Coasts: form, process and evolution

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Introduction

> The scenic features of the coast – its ragged scarps, its ever-changing beaches and bars, its silent marshes with their mysterious past – all excite the imagination, and tempt the wanderer by the shore to seek an explanation for these manifestations of Nature's handiwork. (Johnson, 1925)

Coasts are often highly scenic and contain abundant natural resources. The majority of the world's population lives close to the sea. As many as 3 billion people (50% of the global total) live within 60 km of the shoreline. The development of urbanised societies was associated with deltaic plains in semiarid areas, and the first cities appeared shortly after the geomorphological evolution of these plains (Stanley and Warne, 1993a). The coast plays an important role in global transportation, and is the destination of many of the world's tourists.

The shoreline is where the land meets the sea, and it is continually changing. Coastal scientists, and the casual 'wanderer by the shore', have attempted to understand the shoreline in relation to the processes that shape it, and interrelationships with the adjacent shallow marine and terrestrial hinterland environments. Explaining the geomorphological changes that are occurring on the coast is becoming increasingly important in order to manage coastal resources in a sustainable way.

This book examines the coast as a dynamic geomorphological system. Geomorphology is the study of landforms, and coastal geomorphology is concerned primarily with explaining the many different types of coastal landforms, and understanding the factors that shape them. Physical processes, including both hydrodynamics and aerodynamics, are influenced by substrate and the biota (plants and animals) growing on it. Landforms provide habitats within which coastal ecosystems function. In many cases, the biota themselves contribute to shaping the landforms.

Coastal geomorphologists were one of the first groups of scientists to examine coastal landforms, with interests in the form, process and dynamics of the coast. A wide range of other scientists, however, also study the coast. The physical setting, including rocks and sediments, is examined by geologists, physical geographers and geophysicists. The living organisms are described by ecologists and natural scientists. Processes are studied by oceanographers and climatologists. Economists, human geographers, planners, and other social scientists have separate, and at times conflicting, interests in human use of the coast; and engineers and coastal managers are concerned about the stability of the coast and use of coastal resources. The challenges posed at the land–sea interface by the impact of global environmental change, and by intensive human use of coastal resources, will require further cross-disciplinary collaboration, and interdisciplinary consultation and study. This book focuses on coastal geomorphology, recognising the need to take a multidisciplinary and holistic approach to the diverse factors that influence the present form of the coast and the geomorphological processes that continue to shape it.

1.1 The coastal zone

The coast comprises the interface between the land and the sea. The ‘shoreline’ is the actual margin of the two, whereas the term ‘coast’ is much broader and includes areas below and above the water line, such as shoals, dunes and cliffs (Figure 1.1a). The ‘coastal zone’ is a broad transitional area in which terrestrial environments influence marine environments and in which marine environments influence terrestrial environments (Carter, 1988). Although a statutory definition of the coastal zone may be needed for planning and legislative purposes, it is difficult to identify precise landward and seaward boundaries to the mutual interaction between land and sea. It is often more appropriate for physical, biological or administrative purposes to use a definition relevant to the particular management issue (Kay and Alder, 1999).

Coastal geomorphology focuses on explaining landforms in the coastal zone by examining the form, sediments and depositional history at the modern shoreline. It can include study of the shallow marine environment that is influenced by terrestrial factors and the land where the influence of the sea is felt if this is appropriate to understand the longer-term evolution of the coast. Migration of the shoreline as a result of sea-level fluctuations during the ice ages (the Quaternary Period) means that, in many cases, it is necessary to broaden the area of study beyond the modern coastal zone to include older landforms. Understanding changes at the coast can require examination of processes well outside the coastal zone. A delta is likely to respond to changes within the river

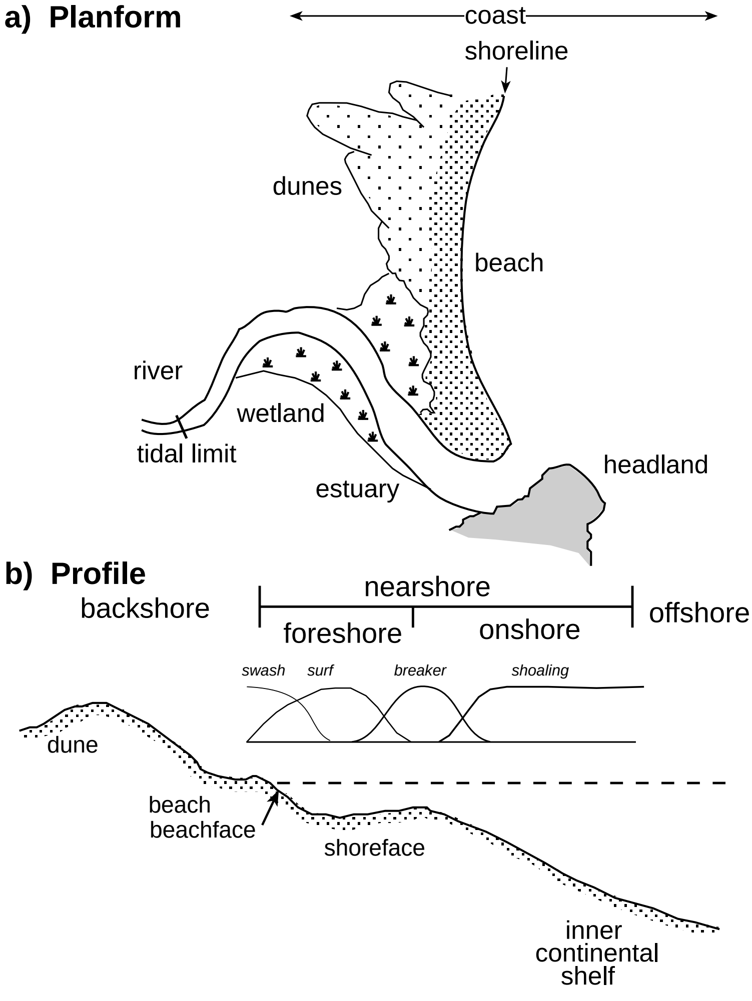

Figure 1.1. A schematic coastal embayment in (a) planform and (b) profile. Some of the key definitions based on proximity to the shore, wave characteristics, and substrate are shown.

drainage basin; for example, construction of the Aswan Dam on the River Nile has decreased the volume of sediment reaching the Nile Delta causing serious coastal erosion (Milliman *et al.*, 1989). Elsewhere, the coast may respond to events seaward of the coastal zone; for instance, mass slumping of delta fronts may carry sediment into deeper water.

1.2 Coastal geomorphology

The shape of coastal landforms is a response of the materials that are available to the processes acting on them. The geomorphology of the coast can be examined in planform (also called shore-parallel, or longshore) or in profile (also called cross-section, cross-shore, shore-normal, or orthogonal) as shown schematically in Figure 1.1. In planform, a coastal embayment can be divided into relatively distinct landforms based on factors such as topography and lithology, or sediment texture and resistance. The most resistant are rocky coasts, characterised by cliffs. Sand and gravel are more mobile in the coastal zone and form coastal barriers on which there are beaches and associated landforms. Deltas or estuaries occur where rivers reach the sea. The coastal zone extends upstream as far as tidal influence is felt, which can vary over time in response to tidal or river flow characteristics. Muddy substrates occur in the more sheltered areas and can support coastal wetlands.

Figure 1.2 shows an example of a coastal embayment in southeastern Australia. The Minnamurra River drains from the Southern Highlands of New South Wales, and its mouth is constrained by a headland to the south. An estuary has developed behind a sandy barrier on which there is a beach and dune. This coastal embayment shows many of the characteristics of barrier estuaries that have been incorporated in an evolutionary model described by Roy and examined further in Figure 1.7 (Roy, 1984; Roy *et al.*, 1994).

Figure 1.2. The estuary of the Minnamurra River in New South Wales, southeastern Australia is an example of a coastal embayment in which the landforms represented schematically in Figure 1.1 can be seen (photograph R.J. Morrison.

1.2.1 Coastal landforms

The broad zones shown in planform in Figure 1.1a, or discernible in Figure 1.2, can be subdivided into smaller-scale landforms which are described in separate chapters in this book. Cliffs and shore platforms typical of rocky headlands and other bold coasts are described in Chapter 4. Beaches and dunes that form on sand and gravel barriers are described in Chapter 6. Estuaries (and deltas) are described in Chapter 7, and muddy shorelines, and the wetlands that characterise them, are described in Chapter 8. Coral reefs contain a distinctive group of landforms, occurring on tropical and subtropical coasts, and are examined in Chapter 5. It is the distribution and interdependence of these landforms, as shown in Figure 1.1a, which determines the topographic character of a particular stretch of coastline. The resistant headlands are obstacles that influence the pattern of wave energy alongshore and consequently affect the shape of sand and gravel barriers. The supply of sediment from a river, filtered through an estuary, can determine changes in the total volume of sediment in the barrier (beach and dune) and nearshore. Muddy shorelines and associated wetlands generally occur where conditions are sheltered within the rocky, barrier or estuarine suite of landforms.

In profile it is also convenient to divide coasts into zones based on morphology and the processes that operate. The terms used to describe these zones differ slightly between geomorphologists and other scientists, such as engineers, and between European and North American researchers. A general scheme is shown in Figure 1.1b, but usage is not always consistent. The backshore is the zone above the water line. The nearshore comprises shallow water in which waves interact with the seafloor, and consists of foreshore where waves break, and onshore. Deeper water areas are termed offshore. The terms can be applied to most coast types, including rocky and muddy coasts, but are illustrated in Figure 1.1b with reference to a sandy embayment, because the subdivisions are generally distinct in a beach setting. The subaerial beach and dune are part of the backshore. The seafloor is termed the shoreface; whereas that part of the beach which is subject to variations in water line (intertidal) is termed the beachface. The nearshore can be further subdivided on the basis of the behaviour of waves in terms of shoaling, breaker, surf and swash zones (see Chapters 3 and 6). Offshore, the shoreface merges into the inner continental shelf.

Coasts are among the most dynamic parts of the earth's surface. The land and the sea rarely meet at a constant boundary. The shoreline migrates daily with the tide; it can change seasonally, and varies over longer time scales as the coast erodes or deposits, or as sea level changes.

Coastal sediment deposits are shaped and reshaped by wave and current processes, which in turn vary through time. The coastal geomorphologist is concerned with the way in which coastal morphology changes with time, both in terms of its present-day dynamics and its longer-term evolution. The techniques by which these morphological adjustments can be determined include monitoring landform changes as they take place, reconstructing past events by comparison of surveys (including maps and aerial photographs), and inferring changes from erosional landforms and depositional sedimentary sequences.

Comparison of coastal landforms from different places can indicate a sequence of modern landforms in different stages of development. The description and interpretation of the sequence of superimposed sedimentary units is called stratigraphy, and stratigraphic units can be examined using subsurface coring or seismic studies. Former shorelines, such as raised terraces or beaches on uplifted coasts or beach and nearshore sediment deposits, give an insight into past coastal conditions. In some cases the shape of a body of sediment can be more diagnostic of environment of deposition than sedimentological characteristics alone, and separate depositional episodes are often distinguished on the basis of surface or subsurface form. Where stratigraphy is examined in association with the shape of former landforms it is called morphostratigraphy. Stratigraphic and morphostratigraphic units provide a sequential, though often incomplete, sedimentary record of past depositional and erosional changes.

Coastal evolution is the study of how and why the characteristics and position of the shoreline have altered (Carter and Woodroffe, 1994). Reconstructions of past coastal landforms are of considerable relevance in view of the dynamic nature of most coastal environments. It is possible to develop 3-dimensional models of the coastal landscape based on sedimentary units (facies) and habitats (paleoecology) determined on the basis of biological remains or activity (e.g. trace fossils). A series of dating techniques have become available which allow a firmer time control on the formation of coastal landforms and sediment deposits (chronostratigraphy). Coastal features may be placed in temporal context based on relative ages, for instance, using archaeological evidence such as artefacts (e.g. pottery, stone tools, midden deposits or other cultural remains), or absolute ages, based on the radiometric decay of a range of isotopes. These analyses reveal that the shoreline has varied markedly in its location through time. For instance, it is now clear that repeated cycles of shoreline adjustment have occurred as a result of sea-level changes (see Chapter 2). Particular sequences of coastal landforms characterise periods of sea-level rise (transgression) and sea-level fall (regression), and complex landforms have developed as a result of erosion and deposition during periods in which sea level has been relatively constant (stillstand).

1.2.2 Coastal morphodynamics

The mutual co-adjustment of coastal form and process is termed coastal morphodynamics (Wright and Thom, 1977). The processes that operate on a section of coast are a function of oceanographic and climatic factors, the nature of the hinterland, and the pre-existing topography. Wave and current processes lead to deposition in some places and erosion elsewhere, modifying form, which in turn alters the rate of operation or effect of the processes themselves. Coastal morphodynamics provides a framework for understanding the interaction of forces and topography that gives rise to the distinctive character of the world's shorelines. Morphodynamic models, based on empirical field and laboratory studies, and supplemented by computer simulations, synthesise these relationships to generate a greater understanding of how coasts operate (Cowell and Thom, 1994).

Models play an important part in the study of the coast, and will play an even more significant role in future, as they become more rigorous and more complex. Models are useful because they are simplifications of real world situations in which it is possible to control variables and look at one thing at a time (see Chapter 9). They also offer a conceptual framework within which patterns of coastal evolution can be extrapolated from one site to another (Carter and Woodroffe, 1994). For example, Figure 1.1a represents a 'model' of the planform of a section of coast, whereas the photograph in Figure 1.2 shows that a real coast is much more complex than the model implies. Nevertheless, several of the key features of the relationship between landforms in an estuary or embayment are portrayed schematically in the 'model' in Figure 1.1a, and this simplification will be used several times in subsequent chapters to generalise about the way that such systems operate. Quantitative models can be developed where there is a good understanding of the interrelationships between form and process. Computer simulations can be based on patterns of change inferred over long time scales and consistent with processes known to operate over shorter time scales (see Section 1.4 below). Simulation modelling is not intended to reconstruct past or predict future coastal evolution exactly, but provides a tool for experimentation and extrapolation within which broad scenarios of change can be modelled and sensitivity to variables examined.

In Chapters 4–8, emphasis is placed on morphodynamic models and their ability to help understand the way that particular coasts function and change with time, synthesising process studies on modern coastal landforms with reconstructions of the way in which coasts have evolved. The response of coastal landforms to rare extreme events or to changes in controlling variables such as oceanographic conditions needs to be understood. The way in which coasts respond to human impacts is less clear, and has become a major challenge for coastal geomorphologists to address (see Chapter 10). The threat of future anticipated sea-level rise as a result of the enhanced greenhouse effect has focused effort towards applied studies of coasts, a trend that will increase in the 21st century. However, it needs to be emphasised that it has only been in recent decades that understanding of the timing and magnitude of Quaternary sea-level changes has improved, and many of the fine details, and the way in which the coast responds, remain to be resolved.

Our understanding of how coasts operate is based on an ever-increasing body of scientific knowledge. The most widely accepted interpretations of today will be revised as that body of knowledge increases further. It is important to recognise that modern models and interpretations are based on the research and insights of many past coastal scientists. The development of ideas in coastal geomorphology, as in other disciplines, comprises a web of interwoven and recurring conjecture, theory and empirical (field and laboratory) study. Many elements of contemporary theory and models can be seen to have a firm basis in early concepts of coastal geomorphology, such as shoreline development through juvenile and mature stages, or the operation of a cycle of change. Consideration of the history of how ideas have changed provides an important perspective on modern theories and models. For this reason, each of Chapters 2–8 also begins with a brief historical perspective on the development of scientific knowledge as background.

This chapter expands on these themes in coastal geomorphology. First, a brief historical perspective of the development of ideas in coastal geomorphology is given, recognising some of the key researchers and research schools that have contributed to ideas which are developed further in subsequent chapters. Second, time scales and space scales appropriate for the study of coastal geomorphology are discussed. Third, a systems approach to the study of coasts is outlined, and some of the fundamental concepts such as feedback and equilibrium are defined. It is important to recognise that human influence now plays a role in most coastal systems and needs to be considered in the longer-term management of coasts. In the chapters that follow, individual coastal landforms are discussed in terms of their morphodynamics. These morphodynamic concepts are re-evaluated in Chapter 9 drawing together themes that emerge from the discussion of various types of coast. The final chapter considers briefly the influence that humans have, or have had, and recognises that this role will become increasingly prominent in study of coasts in the future.

1.3 Historical perspective

People have always been fascinated by the coast; study of the coast is probably as old as any study. The Greeks described the delta at the mouth of the River Nile; Herodotus remarked on the similarity of its shape to the Greek letter 'delta'. The arcuate curvature of the shoreline was accurately portrayed by Leonardo da Vinci in his plan for draining the coastal Pontine Marshes in Italy in the 15th century. However, the first true scientific interest in coasts began post-Renaissance in the context of navigation beyond the Mediterranean. Surveys by hydrographers (e.g. Bellingshausen, Wharton) were essential components of global exploration; geological and biological studies were often extensions of such survey work, undertaken by naturalists.

1.3.1 Pre-20th-century foundations

Coastal geomorphology has its foundations in the geological studies that followed from the recognition of the destructive work of the sea along coastlines (e.g. Lomonosov, 1759). Voyages of discovery, particularly those of Captain James Cook, had increased the known shores, and the naturalists who followed described landscapes in detail. Exploration and survey enabled recognition of the operation of modern-day processes over long periods of time to achieve substantial erosion or deposition, the concept of uniformitarianism (Hutton, 1788; Playfair, 1802). The geological ideas which were derived from this principle (Lyell, 1832; de Beaumont, 1845) matured into the study of physiography, which emphasised the interconnectedness between causal processes and resulting landforms (Huxley, 1878).

The 19th century was a time of increased scientific awareness of the diversity of the world. Charles Darwin's voyage on the Beagle, and James Dana's travels as part of the United States Exploring Expedition led to numerous observations by these great geologists as to how the coast had come to look as it now does. Darwin realised the significance of tectonic activity, not only in terms of the uplift that he observed along the coast of South America, but also in terms of subsidence that he could infer as a process in reef-forming seas (Darwin, 1842). Darwin's 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 1.3) provides one of the earliest examples of a conceptual model of coastal

a) Fringing reef

b) Barrier reef

c) Atoll

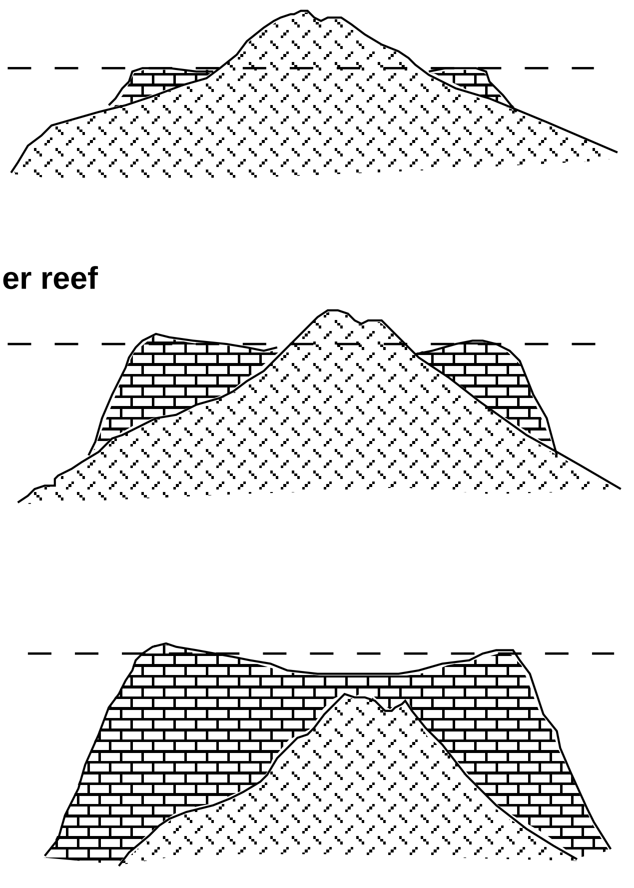

Figure 1.3. Schematic representation of the progression deduced by Charles Darwin showing how (a) fringing reefs around a volcanic island would develop into (b) barrier reefs and barrier reefs would develop into (c) an atoll, as a result of subsidence and vertical reef growth (based on Huxley, 1878).

evolution (preceding publication of his views on evolution of species). It has been largely substantiated by subsequent studies (see Chapter 5), and has stimulated development of other models of coastal change. Dana enthusiastically promoted Darwin's theory recognising that the embayed nature of the shoreline on reef-encircled islands in the Pacific Ocean supported the concept of subsidence, and he described shore platforms (see Chapter 4) and discussed their formation (Dana, 1849).

Detailed interpretations by Grove Karl Gilbert of the stratigraphic relationships of sedimentary units associated with terraces in Lake Bonneville marking abandoned Pleistocene shorelines provided a foundation upon which modern concepts of shoreline equilibrium would become based (Gilbert, 1885). An early classification of coasts recognised straight (Pacific) coasts where the structure of the landscape runs parallel to the shoreline, and irregular (Atlantic) coasts where the structure is at an angle to the shoreline (von Richthofen, 1886; Suess, 1888).

1.3.2 Early-20th-century geographical context

William Morris Davis played a pivotal and charismatic role in physical geography at the close of the 19th century, and his idea of a 'geographical cycle' of uplift and erosion was widely adopted during the early 20th century (Davis, 1899, 1909). Davis was primarily concerned with the development of terrestrial landscapes, recognising the importance of structure, process and time. He emphasised time as the prime factor, and thought of it as progressive, irreversible and orderly. Davis believed that the cycle of erosion, punctuated by periodic uplift rejuvenating an eroded landscape, would have implications for the coast. Figure 1.4a indicates how Davis believed a coast would evolve in planform becoming less indented over time, with erosion of promontories and infill of embayments (Davis, 1896). It shows a remarkable similarity to his concept of planation of the landscape in profile (with reduction of relief and peneplanation of the landscape).

Figure 1.4b shows a detailed study of the evolution of the Provincelands spit at Cape Cod, Massachusetts, by Davis (1896). The initial morphology was hypothesised, and subsequent change was

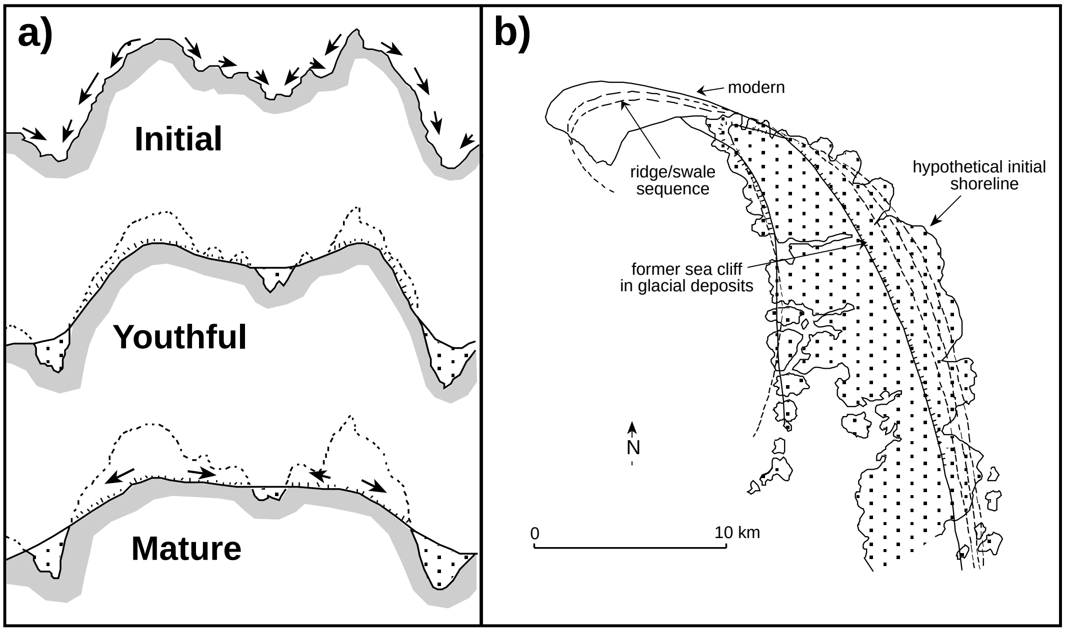

Figure 1.4. The Davisian cycle as applied to the coast. (a) Schematic representation of planform stages as conceived by W.M. Davis. A shoreline progresses from an initial rugged form, through maturity, to a regularised shoreline that is cliffed and infilled with sand (stippled). The arrows indicate direction of sediment movement. He envisaged this in parallel to the geographical cycle of erosion by which mountains (like the initial shoreline form) would be reduced to a peneplain (like the ultimate mature shoreline). (b) Schematic evolution of Cape Cod, Massachusetts (based on Davis, 1896).

accommodated into the progression from youth to maturity. Davis reconstructed the previous positions of the spit's shoreline pivoting around a fulcrum of spit development, and suggested an equilibrium profile developed offshore. Whether the northern end of the spit has really been characterised by a sequence of ridges each of the same length but building seaward (Davis, 1896), or whether the whole spit has remained constant in width but grown longer (Zeigler *et al.*, 1965), is still unresolved (FitzGerald *et al.*, 1994).

The Davisian cycle of erosion was 'by intention a scheme of the imagination and not a matter of observation' (Davis, 1909, p. 281). The concept was extended and applied to coasts by a series of successors (Gulliver, 1899; de Martonne, 1906, 1909), most notably by Douglas Johnson. Johnson included in the study of coastal evolution not only the description of landforms, and the historical reconstruction of the origin of a particular shore, but also a framework in which to view the systematic evolution, from initial to sequential forms. Figure 1.5 shows progressive stages of coastal evolution as proposed by Johnson (1919). He believed that initial form exerted a control on the first stages of coastal erosion. The coast passed through a youthful stage in which there was the greatest diversity of beaches barriers and spits. On the coast of New England, reworking of glacial deposits provided episodic

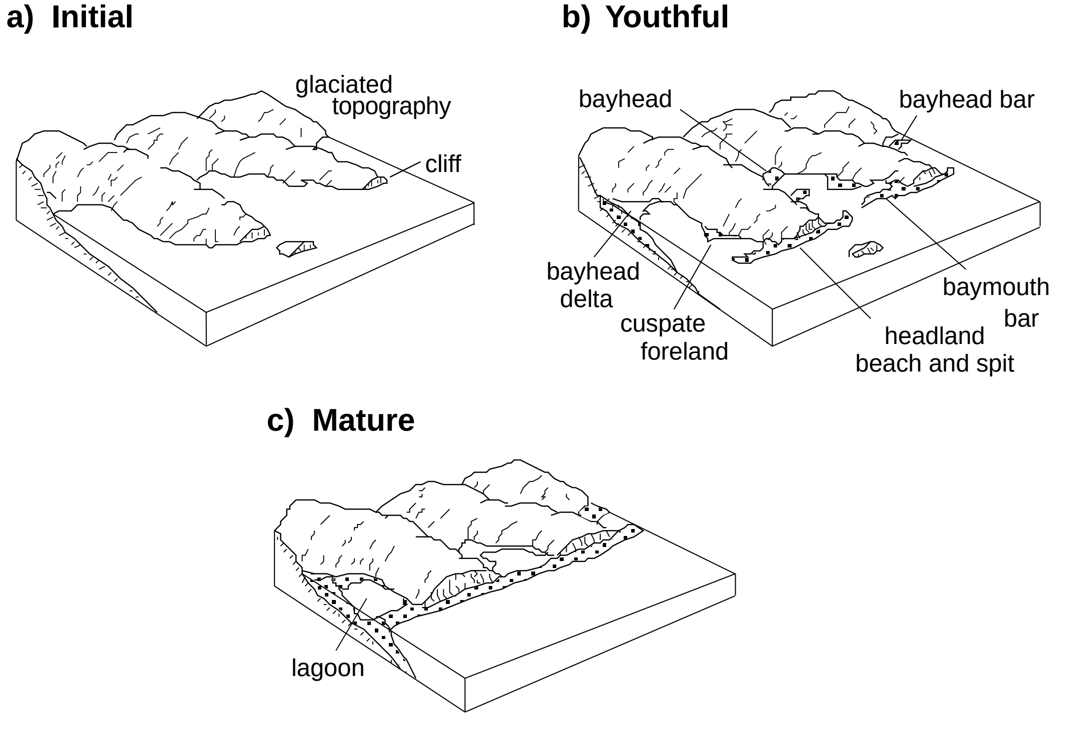

Figure 1.5. Schematic stages in the evolution of a shoreline of submergence as envisaged by Johnson (1919, 1925), (a) initial, (b) youthful and (c) mature.

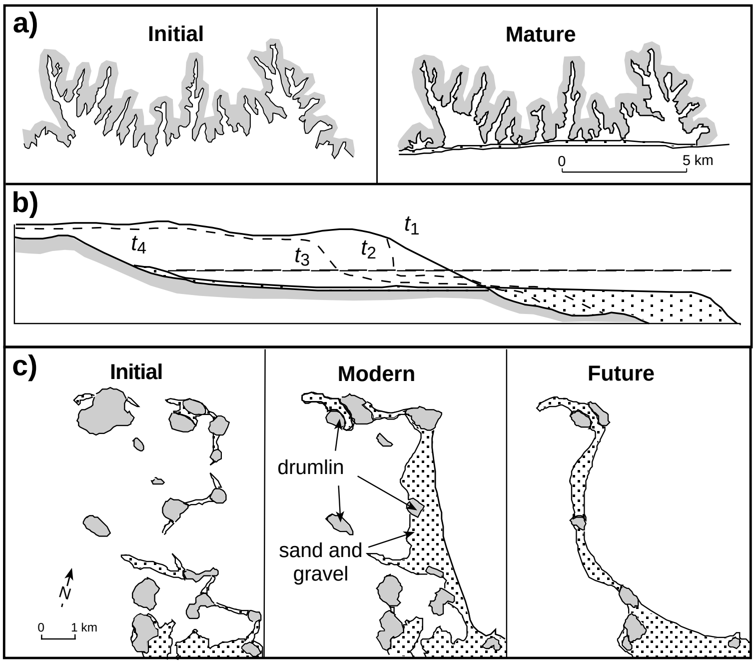

Figure 1.6. Evolution of the coast as envisaged by Johnson. (a) Schematic evolution for the Martha's Vineyard area of New England, showing the hypothesised initial and the modern regularised, mature form of the shore. (b) Stages in the development of an equilibrium shore profile as envisaged for a shoreline of submergence by Johnson (based on Johnson, 1919). (c) Schematic evolution of Nantasket Beach, Massachusetts, showing inferred initial, modern and hypothesised future stages (simplified from Johnson and Reed, 1910).

supply of a range of sediment sizes (Johnson, 1925). In mature stages the coast became less complex. These ideas provided a framework within which to view coastal evolution, and a sequence by which it might be possible to reconstruct former, or future, coastal configurations. Johnson's book on the formation of the Acadian–New England coast is a magnificent example of the use of a selection of landforms in space to infer a sequence through time (Johnson, 1925). Johnson adopted the idea that the coast would become less embayed with time; Figure 1.6a shows his reconstruction of initial form of the coast around Martha's Vineyard, Massachusetts, in comparison to its modern form (Johnson, 1919).

The concept of equilibrium is an important one in coastal geomorphology, and one which is central to much of this book. Johnson believed that the offshore profile formed in soft sediments would tend towards an equilibrium shape within the context of the geographical cycle. The nature of erosion and sedimentation on continental shelves was hypothesised on the basis of very sparse field data, and led to the concept of a nearshore equilibrium profile (Figure 1.6b). This wave-formed terrace was considered to develop as a balance between oscillatory wave action and undertow versus onshore currents (Fenneman, 1902). This early concept of an equilibrium profile applied to continental shelves has not been upheld in the context in which it was initially proposed (Dietz, 1963; see also Chapter 4), although it remains an issue of debate in relation to beach and barrier coasts (Dean, 1977, 1991; see also Chapters 6 and 9).

Figure 1.6c is a detailed coastal reconstruction of Nantasket Beach, on the southern side of Boston Harbor, Massachusetts (Johnson and Reed, 1910). Drumlins, elongate or oval mounds of glacial deposits formed beneath ice sheets, are eroded by wave action and their sediments become incorporated into beaches and spits. Spits connect existing, eroding drumlins, and a sequence of prior drumlins can be envisaged before retreat of the coast to its present position. Drumlins anchor beaches and spits; when they are finally eroded, the beaches retreat landward until they intersect the next drumlin. Johnson and Reed (1910) used this logic to project how a future stage might look (Figure 1.6c). Their interpretations of shoreline reworking of drumlins remain important in understanding this coastline, although it does appear that well-sorted sand has also been derived from an offshore source, and not solely from the drumlins (FitzGerald *et al.*, 1994). This approach to the explanation of coastal evolution, adopted by Johnson, has been the foundation for the development of many conceptual models in coastal geomorphology. The drumlin coast of New England and Nova Scotia has also continued to play a central role in the development of morphodynamic models (Carter and Orford, 1993; Forbes *et al.*, 1995).

The distinction between relative fall (emergence) or rise (submergence) of the sea in relation to the land (Davis, 1909) was extended by Cotton (1916) and particularly by Johnson (1919), who recognised coasts of emergence and coasts of submergence, as well as compound and neutral coasts. However, although Johnson's approach placed relative sea-level changes central to the classification of coasts, it preceded a clear understanding of the way that sea level had fluctuated. Evidence from numerous shores indicating that the sea level had varied, and the realisation that there had been considerable changes in ocean volume associated with the ice ages (Daly, 1910, 1925, 1934) became a central theme for much of the rest of the century.

The Davisian concept of cycles of erosion, progressing through youth, maturity and old age, was heavily influenced by Darwinian evolutionary theory (Stoddart, 1966). It was an approach based on explan-

Table 1.1. Three mid-20th-century approaches to the classification of coasts

Shepard, 1948	Valentin, 1952	Cotton, 1954
I Primary or youthful coasts	I Advancing coasts	I Coasts of stable regions
(a) shaped by terrestrial erosion	(a) emerged coasts	(a) recently submerged
(b) shaped by terrestrial deposition	(b) constructional coasts	(b) previously emerged
(c) shaped by volcanic activity	(i) organic (mangrove, coral)	(c) miscellaneous
(d) shaped by diastrophism	(ii) inorganic (marine, alluvial)	II Coasts of mobile regions
II Secondary or mature coasts	II Retreating coasts	(a) recently submerged
(a) shaped by marine erosion	(a) submerged coasts	(b) recently emerged
(b) shaped by marine deposition	(i) glacial (eroded, deposited)	(c) fault and monoclinal
	(ii) fluvial (folded, flat-lying)	(d) miscellaneous
	(b) retrograded (cliffed)	

atory description, whereby generalising principles were inferred, and observations were interpreted within a preconceived cycle (Rhoads and Thorn, 1996). Meanwhile, the inductive empiricism of geologists such as G.K. Gilbert, in which field observational data were collected based on theoretical premises with the objective of testing between competing or multiple working hypotheses (Gilbert, 1885), received relatively little attention until the second half of the 20th century.

1.3.3 Mid-20th-century coastal studies

During the mid 20th century the development of coasts was considered within the context of complex denudation chronologies that were based on geographical cycles of erosion. Examples include the Weald in south-eastern England (Wooldridge and Linton, 1938, 1955) and the landscapes of Wales (Brown, 1960). These and other interpretations were constrained by presupposition that the landscape had undergone a series of cycles of uplift and gradual erosion. In the absence of techniques to date land surfaces, studies were inevitably conjectural and subject to varying interpretations. Many such landscape narratives have been refuted now that geochronological techniques are available to provide a partial time frame.

Considerable effort was directed towards the classification of coasts. Classifications were either descriptive, concerned with features visible in the modern shoreline, or genetic, concerned with how the coast had evolved. Table 1.1 outlines the principal divisions within three of the more popular schemes (Shepard, 1948; Valentin, 1952; Cotton, 1954). The basic variables which were used to classify different types of coast included the structure of the coast, stage of development, relative movements of land and sea, and progradation and retreat of the coast.

Several classifications expanded Johnson's ideas, either extending the concept of youthful versus mature, or the distinction between submerging and emerging coasts. Although several different coastal classifications were proposed, none received universal acceptance (McGill, 1958; Tanner, 1960; Russell, 1967; King, 1972; Shepard, 1976).

Major descriptive studies were undertaken, with inferred time frames for development; an outstanding example is the history of the Mississippi River valley and delta in the United States by Fisk (1944). Similar detailed coastal studies were undertaken by extremely active individual researchers such as Schou (1945) in Denmark, Kuenen (1950) in Holland, Steers (1953) and King (1959) in Britain, Guilcher (1958) in France, Zenkovich (1967) in Russia, Russell (1967) in the United States, and Cotton (1974) in New Zealand. These, and studies by other researchers, provided the material from which it was possible to develop generalisations from field-based observational facts, drawing upon similarities (or, in some cases, dissimilarities) from wide geographical areas.

During the 1950s and 1960s geomorphology as a whole became more focused upon process operation within the landscape (Strahler, 1952a; Hack and Goodlett, 1960). Process studies had already become an important element of the study of sediment movement in coastal environments (Reynolds, 1933; Saville, 1950; Rector, 1954), with strong traditions established at the University of Cambridge (Lewis, 1931) and in London (Bagnold, 1940, 1946), on which further studies could be based. The growing acceptance of the unifying concepts of plate tectonics provided a framework within which the distinction between Pacific (active plate margin) and Atlantic (passive plate margin) coasts (see Chapter 2) could be placed (Inman and Nordstrom, 1971). Coastal studies provided the foundations from which marine geology and oceanography were to develop.

The poor level of understanding of beach environments had been highlighted by several situations during World War II where landing craft and military personnel had experienced difficulties with beach landings because of the dynamic nature of coastal landforms (Williams, 1960). Research programmes funded through the Geography Program of the US Office of Naval Research in the United States, many based at the Coastal Studies Institute at Louisiana State University or Scripps Institute of Oceanography in California, played a central role (Shepard and Wanless, 1971). The initiation of the Beach Erosion Board in the US Corps of Engineers, later the Coastal Engineering Research Center (Krumbein, 1944), the Wallingford Hydraulics Research Laboratory in Britain, and Delft Hydraulics in the Netherlands reflected these directions of research effort. They have given rise to an extensive body of knowledge on beach behaviour (Bascom, 1964; Komar, 1976), discussed in Chapter 6, with recognition of a series of beach types responding to the energy conditions to which the beach has been subjected.

1.3.4 Late-20th-century process and historical geomorphology

While some coastal geomorphologists were focusing on process studies using laboratory and field experimentation, historical geomorphology was also continuing to expand, especially in the context of sea-level history. The development of dating techniques had a major impact. Availability of radiocarbon dating, especially its application to interpretation of the behaviour of the Mississippi River and the Gulf of Mexico coast, led to some classic studies (Gould and McFarlan, 1959; Frazier, 1967). Geochronology brought a new rigour to studies of coastal evolution and, although not without problems associated with interpretation, provided a means of calibrating rates of development that had previously been conjectural. An approach based on dating the past began which continues to provide a strong focus for coastal geomorphology.

It became clear that sea level, which has been close to its present level during interglaciations and 80–150 m below present during glaciations, had been an important constraint on coastal evolution. Sea-level curves, indicating a presumed global eustatic sea-level trend, were compiled by Fairbridge (1961) and many others. It soon became apparent that sea-level history was different at different places in the world (see Chapter 2), and INQUA (International Quaternary Association) and IGCP (International Geological Correlation Program) projects began to document this variability (Bloom, 1977). Identification of relative sea-level history from individual locations, establishment of regional variability and compilations of global syntheses have been objectives of much recent coastal research (Pirazzoli, 1991, 1996). A further incentive to understand coastal response to sea-level variation in the final decades of the 20th century has been the anticipation of accelerated sea-level rise as a result of the enhanced greenhouse effect (Bird, 1993a).

Coastal studies up until the 1960s had been heavily focused on the shores of northwest Europe, North America and the Soviet states. These coasts are not particularly representative of the world's shorelines as a whole (Davies, 1980); many are still experiencing isostatic adjustment to the melting of Pleistocene ice sheets (see Chapter 2), and are shaped by winter storms (see Chapter 3). Coastal studies were considerably broadened as a result of a series of major overseas research projects, many funded by the US Office of Naval Research. There also developed strong research schools within other countries, including Japan (Horikawa,

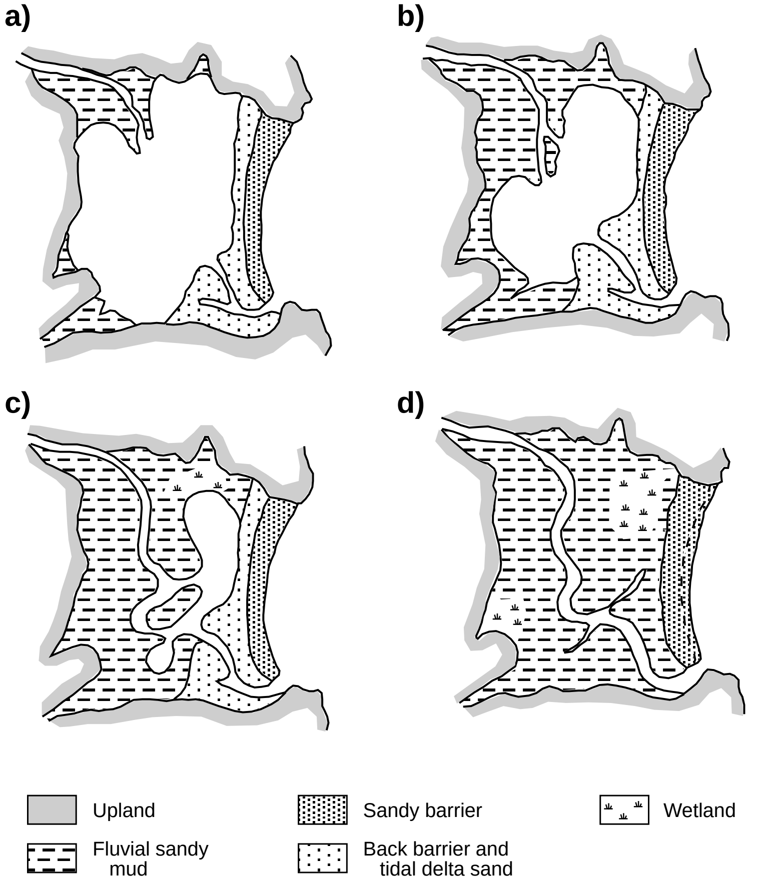

Figure 1.7. Stages in the evolution of barrier estuaries in southeastern Australia. Individual estuaries can be seen that are in each of these different stages (after Roy, 1984). See detailed discussion in Chapter 7.

1988) and Australia, where individuals, such as Trevor Langford-Smith and Joe Jennings, inspired coastal geomorphology research groups at the Coastal Studies Unit of the University of Sydney and at the Australian National University. Research studies combined an understanding of variation in process operation with geomorphological reconstructions of the evolution of landforms (McCann, 1977). These syntheses led to the development of a morphodynamic approach, emphasising the co-adjustment of form and process (Wright and Thom, 1977), and this morphodynamic emphasis has provided the focus for many of the studies described in this book.

Figure 1.7 is an example of an evolutionary model that developed from this collaborative research. It records the stages of Holocene evolution of barrier estuaries in southeastern Australia as a result of sediment input by the contributing river and landward reworking of sand by wave and tidal processes. Sharp gradients in transport potential lead to progressive infill of the muddy estuarine embayment until the river becomes channelised through wetlands and sediment bypasses the estuary and is carried directly to the sea (Roy, 1984; Roy *et al.*, 1994).

Sea-level change has also been shown to be a prominent control on the longer-term stratigraphy of coastal and nearshore sediments in large sedimentary basins as part of development of seismic and other geological studies, called sequence stratigraphy (Vail *et al.*, 1977). Sequence stratigraphy involves recognition of major depositional cycles (termed systems tracts) when the sea was low (lowstand systems tracts) and when it was high (highstand), as well as transgressive systems tracts when it was rising (Miall, 1996). The sequence stratigraphical approach of sedimentologists and the morphostratigraphic approach of coastal geomorphologists can be combined. For example, the classification of sedimentary environments in relation to a continuum of wave and tidal processes proposed by Boyd *et al.* (1992) provides a framework which is described in detail in later chapters (see Figure 7.5).

As a result of conceptual developments during the 20th century, coastal landforms were regarded as very dynamic, responding to frequently changing external factors (boundary conditions) including climate and sea level. This increasing body of coastal studies and literature made possible a series of global syntheses and comparisons of shoreline and coastal types (Bird, 1976; Davies, 1980; Bird and Schwartz, 1985; Kelletat, 1995). It became apparent that coastal sedimentary environments not only responded passively to external stimuli but are also capable of a series of internal morphodynamic adjustments (Chappell and Thom, 1986; Cowell and Thom, 1994).

In the 1990s, concerns about global change, particularly sea-level rise (Barth and Titus, 1984), have given a new impetus to the study of coasts, re-uniting historical and process geomorphology (Bird, 1993a). Major international initiatives, such as the International Geosphere Biosphere Program (IGBP), combine patterns of past behaviour with process studies to address issues relating to future coasts at scales relevant to planning and coastal management (see Chapter 10). In order to be able to extrapolate across scales in time or in space it is necessary to examine the space and time scales over which processes operate and coastal landforms evolve.

1.4 Temporal and spatial scales

The study of coasts is concerned with a range of scales in both space and time. In the case of space, the width of the coastal zone can vary substantially. In some cases it is necessary to include the continental shelf and much of the coastal catchment, for instance where sediment flux is traced from river catchment across a delta and down a submarine canyon. In other cases, such as high cliffs plunging into deep water, there may be little more than the cliff face itself and some salt-affected cliff-top vegetation communities, which are relevant to coastal studies.

The scale of study can also vary in relation to the lithological and sedimentary characteristics of the coast. Featureless cliffs can extend for hundreds of kilometres and change little in either time or space. On beaches, however, subtle sorting of grain size and microtopography of bars can result in variations along the shoreline over a few metres, which change over the progress of a tidal cycle or in response to storms or seasonal events.

There is a hierarchy of time scales relevant to coastal geomorphology. Geologists are generally concerned with events that occur over geological time. Rocky coastal topography can have originated from events that occurred millions of years ago, formed or shaped in the Tertiary or earlier. Other shoreline features have been shaped during the pronounced climate changes of the Quaternary (the past 2 million years, characterised by a sequence of glacial and interglacial phases, termed the Pleistocene, and the past 10 000 years of postglacial, termed the Holocene). Engineers and coastal managers may be more concerned with providing an estimate of the amount of erosion by individual events through observation of processes of sediment movement on a beach during one storm or one season. Coastal geomorphology needs to study landforms at each of these scales; it may be appropriate to consider several time scales to understand adequately modern coastal management issues.

Geomorphological study of landscapes has recognised three time scales: geological time (often termed cyclic time, reflecting the long-term geographical cycle of W.M. Davis); graded time at which a river tends toward a dynamic equilibrium with landscape denudation; and steady-state time, a short-term perspective within which external factors (boundary conditions) are considered not to change (Schumm and Lichty, 1965). There have been attempts to extend these time scales to coastal systems. For instance, the adjustment of soft-rock cliffs composed of glacial deposits in eastern Britain has been considered within cyclic (several thousand years), graded (2–100 years), and steady-state (<1 year) scales (Cambers, 1976). It is convenient to recognise relative scales such as megascale, macroscale, mesoscale and microscale adjustments. However, these terms have been used to cover different scales for different coastal types. For instance, beach adjustment has been described at megascale (10–20 ka), macroscale (7 days – 6 months), and microscale