GEOMORPHOLOGY

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Introduction

Geomorphology is the study of the form of the earth. Coastal geomorphologists study the way that the coastal zone, one of the most dynamic and changeable parts of the earth, evolves, including its profile, plan-form, and the architecture of foreshore, backshore, and nearshore rock and sediment bodies. To understand these it is necessary to examine wave processes and current action, but it may also involve drainage basins that feed to the coast, and the shallow continental shelves which modify oceanographic processes before they impinge upon the shore. Morphodynamics, study of the mutual co-adjustment of form and process, leads to development of conceptual, physical, mathematical, and simulation models, which may help explain the changes that are experienced on the coast.

In order to understand coastal variability from place to place there are a number of boundary conditions which need to be considered, including geophysical and geological factors, oceanographic factors, and climatic constraints.

At the broadest level plate-tectonic setting is important. Coasts on a plate margin where oceanic plate is subducted under continental crust, such as along the western coast of the Americas, are known as collision coasts. These are typically rocky coasts, parallel to the structural grain, characterized by seismic and volcanic activity and are likely to be uplifting. They contrast with trailing-edge coasts where the continental margin sits mid-plate, which are the locus of large sedimentary basins. Smaller basins are typical of marginal sea coasts, behind a tectonically active island arc.

The nature of the material forming the coast is partly a reflection of these broad plate-tectonic factors. Whether the shoreline is rock or unconsolidated sediment is clearly important. Resistant igneous or metamorphic rocks are more likely to give rise to rocky coasts than are those areas composed of broad sedimentary sequences of clays or mudstones. Within sedimentary coasts sandstones may be more resistant than mudstones. Rocky coasts tend to be relatively resistant to change, whereas coasts composed of sandy sediments are relatively easily reshaped, and muddy coasts, in low-energy environments, accrete slowly.

The relative position of the sea with respect to the land has changed, and represents an important boundary condition. The sea may have flooded areas which were previously land (submergence), or formerly submarine areas may now be dry (emergence). The form of the coast may be inherited from previously subaerial landforms. Particularly distinctive are landscapes that have been shaped by glacial processes, thus fiords are glacially eroded valleys, and fields of drumlins deposited by glacial processes form a prominent feature on paraglacial coasts.

The oceanographic factors that shape coasts include waves, tides, and currents. Waves occur as a result of wind transferring energy to the ocean surface. Waves vary in size depending on the strength of the wind, the duration for which it has blown and the fetch over which it acts. Wave trains move out of the area of formation and are then known as swell. The swell and wave energy received at a coast may be a complex assemblage generated by specific storms from several areas of origin. Tides represent a large-wavelength wave formed as a result of gravitational attractions of the sun and moon. Tides occur as a diurnal or semidiurnal fluctuation of the sea surface that may translate into significant tidal currents particularly in narrow straits and estuaries. In addition storm-generated surges and tsunamis may cause elevated water levels with significant geomorphological consequences.

The coast is shaped by these oceanographic processes working on the rocks and unconsolidated sediments of the shoreline. Climate is significant in terms of several factors. First, wind conditions lead to generation of waves and swell, and may blow sand into dunes along the backshore. Climate also influences the rate at which weathering and catchment processes operate. In addition, regional-scale climate factors such as monsoonal wind systems and the El Niño Southern Oscillation phenomenon demonstrate oscillatory behavior and may reshape the coast seasonally or interannually. Gradual climate change may mean that shoreline fluctuations do not revolve around stationary boundary conditions but may exhibit gradual change themselves.

In this respect the impact of perceived global climate change during recent decades as a result of human-modified environmental factors is likely to be felt in the coastal zone. Of particular concern is anticipated sea-level rise which may have a range of geomorphological effects, as well as other significant socioeconomic impacts.

History

Geomorphology has its origins in the nineteenth century with the results of exploration, and the realization that the surface of the earth had been shaped over a long time through the operation of processes that are largely in operation today (uniformitarianism).

The observations by Charles Darwin during the voyage of the *Beagle* extended this view, particularly his remarkable deduction that fringing reefs might become barrier reefs which in turn might form atolls as a result of gradual subsidence of volcanic islands combined with vertical reef growth (**Figure 1**). In the first part of the twentieth century geomorphology was dominated by the 'geographical cycle' of erosion of William Morris Davis who anticipated landscape denudation through a series of stages culminating in peneplanation, and subsequent rejuvenation by uplift. This highly conceptual model, across landscapes in geological time, was also applied to the coast by Davis who envisaged progressive erosion of the coast reducing shoreline irregularities with time (**Figure 2**). Such landscape-scale studies were extended by Douglas Johnson who emphasized the role of submergence or emergence as a result of sea-level change (**Figure 3**).

The Davisian view was reassessed in the second half of the twentieth century with a greater emphasis on process geomorphology whereby studies focused on attempting to measure rates of process operation and morphological responses to those processes, reflecting ideas of earlier researchers such as G. K. Gilbert. The concept of the landscape as a system was examined, in which coastal landforms adjusted to equilibrium, perhaps a dynamic equilibrium, in relation to processes at work on them. Studies of sediment movement and the adjustment of beach shape under different wave conditions were typical.

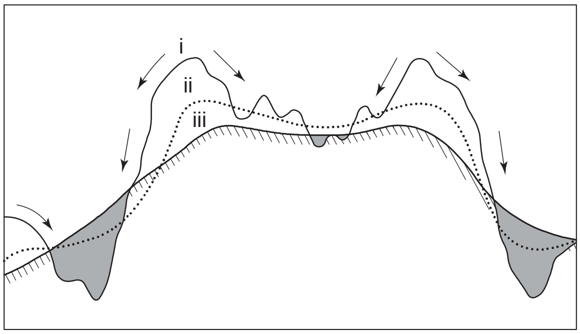

Figure 2 Schematic representation of the planform stages that W. M. Davis conceptualized through which a shoreline would progress from an initial rugged form (1) through maturity (2) to a regularized shoreline (3) that is cliffed (hatched) and infilled with sand (stippled). He envisaged this in parallel to the geographical cycle of erosion by which mountains (like the initial shoreline form, 1) would be reduced to a peneplain (like the solid ultimate shoreline, 3).

Scales of Study

Coastal geomorphology now studies landforms and the processes that operate on them at a range of spatial and temporal scales (**Figure 4**). At the smallest scale geomorphology is concerned with an 'instantaneous' timescale where the principles of fluid dynamics apply. It should be possible to determine details of sediment entrainment, complexities of turbulent flow and processes leading to deposition of individual bedform laminae. The laws of physics apply at these scales, though they may operate stochastically. In theory, behavior of an entire embayment could be understood; in practice studies simply cannot be undertaken at that level of detail and broad extrapolations based on important empirical relationships are made.

The next level of study is the 'event' timescale, which may cover a single event such as an indi-

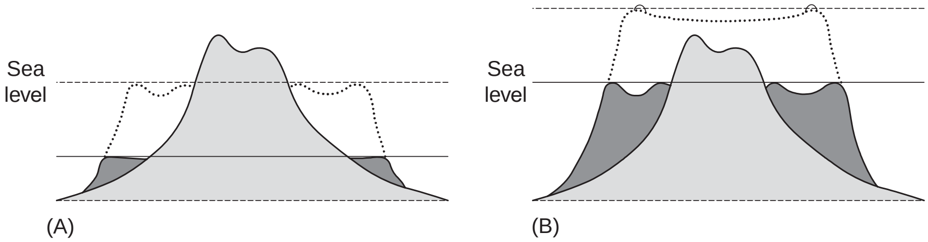

Figure 1 Schematic representation of the original woodcut illustrations by Charles Darwin showing (A) the manner in which he deduced that fringing reefs around a volcanic island would develop into barrier reefs (dotted), and (B) barrier reefs would develop into an atoll, as a result of subsidence and vertical reef growth.

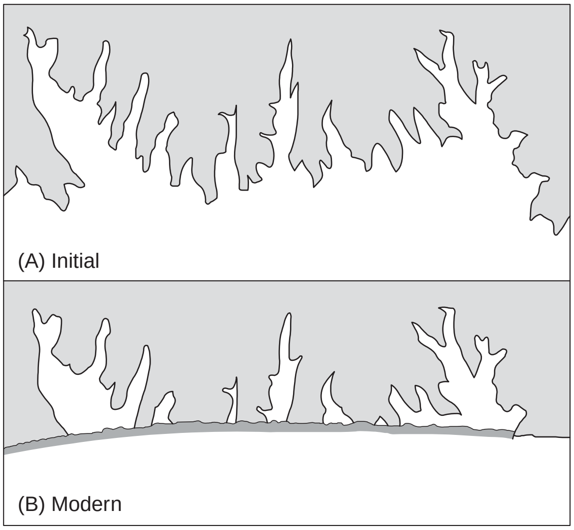

Figure 3 Schematic representation of (A) the initial shoreline form envisaged by Douglas Johnson for an area in Marthas Vineyard, New England, and (B) the modern regularized, form of the shore.

vidual storm or an aggregation of several lesser events over a year or more. The mechanistic relationships from instantaneous time are scaled up in a deterministic or empirical way to understand the operation of coasts at larger spatial and temporal scales. Thus, stripping of a beach during a single storm, and the more gradual reconstruction to its original state under ensuing calmer periods can be observed. Time taken for reaction to the event, and relaxation back to a more ambient state may be known from surveys of beaches, enabling definition of a 'sweep zone' within which the beach is regularly active.

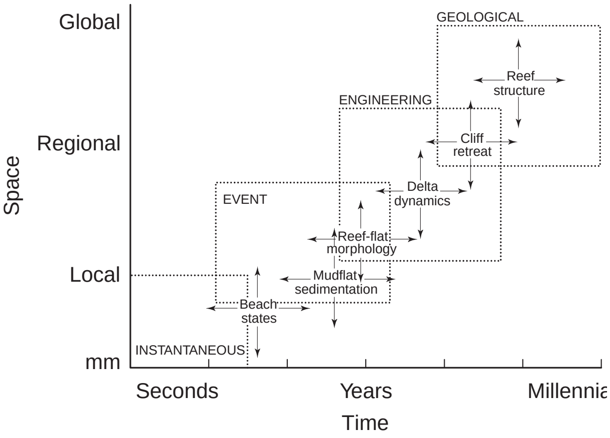

Figure 4 Representation of space and timescales appropriate for the study of coastal geomorphology and schematic representation of some of the examples discussed in the context of instantaneous, event, engineering, and geological scales of enquiry.

At a larger scale of operation, the coastal geomorphologist is interested in the way in which coasts change over timescales that are relevant to societies and at which coastal-zone managers need to plan. This is the 'engineering' timescale, involving several decades. It is perhaps the most difficult timescale on which to understand coastal geomorphology and to anticipate behavior of the shoreline. The largest timescales are geological timescales. Studies over geological timescales are primarily discursive, conceptual models which recognize that boundary conditions, including climate and the rate of operation of oceanographic processes, change. It is clear that sea level itself has changed dramatically over millennia as a result of expansion and contraction of ice sheets during the Quaternary ice ages, and so the position of the coastline has changed substantially between glaciations and interglaciations.

Models of Coastal Evolution

There has been considerable improvement in understanding the long-term development of coasts as a result of significant advances in paleoenvironmental reconstruction and geochronological techniques (especially radiometric dating). Incomplete records of past coastal conditions may be preserved, either as erosional morphology (notches, marine terraces, etc.) or within sedimentary sequences. Although this record is selective, reconstructions of Quaternary paleoenvironments, together with interpretation of geological sequences in older rocks, have enabled the formulation of geomorphological models based on sedimentary evidence. In the case of deltas, where there may be important hydrocarbon reserves, the complementary development of geological models and study of modern deltas has led to better understanding of process and response at longer timescales than those for which observations exist.

Unconsolidated sediments are the key to coastal morphodynamics because coasts change through erosion, transport, and deposition of sediment. Study of coastal systems has led to many insights, particularly in terms of the various pathways through which sediment may move within a coastal compartment or circulation cell. However, it is clear that a completely reductionist approach to coastal geomorphology will not lead to understanding of all components and the way in which they interact. Empirical relationships and the presumed deterministic nature of sediment response to forcing factors remain incomplete and are all too often formulated on the basis of presumed uniform sediment sizes or absence of biotic influence and are ultimately unrealistic. More recently coastal systems have been investigated as nonlinear dynamical systems, because relationships are not linear and behavior is potentially chaotic.

Nonlinear dynamical systems behave in a way that is in part dependent upon antecedent conditions. This is well illustrated by studies of beach state; beach and nearshore sediments are particularly easily reshaped by wave processes, thus a series of characteristics typical of distinct beach states can be recognized (see **Figure 6**). However, the beach is only partly a response to incident wave conditions, its shape being also dependent on the previous shape of the beach which was in the process of adjusting to wave conditions incident at that time.

Coastal systems are inherently unpredictable. However, they may operate within a broad range of conditions with certain states being recurrent. Chaotic systems may tend towards self-organization, for instance patterns of beach cusps characteristic along low-energy beaches which reflect much of the wave energy may adopt a self-organized cuspate morphology in which swash processes, sediment sorting, and form are balanced.

Models may be developed based on patterns of change inferred over geological timescales but consistent with mechanistic processes known to operate over lesser event timescales. Simulation modelling is not intended to reconstruct coastal evolution exactly, but becomes a tool for experimentation and extrapolation within which broad scenarios of change can be modeled and sensitivity to parameterization of variables examined.

Coasts may be divided into rocky coasts, sandy coasts, and muddy coasts, and coral reefs and deltas and estuaries can be differentiated. The geomorphology of each of these behaves differently. Processes operate at different rates, transitions between different states occur over different timescales and the significance of antecedent conditions varies.

Rocky Coasts

Rocky coasts are characterized by sea cliffs, especially on tectonically active, plate-margin coasts where there are resistant rocks. Cliffed coastlines in resistant rock appear to adopt one of two forms (states): plunging cliffs where a vertical cliff extends below sea level, and shore platforms where a broad bench occurs at sea level in front of a cliff (**Figure 5**). Erosion of cliffs occurs where the erosional force of waves exceeds the resistance of the rocks, and where sufficient time has elapsed.

Plunging cliffs occur where the rock is too resistant to be eroded. The vertical face results in a standing wave which reflects wave energy, so that there is little force to erode the cliff at water level. Waves exert a greater force if they break, or if they are already broken. This can only occur if the water depth is shallow offshore from the cliff face in which case the increased energy from the breaking waves is also able to entrain sediment from the floor (or rock fragments quarried from the foot of the cliff). This process of erosion accelerates through a positive feedback cutting a shore platform.

Shore platforms thus develop in those situations where the erosive force of waves exceeds resistance of the rock. A platform widens as a result of erosion at the foot of the cliff behind the platform. The cliff oversteepens, leading to toppling and fall of detritus onto the rear of the platform, which slows further erosion of the cliff face until that talus has been removed. A series of such negative feedbacks slow the rate at which platforms widen over time, and there is often considerable uniformity of platforms up to a maximum width in any particular lithological setting.

Shore platforms adopt either a gradually sloping ramped form, or a subhorizontal form often with a seaward rampart (**Figure 5**). There has been much discussion as to the relative roles of wave and subaerial processes in the formation of these platforms. Platforms in relatively sheltered locations appear to owe their origin to processes of water-layer leveling (physiochemical processes in pools which persist on platforms at low tide) or wetting and drying and its weakening of the rock. In other cases wave quarrying and abrasion are involved. In many cases both processes may be important. Other platforms may

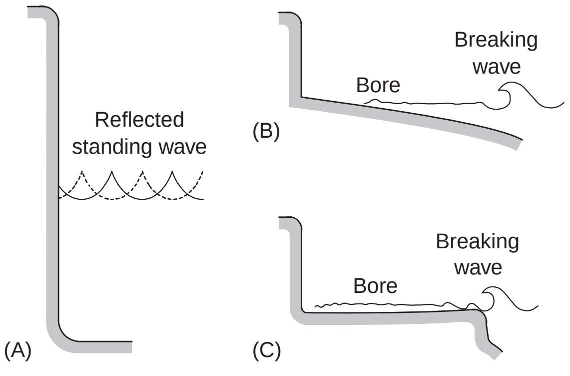

Figure 5 The morphology of cliffs and shore platforms. Plunging cliffs (A) reflect wave energy and are generally not eroded. Shore platforms dissipate wave energy and may be either (B) ramped, or (C) subhorizontal. Change in these systems tends to occur at geological (hard rock) or engineering (soft rock) timescales.

be polygenetic with inheritance from former stands of sea level (reflecting antecedent conditions).

Coral Reefs

A group of coastlines that are of particular interest to the geomorphologist are those formed by coral reefs. Corals are colonial animals that secrete a limestone exoskeleton that may form the matrix of a reef. Coral reefs flourish in tropical seas in high-energy settings where a significant swell reaches the shoreline. In these circumstances the reef attenuates much of the wave energy such that a relatively quiet-water environment occurs sheltered behind the reef.

Not only is this reef ecosystem of enormous geomorphological significance in terms of the solid reef structure that it forms, but in addition, the carbonate reef material breaks down into calcareous gravels, sands and muds which form the sediments that further modify these coastlines.

On the one hand reefs can be divided into fringing reefs, barrier reefs, and atolls, distinct morphological states that form part of an evolutionary sequence as a result of gradual subsidence of the volcanic basement upon which the reef established (see **Figure 1**). This powerful deduction by Darwin relating to reef structure and operating over geological timescales, has been generally supported by drilling and geochronological studies on mid-plate islands in reef-forming seas. On the other hand, the surface morphology of reefs is extremely dynamic with rapid production of skeletal sediments and their redistribution over event timescales, with the landforms of reefs responding to minor sea-level oscillations, storms, El Niño, coral bleaching, and other perturbations.

Sandy Coasts

Beaches form where sandy (or gravel) material is available forming a sediment wedge at the shoreline. The beach is shaped by incident wave energy, and can undergo modification particularly by formation and migration of nearshore bars which in turn modify the wave-energy spectrum. Various beach states can be recognized across a continuum from beaches which predominantly reflect wave energy, and those which dissipate wave energy across the nearshore zone. Reflective beaches are steep, waves surge up the beach and much of the energy is reflected, and the beach face may develop cusps. Dissipative beaches are much flatter, and waves spill before reaching the shoreline (**Figure 6**).

During a storm, sand is generally eroded from the beach face and deposited in the nearshore, often forming shore-parallel or transverse bars. Waves consequently break on the bars and energy is lost, the form modifying the process in a mutual way. It may be possible to recognize a series of beach states intermediate between reflective and dissipative and any one beach may adopt one or several beach states over time (**Figure 6**). Beach state is clearly modified by incident wave conditions, but the rate of adjustment between states takes time, and a beach is also partly a function of antecedent beach states.

Although erosion and redeposition of sand is the way in which the nearshore adjusts, there may also

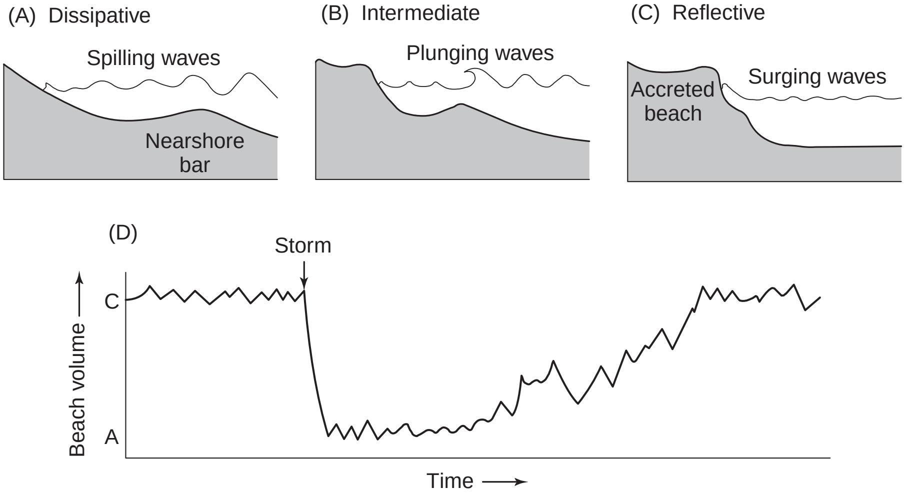

Figure 6 Beach state may be (A) dissipative, where high wave-energy impinges on low-gradient beaches; (B) intermediate (in which several states are possible); or (C) reflective, where low wave-energy surges onto steep or coarse beaches. Change between beach states occurs at event timescales. (D) A beach may react rapidly to a perturbation such as a storm changing from reflective state (C) to more dissipative state (A) but then change much more slowly through intermediate states, readjusting towards state (C) again unless further disrupted.

be long-term storage of sediment. In particular broad, flat beaches may develop dunes behind them. In other cases a sequence of beach ridges may develop. Geomorphological changes in state over geological timescales represented by beach-ridge plains may relate to variations in supply of sediment to the system (perhaps by rivers) as well as variations in the processes operating.

Deltas and Estuaries

Where rivers bring sediment to the coast, deltas and estuaries can develop. In this case the sediment budget of the shoreline compartment or the receiving basin is augmented and there is generally a positive sediment budget. Deltas are characterized by broad wedges of sediment deposition. Delta morphology tends to reflect the processes that are dominant (**Figure 7**). Where wave energy is low and tides are minor, it is primarily river flows which account for sedimentation patterns. River flow may be likened to a jet, influenced by inertial forces, friction with the basin floor or buoyancy where there are density differences between outflow and the water of the receiving basin.

Wave action tends to smooth the shoreline and a wave-dominated deltaic shoreline will be characterized by shore-parallel bars or ridges. Where river-supplied sediment is relatively low in volume, wave action may form a sandy barrier along the coast and rivers may supply sediment only to lagoons formed behind these barriers. Such is the case for much of the barrier-island shoreline of the eastern shores of the Americas; where barrier islands may be continually reworked landwards during relative sea-level rise. On the other hand if sea level is stable, a stable sand barrier is likely to form closing each embayment or creating a barrier estuary as in the case of coastal lagoons in Asia and Australasia.

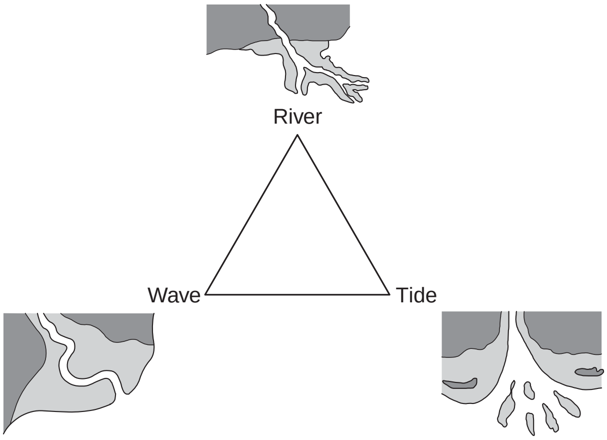

Figure 7 Deltas adopt a variety of forms, but morphology appears to reflect the relative balance of river, wave, and tide action. The broad morphology of the delta tends to be digitate where river-dominated, shore-parallel where wave-dominated, and tapering where tide-dominated.

Estuaries are embayments which are likely to infill incrementally either through the deposition of river-borne sediments or through the influx of sediment from seaward by wave or tidal processes (**Figure 8**). The sediment from seaward may either be derived from the shelf, or from shoreline erosion.

Tidal processes differ from river processes; they are bi-directional, flowing in during flood tide and out during ebb, and the flow is forced by the rising level of the sea. Small embayments are flooded and drained by a tidal prism (the volume of water between low and high tide). Longer estuaries, on the other hand, may have a series of tidal waves which progress up them. Where the tidal range is large this may flow as a tidal bore. Tide-dominated estuarine channels adopt a distinctive tapered form, with width (and depth) decreasing from the mouth upstream (**Figure 8**).

Wave and tidal processes tend to shape deltas and estuaries to varying degrees depending on their relative operation. Many of the deltaic-estuarine processes operate over cycles of change. The hydraulic efficiency of distributaries decreases as they lengthen, until an alternative, shorter course with steeper hydraulic gradient is adopted. The abandoned distributaries of deltas often become tidally dominated with sinuous, tapering tidal creeks dominating what may be a gradually subsiding abandoned delta plain. Wave processes, in wave-dominated settings, smooth and rework the abandoned delta shore, often forming barrier islands.

Muddy Coasts

Muddy coasts are associated with the lowest energy environments. Mud banks may occur in high-energy, wave-exposed settings where large volumes of mud are supplied to the mouth of large rivers. Thus longshore drift north west of the Amazon, and around Bohai Bay downdrift from the Yellow River, enables mud-shoal deposition in open-water settings. Elsewhere mud flats are typical of sheltered settings, within delta interdistributary bays, around coastal lagoons, etc. These muddy environments are likely to be colonized by halophytic vegetation. Mangrove forests occur in tropical settings, whereas salt marsh occurs in higher latitudes, often extending into tropical areas also.

These coastal wetlands further promote retention of fine-grained sediment. The muddy environments are areas of complex hydrodynamics and

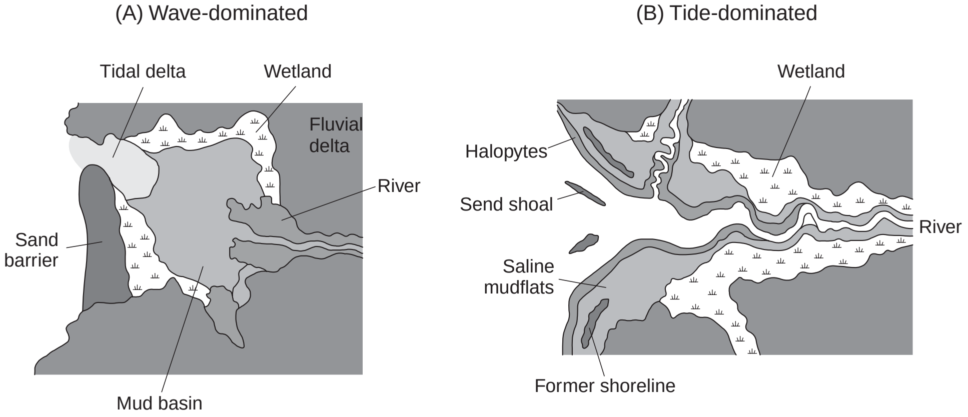

Figure 8 Estuaries are broad embayments which may adopt a wide range of morphologies. They tend to show sand-barrier accumulation where wave-dominated (A), but be prominently tapering where tide-dominated (B). Estuaries are generally sediment sinks with the rates and patterns of infill reflecting the relative dominance of river, wave, and tide processes and sediment sources.

sedimentation. Sedimentation is likely to occur with a negative feedback such that as the tidal wetlands accrete sediment and as the substrate is elevated, they are flooded less frequently and therefore sedimentation decelerates. Boundary conditions, particularly sea level, are likely to vary at rates similar to the rate of sedimentation and prograded coastal plains contain complex sedimentary records of changes in ecological and geomorphological state.

Conclusion

Coastal geomorphology is the study of the evolving form of the shoreline in response to mutually adjusting processes acting upon it. It spans instantaneous and event timescales, over which beaches respond to wave energy, through engineering and geological timescales, over which deltas build seaward or switch distributaries, sea level fluctuates, and cliff morphology evolves. The morphology (state) of the coast changes in response to perturbations, particularly extreme events such as storms, but also thresholds within the system (as when a cliff oversteepens and falls, or a distributary lengthens and then switches). Human action may also represent a perturbation to the system. In each coastal setting, the influence of human modifications is being felt. Thus there are fewer coasts which are not in some way influenced by society. As anthropogenic modification of climate and sea level occurs at a global scale, the human factor increasingly needs to be given prominence in coastal geomorphology.

See also

Beaches, Physical Processes affecting. Coral Reefs. Rocky Shores. Salt Marshes and Mud Flats.

Further Reading

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