Cambridge University Press & Assessment
978-1-108-43986-2 — Introduction to Coastal Processes and Geomorphology
2nd Edition
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Part I

Introduction

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Introduction

1.1 Humans and the Coastal Zone

The coastal zone is a dynamic environment influenced by atmospheric, oceanographic and terrestrial processes. The combination of processes operating in these systems shapes the coastal zone and determines whether dunes, cliffs or marshes are the primary landform along a particular section of coast. These coastal features evolve in response to variations in natural factors such as sea level, wave climate and sediment transfers between the land and ocean, as well as those due to human activities such as harbour construction and sand mining. In some areas, the accumulation of sediments or sea level fall may cause the land to advance seaward, while areas experiencing a net loss of sediment or a rising sea level may be eroded. Our changing climate means that coastal systems will experience significant change over the next century and there is a need to predict the nature and extent of coastal alternation based on a sound understanding of the physical and biological processes involved.

This book describes and explains the physical processes, and some biological ones, that act to shape our coast, and the unique landforms that develop in response to those processes. As in any other branch of applied science, these process–form interactions can be studied for their own interest. However, there are often aspects of this study which are of particular importance to human life and activities. For example, a large proportion of the world population is concentrated in the coastal zone, including almost all of the major cities such as New York, Tokyo, Amsterdam and Shanghai. The coastal zone is used for fishing, transportation, recreation, waste disposal, cooling and drinking water, and is a source of energy from wave and tidal 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, tsunami inundation, as well as 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 the effects of these hazards can be minimised. Such knowledge is also invaluable 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

Figure 1.1 Examples of recreational pressures on the coast: A. Beach, promenade and sea front shops and apartments, Malo les Bains, Dunkirk, 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 now being replaced by apartments that are used for weekends and holidays; B. Resort development, Frigate Bay, St Kitts, West Indies in March, 2014. The advent of cheap air fares from northern parts of the US, Canada and western Europe has fuelled resort development on a massive scale in Florida and much of the Caribbean and Mexico. 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.

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 had a significant proportion of its area reclaimed by dyking, while the other sits on a small coral atoll. In popular tourist locations around the world and in particular in the Caribbean, the coast is quickly being developed and altered leading to new and unprecedented challenges for countries that are particularly vulnerable to sea level rise but lack the resources or the appropriate management agencies. In contrast, in the United States the US Army Corps of Engineers, a federal agency, 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 and the relatively small population and limited resources has left a much greater proportion of the coast relatively pristine.

Canada has one of the longest marine coastlines in the world and within it four distinct regions can be recognised (Figure 1.2). 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. 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. Along this coast, the tidal 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.

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

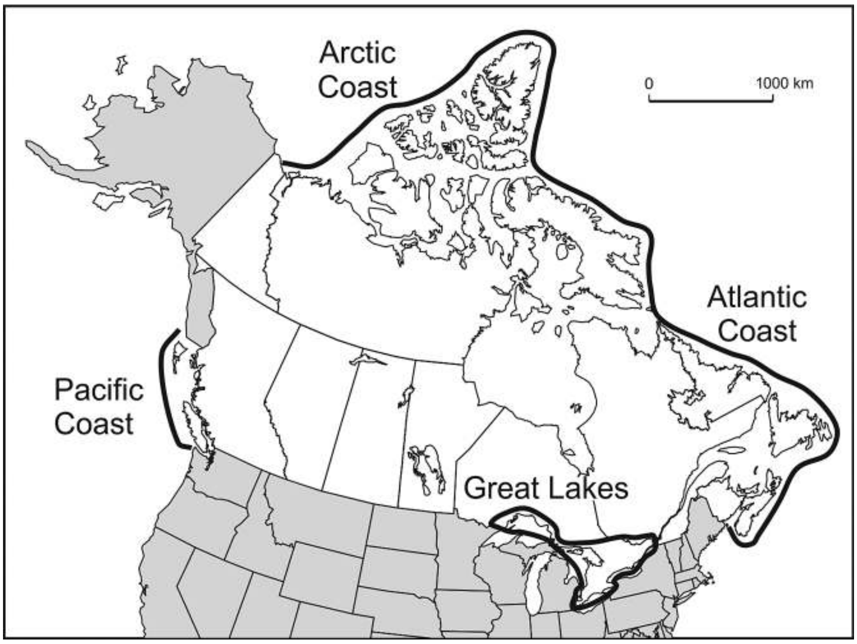

Figure 1.2 Primary divisions of the coasts of Canada (Owens, 1977).

knowledge and understanding of the features and processes.

1.2 Approaches to the Study of Coasts

Coastal geomorphology focuses 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, muddy deltas and sandy beach and dune systems. Many of these landforms are formed through a combination of coastal, fluvial and aeolian processes, requiring close collaboration, and the sharing of paradigms, instrumentation, field methodology and modelling approaches across those areas of geomorphology.

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, 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 divergent, they share a common interest in expanding our understanding of these physical processes on Earth. Indeed, some coastal scientists and engineers are working with astronomers to help interpret the landscape history of Mars (e.g., Parker *et al.*, 1993; Citron *et al.*, 2018; Goudge *et al.*, 2018). In recent 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 the aquatic ecology of beaches, estuaries and marshes. For example, the development of coastal dunes is dependent on the presence and diversity of vegetation, which are in turn stressed by the waves and currents that accompany elevated water levels during large storms. Similarly, seagrass and marsh vegetation promote sediment deposition and substrate stability through the attenuation of waves and currents but are also susceptible to erosion by storm waves and currents. Estuaries and marshes play a significant role as nurseries for juvenile fish, and fisheries biologists have an interest in the functioning and conservation of these systems. The coastal zone provides habitat for many species of fish and shellfish, and some open water species may breed in coastal waters. Waves and currents are important for the dispersal of organisms and influence the presence and survival of shellfish, and a variety of other organisms that live in surface sediments of the sandy beach and nearshore environment. Coral reefs create unique and ecologically important environments because they attenuate swell and storm waves, but these systems are vulnerable to erosion by waves, sea level rise and ocean acidification. Globally, the loss of coral reefs will result in dramatic changes to the coast in tropical environments and a loss of ecological diversity.

1.3 Information Sources

There is a long history of the study of coastal processes and landforms. In the past 100 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. An understanding of coastal geomorphology was important to the Allied invasion of Normandy in Operation Overlord during World War II. The position of the nearshore bars, influenced by the balance of storm and fair-weather waves, determined the distance that soldiers were exposed to the enemy as they stormed the beach. After World War II 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 (1959) and a popular book by Willard Bascom (Bascom, 1964). Both of these highlighted the research that began in World War II. An English translation of a text by Zenkovitch (1967) provided access to a considerable body of literature from what was then the Soviet Union over the same period. This was followed in the early 1970s by the publishing of the *Coastal Engineering Manual* by the US Army Corps of Engineers through the Beach Erosion Board and later the Coastal Engineering Research Centre. This manual provided a background on coastal processes (particularly waves, wave hindcasting and sediment transport) that has guided coastal engineering and management. While designed primarily to support practising coastal engineers, it proved a useful source for people interested in physical processes in the coastal zone.

The past 40 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 Davis, (1984), Carter (1988), Carter and Woodroffe (1994), Trenhaile (1997), Komar (1998), Short (1999), Bird (2000) and Woodroffe (2002), which were all generally aimed at senior undergraduates, graduate students, and researchers. 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. There are also a number of texts that are devoted to a specific aspect of coastal engineering (Kamphuis, 2000) or coastal geomorphology (Trenhaile, 1987; Sunamura, 1992; Nordstrom, 2000).

Much of the material in this book is drawn from articles published in journals and conference proceedings as well as some of the specialist texts noted above. While each chapter in this book can be read independently, one of our 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, and provide access to issues that go back to the journal inception. Increasingly, they provide a number of routes to access related publications. For example, 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 *Earth Science Reviews*, *Annual Review of Fluid Mechanics* and *Annual Review of Earth and Planetary Sciences*. Google Scholar provides an easy way to search journal papers and conference proceedings to explore almost every aspect of coastal geomorphology.

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) began just after World War II and are held every two years, with additional and specialised conferences such as *Coastal Sediments* and *Coastal Dynamics* held every four years. The Coastal Education Research Foundation, which sponsors the *Journal of Coastal Research*, also sponsors an International Coastal Symposium (ICS), which is held every two or three years in countries around the world. In Canada the first Canadian 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). In the past two decades meetings of Coastal Zone Canada have highlighted most work on coastal management and processes in Canada. In addition to these specialised conferences, coastal geomorphology has become an important focus with dedicated sessions at the annual conferences of the Geological Society of America (GSA), American Association of Geographers (AAG), and the American Geophysical Union (AGU). Aeolian processes are discussed at the International Conference on Aeolian Research, which is now held every two years, and aeolian manuscripts are published in *Aeolian Research*, the *Journal of Geophysical Research*, and most other geomorphology journals.

There is, of course, a vast amount of material available on the Internet, 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 websites 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. This is why texts like this are important to training the generation of coastal geomorphologists and scientists who will need to respond to a rapidly changing coastal system. The intense media coverage of natural disasters in the coastal zone such as the December 2004 tsunami in the Pacific and Indian oceans, and Hurricane Katrina (2005) in the United States focused our attention on vulnerability and adaptation to these and other coastal hazards. Recent events such Hurricane Ike (2008), Superstorm Sandy (2012) and an increasing frequency of nor'easters along the Atlantic Seaboard of the United States have maintained and even elevated this focus on coastal geomorphology, particularly given the threat of rapid sea level rise predicted over the next century. Given that several hundred million people live along, at or close to the coast, sea level rise and storm erosion pose a significant socio-economic threat in the future. As a consequence, there is a growing acknowledgement of the need for some comprehensive system of coastal zone management to facilitate adaptation to natural hazards and to reduce human impact on natural coastal systems. It is hoped that the material presented in this book can be used to provide coastal managers with background on the physical processes and features of the coastal zone which need to be considered in developing effective management strategies and plans to ensure resiliency of the coastal environment.

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Coastal Geomorphology

2.1 Definition and Scope

Geomorphology has been defined as the area of study leading to an understanding and appreciation for landforms and landscapes (Bauer, 2004). Coastal geomorphology is, therefore, the branch of geomorphology that is focused on processes and forms in the coastal zone, whether adjacent to oceans, seas, estuaries or lakes. The methods and theories of coastal geomorphology are strongly informed by those in other branches of geomorphology (e.g., fluvial, aeolian, glacial, tectonic), although the interests of coastal geomorphologists also overlap substantially with those of coastal engineers, oceanographers and marine geologists as well as other scientists interested in the environmental, biological, meteorological and sedimentological aspects of coastal regions. Coastal geomorphology is therefore a hybrid science that has both pure and applied aspects.

Coastal systems vary greatly in their dynamics and according to the types of controls that are imposed on their evolution through time. At one end of the continuum, the response of a loose, sediment bed to wave or swash action varies on the scale of fractions of seconds as water particles are accelerated up and down the foreshore or across a bar face with each wave cycle (Figure 2.1A). Individual grains of sand are mobilised, transported and deposited as a consequence of the fluid motion, and this leads to changes in the morphology at scales of minutes to hours (Figure 2.1B). The wave field will continue to evolve during a passing storm, and therefore the potential for sediment transport (hence, morphological adjustment) is altered continuously. The locus of energy dissipation (or work) on the shoreline will also shift up and down the beach face according to tidal stage as well as storm surge. At the other end of the continuum, cliffs and platforms sculpted in resistant rock such as dolomite or granite may show no observable morphological change over decades or centuries despite being acted upon incessantly by waves and tides (Figure 2.2). Tectonic and eustatic changes in relative sea level are important considerations, as are the fracturing patterns and weathering processes that break down the rocks. Often there are biological or chemical components that complicate matters considerably.

Coastal geomorphology, much like the other branches of geomorphology, evolved from highly descriptive, non-theoretical interpretations of landscapes to much more rigorous, scientific investigations of form-process interactions (Goudie, 2004). Field observation during these early stages of the discipline focused mainly on macro features that were easily observable from land, especially the effects of sea level rise in producing partially submerged coastal features such as fjords (drowned glaciated valleys) and rias (drowned river valleys) or the influence of tectonic uplift in revealing the shape of marine terraces and rock platforms that were once submerged. The action

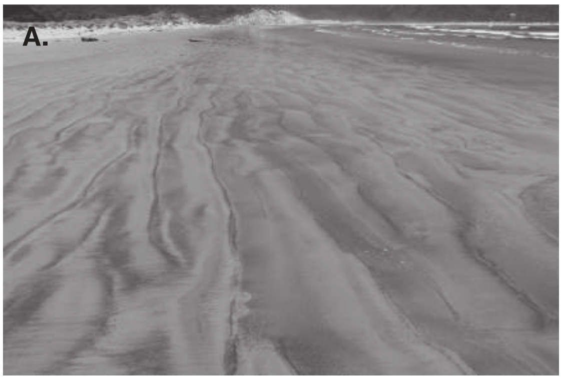

Figure 2.1 Small scale coastal features. A. Large swash ripples on a shallow sloping foreshore, Doughboy Bay, Stewart Island, New Zealand. Ripples are altered after each up-rush and back-wash cycle. Note heavy (black) mineral lines and patterns of seaward drainage between ripple bifurcations. B. Active construction of a sand berm by repeated swash action and overwash, yielding upward growth and landward progradation (near Port Lincoln, Australia).

Figure 2.2 Large-scale coastal features. Rocky shoreline with very resistant materials near Bodega Bay, California. Note old marine terrace being uplifted due to tectonic instability on this coast.

of waves and currents, however, were rarely measured – rather they were believed to operate in a manner that flattened submerged relief (i.e., marine planation theory) and straightened the coastline by trimming rocky headlands and building sandy barriers across bays and inlets (Woodroffe, 2002). However, the advent of new methodologies for coring and geophysical remote sensing, combined with new dating techniques, led to key developments in sedimentology that transformed the way coastal geomorphologists and geologists thought about coastal evolution.

In particular, detailed histories of the glacial and post-glacial evolution of coasts, involving isostatic compensation and the changing nature of sediment supply from drainage basins, shoreline erosion and littoral drift have revolutionised coastal science and engineering.

Much of the research in coastal geomorphology in the past few decades concentrated on the zone influenced by waves, currents and tides, as the primary driving forces for landform evolution along the coast. These forces, mediated by the strength of materials that they act upon, yield a broad range of erosional and depositional features that define the shape of the shoreline and provide the basis for coastal classification. A major stimulus for these scientific efforts was the need during World War II to predict where and when to land personnel-carrying water craft safely so as to facilitate the invasion of hostile territories in Europe and the Pacific theatre. Early efforts in this regard were not always successful, and the cost was major loss of life, as recorded in historical accounts and re-created in Hollywood movies. However, rapid advances in the technologies and instruments available for measuring fluid motion, sediment transport and morphological change (Davidson-Arnott, 2005a) have enabled coastal scientists to better understand the morphodynamics of coasts, which involves the simultaneous measurement of process dynamics (the forcing functions) and morphological change (the system response) in order to decipher cause, effect and feedback relationships. Studies on sandy beaches and barrier islands are especially conducive to this process-based approach because of the rapid adjustments that occur in these high-energy environments. Similar process studies on rock platforms, cliffed shorelines and coral reefs are increasingly commonplace. There have also been revolutionary advances in the capacity to monitor and analyse shoreline change using remote-sensing technologies, precise digital geo-referencing systems and geographic information systems (GIS). These are especially critical at this time in the twenty-first century because of the anticipated impacts of global climate change on the frequency and intensity of major storms superimposed on accelerated sea level rise, which are likely to have significant consequences for human occupation and utilisation of the coastal zone.

2.2 The Coastal Zone

As scientific disciplines mature, the degree of sophistication with which its practitioners approach the subject matter evolves significantly. Initially, there is a phase of observation and description in which a glossary or lexicon of terms is assembled that can be used to describe what is being observed, ideally with reasonable precision and some semblance of common comprehension. After a lengthy phase of description, the practitioners are able to make conceptual sense of the phenomena under investigation (i.e., they begin to theorise about logical order and structure). A first step in this process of theorisation involves proposing a classification system (i.e., taxonomy) that enumerates the broad spectrum of possible states in a rational scheme. There may be weaknesses in the logical underpinnings of the proposed classification system, or perhaps someone discovers new instances that don't fit nicely into the categories or classes, which usually leads to new and different classification systems being proposed with new (and perhaps different) terminology. It should be appreciated that there is no single 'correct' classification system because each may have a different purpose and orientation – i.e., they provide insight into how scientists were thinking about the coastal zone at the time of development of the classification scheme, and they provide a general perspective on how the coastal zone can be conceptualised and understood.

2.2.1 Zonation and Terminology

There are many terms used to describe coastal features and processes, and sometimes they are defined inaccurately or used incorrectly. Differences in meaning are also hampered by the tendency for different disciplines (or sub-disciplines) to work in isolation or towards different objectives for which an existing lexicon may be inadequate. Thus, coastal scientists in biology, engineering or geology sometimes adopt terms