Beaches and Coasts

Richard A. Davis Jr and *Duncan M. FitzGerald*

Blackwell Publishing

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350 Main Street, Malden, MA 02148-5020, USA
108 Cowley Road, Oxford OX4 1JF, UK
550 Swanston Street, Carlton, Victoria 3053, Australia

First published 2004 by Blackwell Science Ltd

Library of Congress Cataloging-in-Publication Data
Davis, Richard.
Beaches and coasts / Richard Davis Jr. and Duncan FitzGerald.
p. cm.
Includes bibliographical references (p.).
ISBN 0-632-04308-3 (alk. paper)
1. Beaches. 2. Coasts. 3. Coast changes. I. FitzGerald, Duncan. II. Title.

GB451.2.D385 2003
551.45′7—dc21

2002151119

ISBN 0-632-04308-3 (hardback)

A catalogue record for this title is available from the British Library.

Set in 10/12pt Caslon
by Graphicraft Limited, Hong Kong
Printed and bound in the United Kingdom
by The Bath Press

For further information on
Blackwell Publishing, visit our website:
http://www.blackwellpublishing.com

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Acknowledgments

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1 Coastline variability and functions in the global environment

1.1 Introduction

The surface of the Earth is covered by two contrasting media: land and sea. They meet at the coast. There are, of course, glaciers that span parts of both the land and sea, such as in Greenland, in parts of the Canadian Arctic, and on Antarctica. Each of the two surfaces may cover millions of square kilometers over continents and oceans or much less in the case of small oceanic islands or some lakes within continental masses. Nevertheless, a narrow coastal zone separates these two major parts of the Earth's surface.

The world's coastline extends for about 440,000 km, but the coastal zone comprises less than 0.05% of the area of the landmasses combined. Because nearly half of the global population lives within less than 100 km of the coastline, the coastal zone has become arguably the most critical part of the Earth's surface in terms of global economy, strategies, and management needs.

1.2 Coastal settings

What do we actually mean by the coast? The coastline or shoreline is simply the contact between the land and the sea; an easy definition. The **coastal zone**, however, is a bit more difficult to delimit. For practical purposes it is any part of the land that is influenced by some marine conditions, such as tides, winds, biota, or salinity. The coast is global in its distribution but limited in width. We cannot give an average width, an average character, or any other average category that adequately typifies the coast. It is much too varied and complicated in its characteristics. In some places the coastal zone might be only a few hundred meters wide, whereas in others it might be more than 100 km wide. Some coastal zones include a wide range of environments that separate the true ocean from the terrestrial environment. In other situations, a single coastal environment may define the land–sea boundary.

In this book we consider the controlling factors that determine what type of coast develops. The processes that develop and maintain coastal environments, as well as those that destroy the coast, are discussed in order to convey the dynamic nature of all coastal environments. Each of the major environments is considered in light of these controlling factors and processes. The impact of human activity along the coast has been enormous, especially over the past century. Many examples of this impact appear throughout the book but a special chapter devoted to the topic is also included. Most of the emphasis in the book is directed toward geologic and physical attributes of the coast, although organisms are not overlooked.

Fig. 1.1 Photograph of an erosional coast in Oregon. The bluffs here are composed of a friable Miocene sandstone. Houses on top are in serious jeopardy.

Open coasts can be divided into two general categories: those that are dominantly erosional (Fig. 1.1) and those that are primarily depositional (Fig. 1.2) over long periods of time, i.e. thousands of years or more. Erosional coasts are extensive and have considerable variety, although they tend to be narrow. They typically are the high relief rocky coasts but also include some bluffs of unconsolidated sediments, beaches, and other local depositional features. Although erosional coasts are among the most beautiful and spectacular of all coastal types, there is less variation in this generally rocky type of coast than in those that are characterized by deposition.

Depositional coasts include a wide spectrum of systems, such as river deltas, barrier island systems, strandplain coasts, reef coasts, and glaciated coasts.

Fig. 1.2 Photograph of a depositional coast on the Atlantic coastal plain of the United States. This shows a barrier island coast with two large estuaries.

Fig. 1.3 Huge dunes that extend to the shoreline along the coast of Namibia in southwest Africa. These dunes may be up to 100 m high and the absence of vegetation makes them quite mobile. (Courtesy of N. Lancaster.)

Fig. 1.4 Sabkha along the northern coast of Libya. These environments are quite flat surfaces that are essentially at mean sea level and are located where tidal range is very small. (Courtesy of the US Geological Survey.)

Each of these may contain numerous distinct environments. The variety of morphologic features and the complex interaction of depositional coasts deserves extensive attention and is emphasized in this book.

Climatic differences cause a wide variety of coastal types, in that temperature and rainfall exert a major influence on coastal development. Extreme climates such as those in the very high latitudes cause coastal areas to be covered with ice; all the time in some places, and for only a few months in others. Parts of Greenland and the Antarctic coast are covered with ice continually, whereas some of the coasts of Alaska, Canada, the Scandinavian countries, and Russia have ice cover for at least a few months each year. Desert conditions can directly influence coastal environments as well. Few significant rivers and therefore few river deltas are produced from desert areas. Some coastal deserts are dominated by huge sand dunes, such as along Namibia (Fig. 1.3) on the southwest coast of Africa. Along the Persian Gulf and in north Africa the arid, low-latitude environment produces extensive coastal environments called sabkhas that are nearly at sea level and have an almost horizontal surface (Fig. 1.4) dominated by chemically precipitated salts and other minerals.

The tectonics of the Earth's crust also exert a major influence on the coastal zone. Coasts that coincide with or that are near plate boundaries tend to have more relief and are narrow compared to those that are away from plate boundaries. Colliding plates provide for a particularly rugged coast, such as we see along the Pacific Northwest of the United States. The relationships between plate tectonics and coastal development are treated in detail in Chapter 2.

1.3 Population and the coast

The coast is many things to many people. Depending on where and how we live, work, and recreate,

Fig. 1.5 Photograph of the coast at Alexandria, Egypt, an ancient city in the eastern Mediterranean. This development has been here for many centuries but this coast has only been erosional since the construction of the Aswan Dam in the twentieth century. (Courtesy of D. Stanley.)

our perception of it varies greatly. Large populations live on or near the coast because it is typically very beautiful and interesting. Many more visit the coast for the same reasons. A large number of people gain their livelihood directly or indirectly from the coast, and some have the task of protecting it from intruders or enemies.

1.3.1 History of coastal occupation

The ancient civilizations of the eastern Mediterranean Sea were largely associated with the coast, including the famous Greek, Roman, and Phoenician settlements and fortifications of biblical times and before. Many of the great cities of the time were located on the natural harbors afforded by the geologic and physiographic conditions along the coast (Fig. 1.5). These cities provided a setting that was conducive to trade and that could be defended against enemies.

Far to the north, Viking settlements in the Scandanavian countries of Norway, Sweden, and Denmark were typically located along the coast as well. Here the great fjords provided shelter, fortification, and ready access to the sea, which was a primary food source and the main avenue of transportation, and were the sites of many battles. At about the same time, the northern coast of what is now Germany and the Netherlands was also occupied for similar reasons but in a very different coastal setting: one of lowlands and barrier islands.

Many centuries later, cities in the New World such as Boston, New York, Baltimore, and San Francisco owe their location to the presence of a protected harbor. In their early stages of development many of the major civilizations of the world were directly on the coast or had important interaction with it.

In the early civilizations, reasons for this extensive occupation of coastal areas were strictly pragmatic. Coasts were essential for harboring ships, a primary means of transporting goods, one of the major activities of the time. The adjacent sea was also a primary source of food. Similar reasons were the cause for the settlement of many of the great cities of Europe, such as London, Amsterdam, Venice, Copenhagen, and others. All were settled on the water because their location fostered commerce that depended on transportation over water.

This pattern of coastal occupation and utilization continued until the latter part of the nineteenth century. By that time the interior areas of the United States had been settled and large cities were scattered all over the country. Many of these cities, however, are near water as well. In North America they are either on the Great Lakes (Chicago, Detroit, Cleveland, and Toronto) or on the banks of large rivers (St Louis, Cincinnati, Pittsburgh, and Montreal).

Since ancient times, the coast has been a strategic setting for military activity. At first the cities housed military installations. Later it became important as a staging ground for large-scale invasions; examples include the British conquest of France in the fourteenth century and Allied troop landings on the beaches of Iowa Jima and other islands of the Pacific and on the Normandy coast of France during the Second World War in the twentieth century.

It was only in the latter part of the nineteenth century that coastal activities expanded into broad-based recreational use, with related support industries. As a result of the Industrial Revolution and overall prosperity, both in North America and, to a lesser extent, in Europe, people began to look to the coast as a place to take family holidays.

Box 1.1 Venice, Italy: a city waiting to die

A unique city on the Adriatic Sea coast of northern Italy, Venice is a major historic treasure, and a very popular tourist stop for people from throughout the world. The city is commonly known for its canals, gondolas, and the absence of automobiles, as well as for its excellent cuisine. It is located within a large, shallow, backbarrier lagoon and is offshore from the mainland. Venice began in the eighth century as a city-state, with trading and fishing as its major industries. It became very famous and its merchants became very wealthy as the city developed into a major economic center of the eastern Mediterranean area.

The general setting is a few kilometers offshore, where there are several low islands that have become developed as residential and commercial centers. These islands have essentially no natural relief and they rest on thick muddy sediments deposited by rivers that used to flow into the lagoon. The main island, Venice, is almost entirely covered with buildings that are mostly several hundred years old and that have great historic significance to Italy. Included are numerous churches, governmental buildings, plazas, old military installations, etc. The entire city was built within a meter or two of sea level, but with the protection of the barrier islands a few kilometers seaward of them.

As time passed, three things occurred to jeopardize the future of the city: (i) the underlying mud began to compact; (ii) the rate of sea-level rise increased; (iii) the combination of these phenomena has resulted in a significant relative rise in sea level, essentially flooding the city. This has been exacerbated by the unfortunate decision to relocate the mouths of two rivers, the Sile River and the Brenta River, which naturally emptied into the Venice lagoon. It was feared that the discharge of sediment would fill up the lagoon. In order to prevent this from happening, the lower course was changed so that both rivers now empty directly into the Adriatic Sea, one north of the Venice lagoon and one to the south. This has resulted in a lack of sediment to nourish the marshes, which are vital to both the ecology of the lagoon and the protection of the developed islands from wave attack and erosion.

At the present time the city remains vital but the population, which peaked at more than 250,000 a couple of centuries ago, is now down to about 50,000. Much of this decrease is the result of the tremendous cost of renovating properties for residential or commercial use. Virtually all buildings fall within the historic preservation regulations and therefore must be restored in order to be occupied, and such expense is more than most people can bear. Another deterrent to Venetian residence is the lack of jobs.

The current rate of sea level rise is 2.5 mm yr^{-1}. With a city that is nearly at the level of spring high tide, the future is limited. The most popular location in Venice is Piazza San Marco, which is also one of the lowest elevations in the city. A hundred years ago this area was flooded only a few times per year, but with an increase in sea level of about 30 cm over that time, it is now flooded about 50 times each year, a couple of days during each spring tide situation plus times when winds blow for a sustained period. As sea-level rise increases and continues, the city will literally drown.

Numerous engineering approaches have been tried and others have been suggested to help to sustain the city. First, the barrier islands have been stabilized and nourished at great expense. This will: (i) protect the numerous communities that inhabit them; (ii) keep the barriers from migrating landward; and (iii) maintain the size and geometry of the lagoon, and therefore stabilize the tidal flux in and out of the three large inlets that serve the lagoon. The inlets have been stabilized to keep their channels fixed and to allow the large volume of ship traffic to the port of Venice to continue.

At the present time a plan has been developed, but not yet funded, to construct large floating gates that will prevent wind from blowing large amounts of water into the lagoon and raising its level beyond that which the city of Venice can withstand. These gates rest on the inlet channel floor during normal times, then when strong winds begin to raise the water level in the lagoon, water is evacuated from them, causing one end to float up above the surface and to act as a dam to water being blown into the lagoon.

In the long term, there seems to be little that can be done to save this beautiful and historically significant city other than encasing it in a large dike. It will be a very expensive and time-consuming project, but it might be the only way.

1.4 General coastal conditions

Varied geologic conditions provide different settings for the coast, and give variety and beauty to that part of the Earth's surface. As a consequence, some coasts are quite rugged, with bedrock cliffs and irregular shorelines, whereas others are low-lying, almost featureless areas with long, smooth shorelines. To be sure, with time, any coast can change extensively, but some important relationships continue through geologically significant periods of time, up to many millions of years.

Changes at a given part of the coast are typically slow and continuous, but they may be sporadic and rapid. Rocky cliffs tend to erode slowly but hurricanes can change beaches or reefs very quickly. Overprinted on this combination of slow and rapid processes of change is the very slow fluctuation in sea level over time, about 1–2 mm yr^{-1}. In the geologic past this rate was both much faster and even a bit slower. The point is that as coastal processes work to shape the substrate and the adjacent land, the position of the shoreline changes as well. This translates the processes and their effects across the shallow continental shelf and the adjacent coastal zone, producing long and slow, but relatively steady, coastal change.

Each specific coastal setting, regardless of scale, is unique yet is quite similar to other coastal settings of the same type. Although each delta is different, a common set of features characterizes all deltas. The approach of this book is to consider the general attributes of each of the various types of coastal environments. Numerous examples of each environmental type provide some idea of the range available. Finally, the overprint of time demonstrates the dynamic nature of all of these coastal elements.

1.5 Coastal environments

The variety of coastal environments is wide. This section briefly introduces each of the major environments to demonstrate this variety. All of these and more are discussed in detail in the following chapters.

Fig. 1.6 Satellite photo of the Mississippi delta showing considerable suspended sediment being discharged through numerous distributaries. Although it appears that the sediment load is very large, it has been reduced greatly during the past century as the result of dams on the river. (Image from EROS Data Center.)

Rivers carry tremendous quantities of sediment to their mouths, where they deposit it. Much of the sediment is then entrained by waves and currents, but commonly there is a net accumulation of sediment at the river mouth: a delta (Fig. 1.6). In fact, most of the sediment along all types of depositional coasts owes its presence, at least indirectly, to a river. Deltas range widely in size and shape. Most are dominated by mud and sand but some have abundant gravel. The primary conditions for delta formation are a supply of sediment, a place for it to accumulate, and the inability of the open water processes to rework and remove all of the sediment from the river mouth.

Sea level has risen considerably over the past several thousand years as the result of glaciers melting and a combination of other factors. This increase in sea level flooded many parts of the land and developed extensive and numerous coastal bays. Streams feed most of these bays. These bays are called estuaries (Fig. 1.7) and are commonly surrounded by some combination of wetlands (usually either salt marshes or mangrove swamps) and tidal flats.

Fig. 1.7 Headland on the Oregon coast with an associated barrier spit protecting the small estuary. Even though this coast has a high tidal range, it is eroded at the headlands, with the sediment carried along the coast to form these barrier spits. (Photograph courtesy of W. T. Fox.)

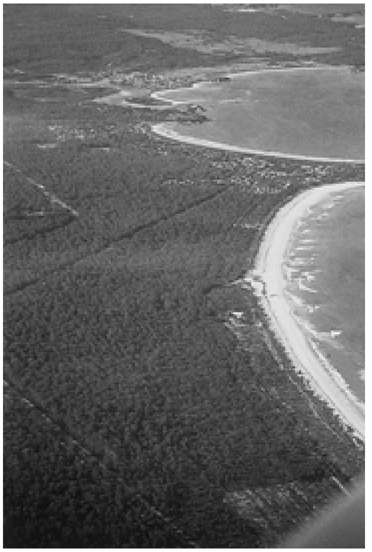

Fig. 1.8 Aerial photograph showing a strandplain coast where there is no significant estuary and no barrier island. Such a coast typically develops where there are no coastal bays and the gradient offshore is relatively steep, thus letting large waves reach the surf zone.

Another common type of coastal bay is one that tends to parallel the coast and is protected from the open ocean by a barrier island. These elongate water bodies have little influx of fresh water or tidal exchange. They are lagoons. Tidal flats and marshes are uncommon along this type of bay. Other coastal embayments that cannot be considered as either an estuary or a lagoon are simply termed coastal bays.

Barrier islands are another important part of the scheme of coastal complexes. These islands are a protection in front of the mainland, typically fronting lagoons and/or estuaries. These barriers include beaches, adjacent dunes, and other environments. Wetlands, especially salt marshes, are widespread on the landward side of barrier islands. Tidal inlets dissect barrier islands and are among the most dynamic of all coastal environments. They not only separate adjacent barrier islands, but also provide for the exchange of water and nutrients between the open ocean and estuarine systems.

Strandplain coasts are low-relief coastal areas of a mainland that have many characteristics of the seaward side of a barrier island. They contain beaches and dunes but lack the coastal bay (Fig. 1.8). Examples include Myrtle Beach, South Carolina, and the Nayarit Coast of western Mexico.

Rocky or headland coasts can be present as short isolated sections within extensive sandy depositional coasts, such as along parts of the east coast of Australia or the Pacific Northwest coast. Other geomorphically similar coasts may have their origin in glacial deposits, with New England being a good example. In both cases, the coast is characterized as erosional and they may provide sediments for nearby depositional beaches.

Reef coasts (Fig. 1.9) owe their origin to the construction of a framework by organisms; both plant and animal. Not only are these coastal environments very beautiful, but they also protect the adjacent mainland or island from erosion and wave attack from severe storms.

1.6 Historical trends in coastal research

Scientists have only recently undertaken comprehensive investigations of the coast. Some nineteenth-century publications considered the origin of barrier islands, scientists speculated on the development

Fig. 1.9 Oblique aerial photograph showing a well developed reef along the Florida Keys coast. The portion of the reef that has the linear features is the seaward and deeper area, while the remainder of the reef is the flat, shallow, upper portion.

Fig. 1.10 Photograph of a seawall designed to protect the coast from erosion. These features are designed to stop erosion along the shoreline and to protect buildings or infrastructure that is close to the shoreline

of coral reef coasts, including Charles Darwin on his famous voyage on the *Beagle*, and observations detailed characteristics of the cliffed coasts of the British Isles and Brittany in France.

The first systematic efforts at studying the coast in the early twentieth century were made by **geomorphologists**, those who study the morphology or landforms of the Earth. Geomorphologists also investigate mountains, deserts, rivers, and other Earth features. Their studies produced various classifications, maps, and reports on coastal landforms. Some scientists focused on the evolution of coasts and the processes responsible for molding them. For example, Douglas W. Johnson, a professor at Columbia University, wrote a classic and pioneering book in 1919 entitled *Shore Processes and Shoreline Development*, a monograph that is still commonly referenced.

Engineers have also given special attention to the coast over several centuries. Their interest was directed toward construction of dikes, harbors, docks, and bridges on the one hand, and stabilization of the open coast on the other. Although the two groups of professionals directed their efforts toward different aspects of the coast, their interests overlapped in many circumstances.

Ancient people recognized that the coast is potentially dangerous during storms and is continually changing due to processes associated with wind waves and storms. They understood that the shoreline is one of the most dynamic areas on the Earth. Erosion was a particularly important problem (Fig. 1.10) and settlements were lost or threatened as the shoreline retreated. For centuries dikes have been constructed along the North Sea coast of the Netherlands and Germany, both for protection (Fig. 1.11) and for land reclamation. In many other areas, however,

Fig. 1.11 Photograph of a dike along the Netherlands coast on the North Sea. Such structures protect the adjacent land, which is below sea level, from flooding. Like many of the dikes, this one supports a roadway. Some are used to graze sheep and cattle.

construction on the open coast was designed to slow or prevent erosion. As a result, various types of structures were emplaced at critical locations along densely inhabited areas of the coast in attempts to stabilize the beach and prevent erosion.

For decades these activities represented the major efforts of science and technology to understand and, in some respects, to control the response of the coast to natural processes. The Second World War was also an important period in furthering our understanding of the coast. Major war efforts took place along the coast, particularly the landing of troops, supplies, and equipment, whether on the European mainland or on Pacific islands. All branches of the military were involved in studying coastal geomorphology, coastal processes including waves, tides, and currents, and the analysis of weather patterns along the coast. Much of the world's coast was mapped in detail during this period. The Beach Erosion Board, a research branch of the US Army affiliated with the Corps of Engineers, made many very important contributions to our knowledge of coasts. This group conducted extensive research on beaches, waves, erosion, and other important aspects of the coast, using both their own staff and academic researchers from many of the best universities. Francis P. Shepard and Douglas L. Inman of the Scripps Institution of Oceanography (Fig. 1.12) were prominent contributors to the research programs of this group and later became among the most prominent coastal researchers in the world.

This coastal research effort continued after the Second World War, but with a distinctly engineering emphasis. The name of the original research organization was changed to Coastal Engineering Research Center, originally housed at Fort Belvoir, Virginia, and now located in Vicksburg, Mississippi. At about this time the Office of Naval Research (ONR) became heavily involved in basic research on the coast. Its first major efforts in this endeavor were through the Coastal Studies Institute of Louisiana State University. Although this organization conducted a variety of coastal research projects, its major effort was a global study of river deltas, beginning near home with the Mississippi delta. As time passed, the ONR expanded its coastal research support to emphasize beaches, inlets, and deltas – places where military activity could potentially take place. During the 1960s and 1970s this agency, through the leadership of Dr Evelyn Pruitt, supported most of the research on modern open coastal environments. This period began the modern era of coastal research, which emphasizes process-response systems. In other words, it is no longer enough to observe, describe, and classify coastal features and environments. The focus is now directed at determining the origin and development of these features, which necessitates the study of the physical and biological processes that operate on the coast and then the integration of these data with the resulting landforms. Thus began the process-response approach to coastal research. Coastal research of this type is only a few decades old.

Fig. 1.12 The old Scripps Pier at Scripps Institution of Oceanography at La Jolla, California. Considerable data on nearshore processes have been collected from this structure over several decades. It has now been replaced by a new version. (Photograph courtesy of Scripps Institution of Oceanography.)

Box 1.2 Beach Erosion Board of the US Army, Corps of Engineers

The Corps of Engineers is the part of the US Army that typically deals with construction: generally structures like dams, jetties at inlets, and seawalls to protect from erosion. It is also responsible for maintaining waterways, commonly through dredging the channels to permit shipping traffic, and for harbors for berthing the ships. During the Second World War there were some special needs associated with the deployment of ships and personnel in coastal waters. Landing troops on the beaches of Europe and in the Pacific were important military activities, and had to be done with careful planning and understanding of the coast and its various conditions.

As a consequence, the military, through the US Army, Corps of Engineers, enlisted a peacetime organization, the Beach Erosion Board, to assist in the task of learning as much as possible about coastal dynamics and geomorphology in order to aid the military effort in both the Eurpoean and Pacific theaters of war. The Beach Erosion Board, which had been a group of experts that advised the Corps on matters relating to ports, harbors, beach erosion, and navigation, now became an important aspect of the war effort. In order to carry out these activities several projects to be conducted at universities were developed and funded by the Army.

Much of the work was done in California at Scripps Institution of Oceanography and at the University of California at Berkeley. The Scripps researchers had long been noted for their marine research in physical oceanography and marine geology. The pier there was one of the first research piers equipped with instruments to record wave data, meteorology, and other coastal environmental phenomena. Such prominent scientists as Francis Shepard and Douglas Inman were in the group at Scripps that conducted this research. The coastal engineering group at Berkeley was also a leader in the field and was composed of experts at designing temporary facilities for military operations, including harbors, breakwaters, and bridges. Among them were Murrough P. O'Brien and Robert Weigel, two of the pioneers in coastal engineering.

Several prominent scientists and engineers were employed full-time as researchers for the military and some joined the military as scientific advisors. Although it is impossible to tell precisely, the efforts of both the academics and the military in aiding these war efforts saved many lives and countless dollars. Most of their work was unnoticed by the general public but is well known to the coastal research community.

Eventually, the Beach Erosion Board became the Coastal Engineering Research Center, the research branch of the US Army, Corps of Engineers. It has aided and continues to aid both civilian and military coastal and navigational operations. Originally located in Arlington, Virginia, near Washington DC, it is now combined with the Waterways Experiment Station of the Corps in Vicksburg, Mississippi. It is the premier coastal engineering research unit of the federal government of the United States.

Suggested reading

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2 The Earth's mobile crust

(a)


(b)


Fig. 2.1 Dissimilar tectonic settings produce very different types of coastlines. (a) The coastal plain setting of South Carolina fronted by barriers and tidal inlets (Murrells Inlet, 1977) is in sharp contrast to (b) the mountainous fjord coast of Kenai, Alaska.

2.1 Introduction

Coastlines of the world exhibit a wide range of morphologies and compositions in a variety of physical settings (Fig. 2.1). There are sandy barrier island coasts such as those of the East and Gulf coasts of the United States, deltaic coasts built by major rivers including those at the mouths of the Nile and Niger rivers, glacial alluvial fan coasts of the Copper River in Alaska and the Skiedarsar Sandar coast of southeast Iceland, coastlines fronted by expansive tidal flats such as the southeast corner of the North Sea in Germany, volcanic coasts of the Hawaiian Islands, carbonate coasts of the Bahamas and the South Pacific atolls, mangrove coasts of Malaysia and southwestern Florida, bedrock cliff and wave-cut platform coasts of the Alaskan peninsula and southwest Victoria in Australia, and many other types of coastlines. The diversity of the world's coastlines is largely a product of the Earth's mobile crust. The eruptions of Mount Saint Helens in Washington state (1980) and Mount Pinatubo in the Philippines (1991), and the devastating earthquakes in Mexico City (1985) and in Kobe, Japan (1995), are dramatic expressions of this mobility. The formation of pillow basalts and new oceanic crust at mid-ocean ridges and the presence of hydrothermal vents at these sites are also a manifestation of crustal movement. The theory that explains the mobility of the Earth's crust and the large-scale features of continents and ocean basins, including the overall geological character of coastlines, is known as plate tectonics.

Plate tectonics theory has done for geology what the theory of evolution did for biology, the big bang theory for astronomy, the theory of relativity for physics, and the establishment of the periodic table for chemistry. Each of these advancements revolutionized its respective field, explaining seemingly unrelated features and processes. For example, in geology the cause and distribution of earthquakes, the construction of mountain systems, the existence of deep ocean trenches, and the formation of ocean basins are all consequences of the unifying theory of plate tectonics. The germination of this theory began many centuries ago with scientists' and world explorers' interest in the distribution of continents and ocean basins. As early as the 1620s, Sir Francis Bacon recognized the jigsaw puzzle fit of the eastern outline of South America and the western outline of Africa. By 1858, Antonio Snider had published two maps illustrating how North and South America were joined with Africa and Europe during Carboniferous time (~300 million years ago) and how the continents had split apart to form the Atlantic Ocean. He reconstructed the positions of continents 300 million years ago to show why plant remains preserved in coal deposits of Europe are identical to those found in coal seams of eastern North America. Snider's maps were an important step in promoting a theory that later became known as continental drift (the theory that envisions continents moving slowly across the surface of the Earth).

In the early twentieth century, the idea of continental drift was popularized by Alfred Wegener, a German scientist at the University of Marburg (Fig. 2.2). Wegener was a meteorologist, astronomer, geologist, and polar explorer, and led several expeditions to Greenland. He was the first to present a sophisticated and well researched theory of continental drift, which he did in a series of lectures to European scientific societies in 1912. Three years later he published his ideas in a book entitled *Die Entstehung der Kontinente und Ozeane* (*The Origin of Continents and Oceans*). Wegener believed that all the continents were once joined together in a super continent he called Pangaea (Greek for "all Earth") which was surrounded by a single world ocean he named Panthalassa (all ocean) (Fig. 2.3). The northern portion of this supercontinent, encompassing North America and Eurasia, was called Laurasia, and the southern portion, consisting of all the other continents, was Gondwanaland. Partially separating these two landmasses was the Tethys Sea.

Fig. 2.2 This picture of Alfred Wegener was taken when he was 30 years old during one of his expeditions to Greenland. It was during this period of his life that he proposed his theory of "continental drift."

Wegener used a variety of supporting evidence to bolster his theory of a single continent, including the continuity of ancient mountain fold belts and other geological structures that extend across continents now separated by wide oceans. He noted that the coal deposits in frigid Antarctica and glacial

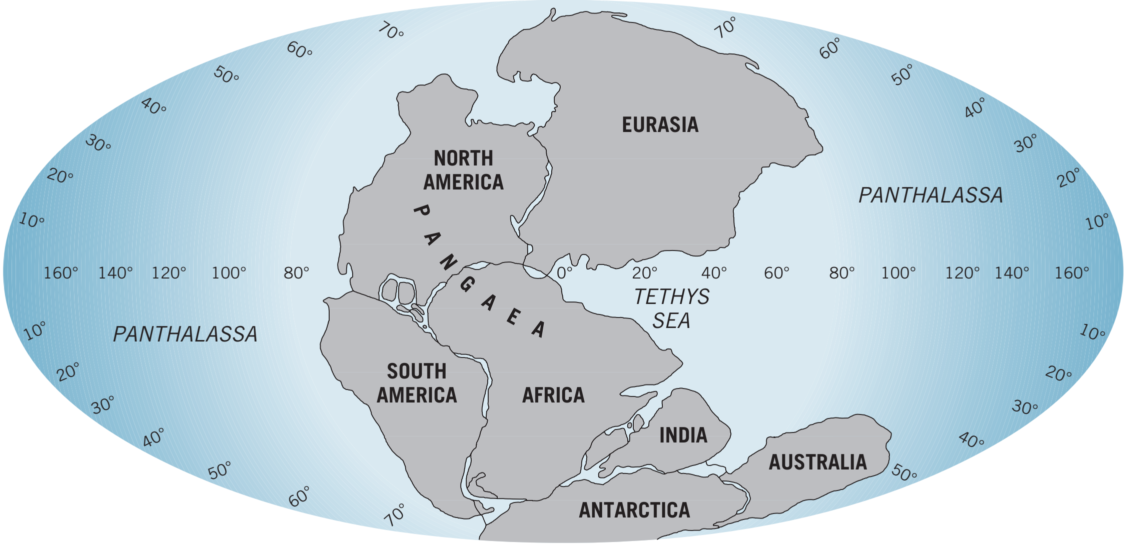

Fig. 2.3 One of the compelling pieces of evidence that Wegener used to argue for his continental drift theory was the geometric fit of South America and Africa. In fact, he believed that about 200 million years ago all the continents were joined together in a supercontinent he called Pangaea.

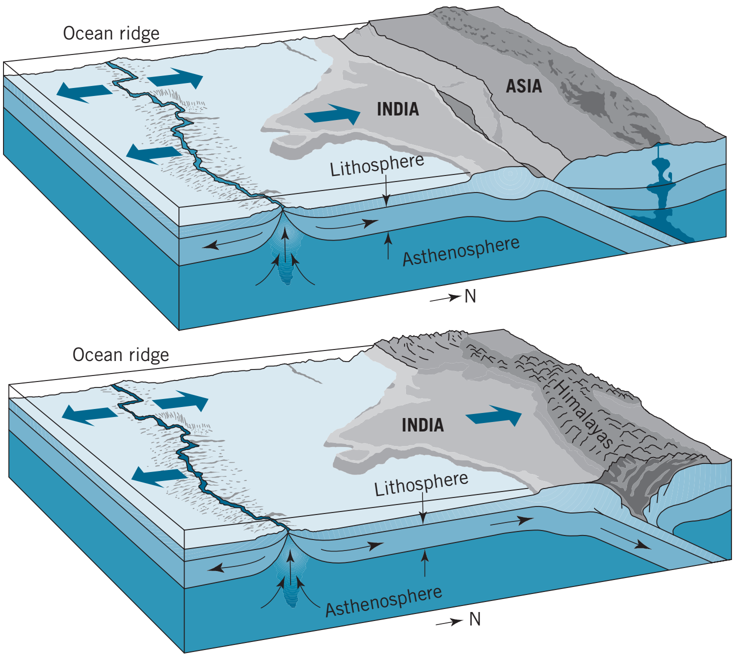

Fig. 2.4 According to Wegener the Indian subcontinent traveled northward following the breakup of Gondwanaland and eventually collided with Asia, forming the Himalayan Mountains.

sediments in what are now the tropical regions of South Africa, India, and Australia could only be logically explained by moving the continents to different latitudinal settings. He also demonstrated that identical fossils and rocks of similar age could be found on widely separated continents but actually plot side by side when Pangaea is reconstructed. Using additional fossil evidence, he theorized that Pangaea separated into a number of pieces approximately 200 million years ago, forming the Atlantic Ocean among other features. He reasoned that if continents could move, then the presence of glacial deposits in India meant that India had once been close to Antarctica and that following the breakup of Gondwanaland, its northward movement and ultimate collision with Asia caused the formation of the Himalayan Mountains (Fig. 2.4).

Although Wegener's book and ideas were initially very popular, the geological community of that time ultimately scorned his new theory. His failure to convince the scientific community stemmed from his weak argument that the continents plowed their way through or slid over the oceanic crust. He believed that this movement was caused by the gravitational pull of the sun and moon (tidal force) acting with a differential force on the surface crust relative to the underlying mantle. Contemporary scientists showed that the tidal forces were much too weak to account for the drifting of continents and thus his theory was abandoned. Wegener did not live long enough to witness the revival and acceptance of many aspects of his theory, as he perished in 1930 at age 50 during a fourth expedition to Greenland while on a rescue mission. Indeed, it was not until the late 1950s and early 1960s that scientists solved the puzzle of the moving continents and Wegener's theory was revived.

In this chapter we demonstrate that the overall physical character of the edge of continents for several thousands of kilometers of coast, such as the west coasts of North and South America, is a function of plate tectonic processes. This includes whether a coast is seismically and volcanically active, whether it is bordered by mountain ranges, a broad coastal plain, or something in between, and whether it is fronted by a narrow or wide continental shelf. Plate tectonics are also shown to have an important influence on the supply of sediment to a coastline and the extent of depositional landforms such as deltas, barrier chains, marshes, and tidal flats.

2.2 The Earth's interior

In order to grasp why continents have "drifted" to new positions, why ocean basins have opened and closed, how mountain systems and ocean trenches have formed, as well as the dimensions of these systems, it is necessary to understand the composition, layering, and processes that occur within the Earth's interior. In its early beginning, the Earth was essentially a homogeneous mass consisting of an aggregate of material that was captured through gravitational collapse and meteoric bombardment. The heat generated by these processes, together with the decay of radioactive elements, produced at least a partial melting of the Earth's interior. This melting allowed the heavier elements, especially the metals of nickel and iron, to migrate toward the Earth's center, while at the same time the lighter rocky constituents rose toward the surface. These processes, which have decreased considerably as the Earth has cooled, ultimately led to a layered Earth containing a core, mantle, and crust. The layers differ from one another both chemically and physically (Fig. 2.5). Most of our knowledge of the Earth's interior comes from the study of seismic waves that pass through the Earth and are modified by its different layers.

The center of the Earth is divided into two zones: a solid inner core (radius 1250 km) with a density almost six times that of the crust and with a temperature comparable to the surface of the sun; and a viscous molten outer core (width 2220 km) some four times as dense as the crust. The mantle is 2880 km thick and contains over 80% of the Earth's volume and over 60% of its mass. It is composed of iron and magnesium-rich silicate (silica–oxygen structure) minerals, which we have observed at locations where material from the mantle has been intruded into the overlying crust and subsequently exposed at the Earth's surface. The chemical composition is consistent throughout the mantle, but due to the increasing temperature and pressure the physical properties of the rocks change with increasing depth.

Compared to the inner layers, the outer skin of the Earth is cool, very thin, much less dense, and rigid. The crust is rich in the lighter elements that rose to the surface during the Earth's melting and differentiation stage, forming minerals such as quartz and feldspar. There are two types of crust: the relatively old (up to 4.0 billion years) and thick granitic crust of the continents (20–40 km thick) and the thin and geologically young (less than 200 million years) basaltic crust beneath the ocean basins (5–10 km thick). Continental crust can be up to 70 km thick at major mountain systems. The less dense and greater thickness of the continental crust (2.7 g cm^{-3}) as compared to the thinner more dense (2.9 g cm^{-3}) ocean crust has important implications for how these two crusts have formed and the stability of the crusts.

The divisions described above are based mostly on the different chemical character of the layers. However, in terms of plate tectonic processes, especially in understanding the movement of plates, the crust and mantle are reconfigured into three layers on the basis of physical changes in the nature of the rocks:

1 **Lithosphere**. This is the outer shell of the Earth and is composed of oceanic and continental crust and the underlying cooler, uppermost portion of the mantle (Fig. 2.5). The lithosphere is approximately 100 km thick and behaves as a solid, rigid slab. In comparison to the diameter of the Earth, the lithosphere is very thin and would represent the shell of an egg. The outer shell is broken up into eight major plates and numerous smaller plates. The Pacific Plate is the largest plate, encompassing a large portion of the Pacific Ocean, whereas the Juan de Fuca Plate off the coasts of Washington and Oregon is one of the smallest. The tectonic or lithospheric plates, as they are called, are dynamic and are continuously moving, although very slowly, with an average rate varying from a few to several centimeters per year. Whereas once this movement was calculated through indirect means, such as age determinations of oceanic crust, rates can now be measured directly from satellites orbiting the Earth.

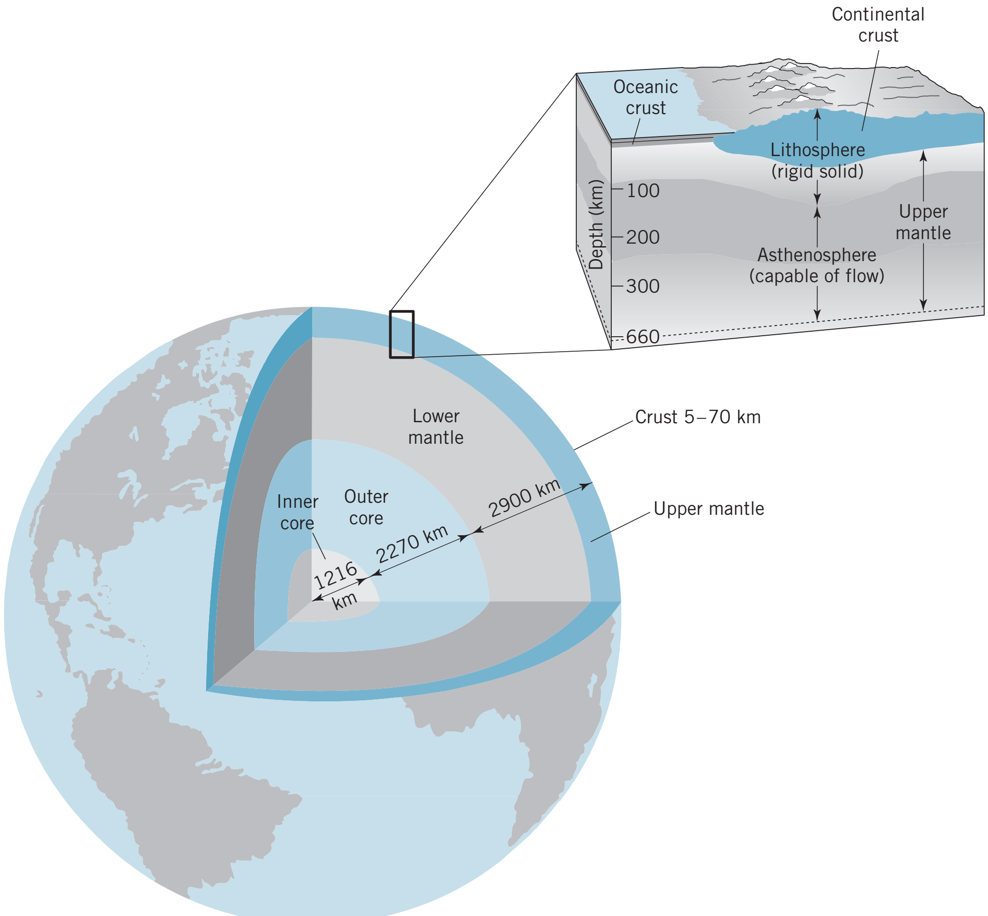

Fig. 2.5 The layered Earth reflects gross chemical and physical changes of the rocks with depth. These changes (which are really gradual changes) are responsible for the major boundaries in the Earth, including the inner and outer core, lower and upper mantle, and thin crust.

2 Asthenosphere. The lithospheric plates float on top of a semi-plastic region of the mantle called the asthenosphere, which extends to a depth of about 350 km. In this part of the mantle the high temperature and pressure causes the rock to partially melt, resulting in about 1–2% liquid. The partially melted rock allows the asthenosphere to be deformed plastically when stress is applied. Geologists have compared this plasticity to cold taffy, hot tar, and red hot steel. One way of illustrating this concept to yourself is by putting a chunk-sized piece of ice between your back teeth and applying slow constant pressure. You will see that the ice will deform without breaking in a manner similar to how the asthenosphere behaves when stressed. In terms of plate tectonics, the semi-plastic nature of this layer allows the lithospheric plates to move.

3 Mesosphere. Below the asthenosphere is the mesosphere, which extends to the mantle–core boundary. Although this layer has higher temperatures than the asthenosphere, the greater pressure produces a rock with a different, more compact mineralogy. This portion of the mantle is mechanically strong.