (CHL, 2013).

Bulkheads protect bluffs and cliffs by retaining soil from eroding at the toe, thereby increasing stability. Bulkheads may cause increased erosion immediately seaward and adjacent to the structure (flanking) due to wave reflection, and they offer no protection to adjacent areas. Bulkheads may be cantilevers, anchored (e.g., sheet pile), or gravity structures (e.g., stone) (USACE, 1981; USACE, 1984; USACE, 2002).

Cantilever bulkheads require adequate ground embedment to retain soil and prevent overturning and are typically used where lower structures are needed. Scour at the toe of the structure can effectively reduce the embedment length and cause failure (USACE, 1981).

Anchored or tie-backed bulkheads require adequate embedment (less than cantilever bulkheads), gain additional support from anchors embedded on the landward side or from structural piles placed at a batter on the seaward side, and are usually used where higher structures are needed. Anchored bulkheads tend to be less susceptible to toe scour; however, they require corrosion protection at the connectors (USACE, 1981).

Gravity bulkheads require strong foundation soils to adequately support their weight (e.g., gabion baskets and concrete blocks), do not sufficiently penetrate the ground to develop reliable soil resistance, and are appropriate where subsurface conditions hinder pile penetration. Gravity bulkheads are typically low-height structures, depend on shear resistance at the base of the bulkhead to support the applied loads, and cannot prevent rotational slides (USACE, 1981).

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Cross-references

Revetments