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Part I

Introduction

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Introduction

1.1 Humans and the coastal zone

Beaches and, more generally, the coastal zone occur at the interface between the three major natural systems at the earth's surface – atmosphere, ocean and land surface. Processes operating in all three of these systems are responsible for shaping the coastal zone, and the interaction between the three different sets of processes makes the coastal zone an extremely dynamic one. The coastal zone is also a zone of transfer of material from the land surface to the ocean system, with sediments eroded by rivers, glaciers, etc., being moved to the beach and nearshore, and ultimately some to the ocean floor. In some areas accumulation of sediments may add to the land mass.

The focus of this book is on describing the physical processes that act to shape the coast and the landforms that make up the coast. As in any other branch of applied science, we can study these for their own interest, without the need to justify it in terms of potential benefits. However, in addition to its geomorphological significance, the coastal zone is particularly important from a human perspective. A large proportion of the world population is concentrated in the coastal zone, including almost all of the major cities. The coastal zone is used for fishing, transportation, recreation, waste disposal, cooling and drinking water and is potentially a source of energy from tidal and wave power. Many of these activities pose an environmental threat to coastal systems, both physical and biological, through pollution, siltation, dredging, infilling and a host of other activities that alter the way natural systems operate. In recent years there has been increasing pressure from leisure activities focused on water sports, and recreation at the seashore (Figure 1.1). In addition, natural processes often pose a hazard to human occupation and utilisation of the coastal zone through wave action, flooding, storm surge, and through coastal erosion and sedimentation. Because of the threats to human life and activities posed by both environmental impact and natural hazards, there is a strong economic incentive to improve our understanding of processes operating in the coastal zone so that we can minimise their effects, and use this knowledge in the development of comprehensive coastal zone management planning.

Each maritime country has a unique perspective of their coastline, shaped by history and culture, and by the physical and biological nature of the coast itself. There are commonalities among great differences; for example, the people of the Netherlands and of the Maldives both face a similar threat posed by a dense coastal population and rising sea level even though one nation is situated on a large delta that has largely been reclaimed by dyking and the other sits on a small coral atoll. In the United States a Federal Agency, the US Army Corps of Engineers has played a key role in coastal development and the management of coastal hazards and they have been in the forefront of applied research on coastal processes and engineering. In Canada there is no equivalent federal agency

Figure 1.1 Examples of recreational pressures on the coast: (A) beach, promenade and sea front shops and apartments, Malo les Bains, Dunkerque, France. Development of the seafront in many coastal towns in Britain, France and Western Europe began in the late nineteenth century with the advent of cheap rail travel. Small seafront guest houses are being replaced by apartments that are used for weekends and holidays; (B) resort development, Frigate Bay, St Kitts, West Indies in June, 2008. The advent of cheap air fares from northern parts of the USA, Canada and Western Europe has fuelled resort development on a massive scale in Florida and much of the Caribbean. Developments here include a large five star hotel and golf course, other smaller hotels, time share and condominium apartments and individual houses that are privately owned or rented.

and the relatively small population and limited resources has left a much greater proportion of the coast relatively pristine.

My own experience has been shaped by living in Canada and by carrying out much of my research here. Canada has one of the longest marine coastlines in the world, totalling nearly 250 000 km and bordering on three oceans (Figure 1.2). It has an additional 15 000 km of coastline in the Great Lakes and tens of thousands more along smaller, but still significant lakes. There is a great variety of coastal environments. The Pacific coast is dominated by swell waves and is generally ice free, while the Arctic coast is dominated by the presence of ice year round and, in the eastern Arctic by ongoing post-glacial isostatic uplift. The East coast experiences strong mid-latitude storms as well as the effects of one or two hurricanes a year, and much of it is influenced by a seasonal ice cover. On this coast the tidal

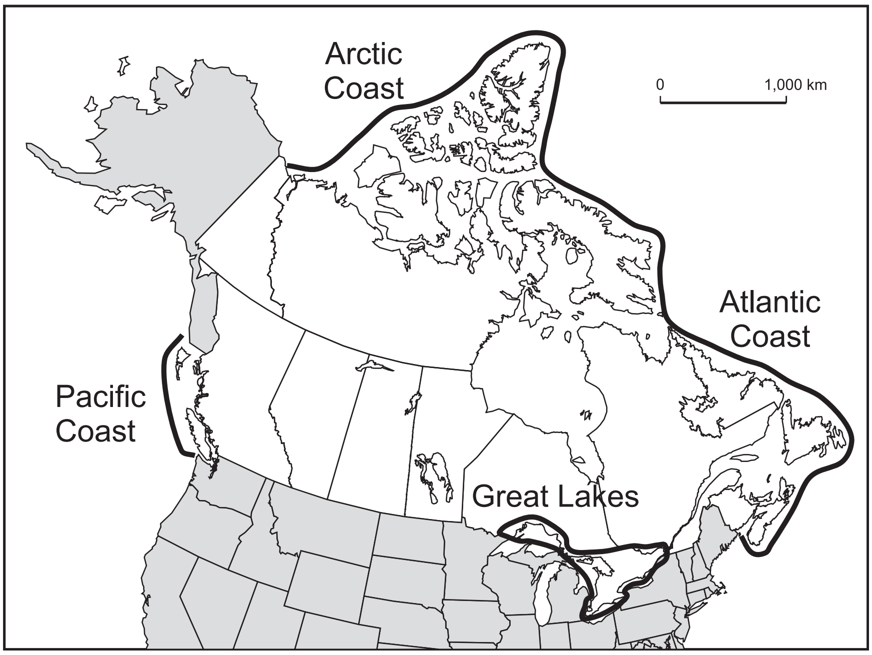

Figure 1.2 Primary divisions of the coasts of Canada (Owens, 1977)

range is <1 m in parts of the Gulf of St Lawrence and may be over 15 m in the Bay of Fundy. Finally, the Great Lakes are freshwater, but act as small seas, with tides being replaced by seasonal and long-term water level fluctuations. Like the Atlantic coast, seasonal ice foot development occurs in all the lakes and there is considerable surface ice cover on Lakes Erie and Huron.

Almost all of the population of Canada lives within 50 km of one of these coasts, and more than half along the Great Lakes-St Lawrence system. All of the activities noted above are carried out on the coast and thus the coastal zone is as significant for Canada as it is for any other country. The potential impact of oil exploration and exploitation off the Arctic and Atlantic coasts, destruction of coastal wetlands and interference with longshore sediment transport, as well as the effects of coastal erosion and storm wave damage are examples of some of the conflicts that exist in the Canadian coastal zone and that provide a stimulus for developing an improved knowledge and understanding of the features and processes. There is also recognition that human-induced climate change will have a significant impact on many of the coastal areas of Canada, as it will in many other parts of the world.

1.2 Approaches to the study of coasts

Geomorphology encompasses the study of the landforms of the earth and the processes that form them, especially those that lead to the erosion, transport and deposition of sediments. The focus of coastal geomorphology is therefore on the morphology of the coastal zone and on processes such as waves, tides and currents that act to shape features as disparate as high rock cliffs, low coral atolls, and sandy beach and dune systems. Research in coastal geomorphology is greatly influenced by other fields of geomorphology, especially fluvial and aeolian geomorphology, and there is a common set of paradigms, instrumentation and methodology.

The coastal zone and coastal processes are also the subject of study by a number of other disciplines, each of which brings a different focus or approach. In particular there is considerable overlap of interest between coastal geomorphologists and sedimentologists, coastal oceanographers and coastal engineers in the study of waves and currents, and coastal erosion and deposition. While the ultimate objectives of the different disciplinary groups may be somewhat different, they share a common interest in expanding our understanding of these physical processes. In the past few decades many of the artificial barriers that often separated these groups have disappeared. This is evident in the range of disciplines represented at international coastal conferences, in the groups of collaborators carrying out large projects, and in the contributors to most of the journals that appear in the reference lists at the end of each chapter in this book.

There are also areas of overlap between coastal geomorphologists and biologists studying plant and animal life in coastal waters, beaches, estuaries and marshes. Waves and currents may place stresses on plants and animals on the coast and in shallow water and they may also be important for dispersal of organisms. An understanding of processes of erosion and deposition may be helpful in the study, for example, of shellfish and a variety of other organisms that live in surface sediments of the sandy beach and nearshore environment. The interaction between plants and wave and current action is important in the study of sea grass beds and coastal marshes. On the one hand, waves and currents impose stresses on plants, and on plant establishment, and on the other hand the presence of the vegetation serves to modify flow conditions near the bed and to stabilise the substrate. A similar relationship exists for coral reef systems. The coastal zone provides a habitat for many species of fish and shellfish, and some open water species may breed in coastal waters. Estuaries and marshes may play a significant role as nurseries for juvenile fish and so Fisheries Biologists have an interest in the functioning and conservation of these systems.

1.3 Information sources

There is a long history of the study of coastal processes and landforms and in the past 50 years or so there have been a number of textbooks, published in English, aimed at various levels of undergraduate and graduate instruction, and as resources for researchers of all kinds. Two books by D.W. Johnson (Johnson, 1919, 1925) provide a wealth of information about the coast of the United States and approaches to the study of coasts in the early twentieth Century. After 1950 there was a rapid growth in studies of coastal geomorphology, marked by the appearance of the first edition of *Beaches and Coasts* by Cuchlaine King (King, 1959) and a popular book by Willard Bascom (Bascom, 1964). Both of these highlighted research experiences that began in the Second World War. An English translation of a text by Zenkovitch (1967) provided access to a considerable body of literature from what was then the Soviet Union. The US Army Corps of Engineers through the Beach Erosion Board and later the Coastal Engineering Research Centre published the *Coastal Engineering Manual* which provided background on coastal processes, particularly waves, wave hindcasting and sediment transport as well as engineering applications. While designed primarily to support practising coastal engineers, it proved a useful source for people interested in physical processes in the coastal zone. The last paper edition was published in 1984 and updated versions are now available in PDF format on the web. Finally, an eclectic book by Jack Davies (1972) emphasised the importance of climate, tidal range and wave climate in controlling coastal processes and coastal evolution.

The past thirty years have seen a number of textbooks that provide a variety of different perspectives and many of these still provide a good source for information and insights on both processes and coastal landforms. Included in these are books by Komar (1998); Davis (1984); Carter (1988); Carter and Woodroffe (1994); Bird (2000); Trenhaile (1997); Short (1999) and Woodroffe (2002) which were all generally aimed at senior undergraduates, graduates and researchers. There are also a number of texts that are devoted to one aspect of coastal geomorphology, such as Sunamura (1992), Trenhaile (1987), Nordstrom (2000), and to Coastal Engineering (Kamphuis, 2000). Books by Pethick (1984), Masselink and

Hughes (2003) and Davis and FitzGerald (2004) were aimed at providing an introduction to the subject that was accessible to undergraduates, both in terms of content and affordability.

In addition to the specialist texts in coastal processes and geomorphology, much of the material in this book is drawn from articles published in journals and conference proceedings. While the material in this book can be read on its own, one of its aims is to provide sufficient basic information on vocabulary, methods and processes to make exploring this literature much easier. Almost all the journals are now available online. Many provide access to back issues that go back twenty years or more and, increasingly, they provide a number of routes to access related publications. The *Journal of Coastal Research* provides broad coverage of all the material covered in this book and includes physical and biological processes, aspects of coastal management and case studies from around the world. There is also considerable coverage in *Marine Geology*, *Continental Shelf Research*, *Coastal Engineering* and the *Journal of Estuarine, Coastal and Shelf Science*. Both *Geomorphology* and *Earth Surface Processes and Landforms* encourage papers on coastal geomorphology. Useful updates can be found in *Progress in Physical Geography* and substantial reviews often appear in *Annual Review of Fluid Mechanics* and *Annual Review of Earth and Planetary Sciences*.

Conferences provide a major forum for the exchange of information and ideas and published conference proceedings still provide a useful source of new information. The Coastal Engineering Conferences sponsored by the American Society of Civil Engineers (ASCE) which began just after World War II are held every two years and more specialised ones such as Coastal Sediments and Coastal Dynamics every four years. The Coastal Education Research Foundation, which sponsors the *Journal of Coastal Research*, also sponsors an international Coastal Symposium which is held every two or three years in countries around the world. In Canada the first coastal conference was held in Halifax in 1978 (McCann, 1980) under the auspices of the Geological Survey of Canada. Beginning in 1980, Canadian Coastal Conferences were held every two or three years, sponsored initially through a committee of the National Research Council and later by its successor the Canadian Coastal Science and Engineering Association (CCSEA). They brought together scientists from a range of disciplines as well as coastal engineers and some people working in coastal management. They also sponsored several specialist conferences, including one on cohesive shores and another on coastal dunes.

There is of course a vast amount of material available on the web from real time access to data from wave buoys and cameras set up at various beaches, to data and information provided by a host of Government departments and agencies and from web sites of individual organisations and researchers. A good search engine will open up a huge range of possibilities and the problem is to determine what is relevant and what is not.

1.4 Approach and organisation

The book is organised into three sections. In Part I, following this introductory chapter, Chapter 2 provides some background on the scope of coastal geomorphology, some basic definitions and terminology, and an overview of the major factors controlling the appearance and development of coasts worldwide.

Part II, Coastal Processes, has five chapters which cover sea level changes and processes associated with waves and currents that together act to transform the coast on a range of timescales. An understanding of these processes is also important for managing coastal hazards and human impacts on the coastal zone. It begins in Chapter 3 with an examination of the processes controlling sea level at temporal scales ranging from seconds to thousands and millions of years. Following this, Chapters 4 and 5 cover waves and wave processes. The first of these provides a general description of waves and the factors that control their formation, as well as the range of wave conditions that can be experienced at any location. The second makes use of wave theory to describe wave oscillatory motion and the processes involved in wave shoaling and breaking as waves move from open water to the coast. Chapter 6 examines wave-generated currents and circulation patterns in the nearshore. Finally, Chapter 7 draws on the water motion described in the previous three chapters to describe the processes of sediment transport, both onshore–offshore and alongshore.

Part III, Coastal Systems, contains six chapters that describe the geomorphology, sedimentology and processes that are characteristic of major coastal systems. Chapter 8 begins by examining the characteristics of beaches and the response of beach form to varying wave, tide and water level conditions. Chapter 9 covers aeolian sediment transport on beaches and the development of coastal dune systems. Chapter 10 describes coastal barriers such as spits and barrier islands and their associated lagoon. Saltmarshes and mangroves, which are both formed in the intertidal zone in sheltered areas, are covered in Chapter 11. Chapter 12 deals with coral reef coasts which are a significant element of coasts within the tropics. Finally, Chapter 13 covers coastal cliff systems.

A more comprehensive coverage might also include treatment of coastal systems such as estuaries, fiords, deltas and muddy coasts (including intertidal mudflats), but to describe them in the same level of detail as the other coastal systems would have made the book too long. Rather surprisingly, given the Canadian content, there is no detailed treatment of the role of ice in the coastal zone. This is justified partly in the interest of length and partly because the role of ice is primarily a passive one, restricting the operation of wave and current processes for some period of the year.

Each chapter after Chapter 2 begins with a synopsis. Also included are Boxes which expand on some aspect covered in the chapter but are not essential to understanding it. I have chosen to include a reference list for each chapter, rather than consolidating all the references at the end of the book. This is done to provide a sense of where published material from which the chapter is drawn is located, as well as to highlight the people who are actively involved in research in that field or fields. A consolidated reference list is available on the web site for the book.

Diagrams and photographs for the book were all prepared in both grey scale and colour. The book of necessity only uses grey scale figures but all of them are available on the web site for the book in full colour. Additional materials are provided on the web site and these can be used to supplement the text and as an aid to teaching.

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Coastal geomorphology

2.1 Definition and scope of coastal geomorphology

Coastal geomorphology is a branch of geomorphology in which the focus is on the area influenced by large bodies of water, including seas and oceans, and large lakes such as the Great Lakes in North America. It is perhaps best viewed as an applied science and overlaps with other applied sciences such as geology, meteorology, oceanography, coastal engineering and elements of biology.

Prior to 1950, coastal geomorphology was highly descriptive and much of it was influenced by concepts related to the Davisian Cycle of Erosion. Coastal classification and description paid considerable attention to the effects of sea level change and especially the role of the Holocene sea level rise in producing drowned coastal features such as fjords (drowned glaciated valleys) and rias (drowned river valleys). Waves and currents were seen to operate to straighten and simplify the coastline by trimming headlands and building barriers across bay mouths (Woodroffe, 2002). Coastal evolution was therefore directed towards a simple, relatively static equilibrium. One branch of coastal geomorphology also followed the paradigm of denudation chronology, which attempted to reconstruct the detailed geological evolution of coastal landscapes. Much of this was guided by concepts of erosion cycles and interpretation based primarily on landforms rather than stratigraphy. The advent of a range of methodologies for coring and geophysical remote sensing, combined with new methods for dating sediments, has transformed this branch of coastal geomorphology/sedimentology. In particular, it has allowed the building of detailed histories of the glacial and post-glacial evolution of coasts worldwide.

Much of the research in coastal geomorphology in the past four decades has been concentrated on the zone influenced by waves and tides, wave-generated currents, and tidal currents, and on the erosional and depositional features associated with these. There has been a rapid change in the instrumentation available for measuring fluid motion and sediment transport, as well as for measuring morphological change (Davidson-Arnott, 2005) and this has permitted a focus on studies of morphodynamics – simultaneous measurements of process and morphological change, especially in the sandy nearshore. As is the case in other areas of geomorphology, the reductionist paradigm guided much of the field and laboratory experimentation. The ultimate goal of this approach is to build models from an understanding of how the system functions at the smallest scale – time scales of a second or less and spatial scales of millimetres to tens of centimetres – and then to upscale these to simulate or make predictions at larger spatial and temporal scales.

There is no doubt that improved technology and the efforts of a large number of scientists and engineers, working in the field and in the laboratory, have greatly expanded our understanding of coastal processes in this period. This has been accompanied by similar improvements in numerical modelling and in the development of theory. At the same time there has been a recognition that modelling large-scale coastal evolution (defined as temporal scale of decades and spatial scale of tens to hundreds of kilometres) may require a different approach than simply running the small-scale models for larger areas and over longer periods of time (Cowell *et al.*, 1995; Ashton *et al.*, 2001; Harvey, 2007; Baquerizo and Losada, 2008; Kroon *et al.*, 2008.). Some of this is driven by consideration of the potential impacts of global climate change and especially of an increase in the rate of eustatic sea level rise (Stive, 2004; Cowell *et al.*, 2006; Slott *et al.*, 2006).

Coastal systems vary greatly in their dynamic range and in their response to changing controls. At one end of the continuum, the beach foreshore morphology can respond at a temporal scale of seconds and minutes to changes in incident wave conditions and tidal elevation. At the other end of the continuum, cliffs in resistant rock such as dolomite or granite may show no observable morphological change over hundreds of years. Concepts of systems interrelationships, feedback paths, dynamic equilibrium and thresholds that have been part of geomorphology for the past 40 years (Chorley and Kennedy, 1971) are a part of the current paradigm of coastal geomorphology. Above all, there is a firm belief among coastal geomorphologists and, perhaps especially among coastal engineers, that dynamic coastal systems can be modelled deterministically as long as we have sufficient understanding of processes and the data needed to carry out the modelling. Furthermore, much of the research is guided by a belief that coastal systems tend towards dynamic equilibrium and that a change in the incident conditions will rapidly be reflected in a predictable change in morphology towards another dynamic equilibrium. This is perhaps best seen in describing beach profile response to a change from steep, short period storm waves, to low, long period swell waves (see Section 8.3.3). Another example is the persistence of the so-called Bruun rule (Schwartz, 1967) for predicting the response of sandy shorelines to sea level rise.

While uncertainty and the stochastic nature of many events are increasingly being acknowledged, coastal geomorphologists have perhaps been less willing to let go of their vision of an orderly and predictable universe than in other branches of the discipline and to embrace, for example, non-linear dynamics (Phillips, 1995). We may, however, see more examples of the concept of self-organisation (Werner, 2003; Baas, 2007), perhaps because this produces some form of recognisable order.

2.2 The coastal zone: definition and nomenclature

As is the case in most areas of geomorphology, there are many terms used to describe coastal features and processes that are poorly defined and occasionally subject to misuse. Differences in meaning are also common between the different disciplines working in the coastal zone – e.g. biologists, engineers, geologists and geomorphologists. Features associated with a general coastal profile as used in this book are illustrated in Figure 2.1. Other definitions related to waves and to specific coastal environments are defined in the relevant chapters.

Coastal zone broad term for the area influenced by proximity to the coast; both the onshore and offshore limits are (deliberately) imprecisely defined. The limit on land may be a few hundred metres inland from a cliff top or several kilometres where there are extensive sand dunes, or along tidal estuaries (Figure 2.2). The seaward limit may be the edge of the continental shelf and is usually at least several kilometres.

Offshore zone portion of the profile where there is no significant transport of sediment by wave action. The landward boundary can be defined precisely as the transition to water depths less than one-half the wave length of large storm waves. Note that the landward boundary is often defined (especially by coastal engineers) as the outer limit of the breaker zone. It is also occasionally used simply to include everything seaward of the low-tide line.

Littoral zone portion of the coastal profile where sediment can be transported by