CHAPTER 1

The Ocean as a Habitat

STUDENT LEARNING OUTCOMES

1. Become acquainted with terminology used in the study of marine biology and oceanography. Use flash cards or other techniques to help memorize important terms in **bold**.
2. Begin to think in an ocean-minded manner, in oceanic size and time scales, and from the perspective of an organism living in the sea.
3. Analyze different methods for mapping the seafloor. Understand how mapping the seafloor will be useful for our study of the ocean and its inhabitants.
4. Explain why we refer to the oceans of the world as "one world ocean."
5. Recall the various areas of the seafloor and water column, and describe how these classifications may affect how marine organisms are distributed.
6. Become familiar with evolution by natural selection.

CHAPTER OUTLINE

The National Oceanic and Atmospheric Administration's ship, the *Okeanos Explorer*, as seen from the water. The mission of this ship is to explore our unknown ocean for the purpose of discovery and to advance our knowledge of the sea.

The ocean is an extremely unique and dynamic habitat. First and foremost, it is full of water, a phenomenal and yet simple substance, with properties that allow a great diversity of life forms to exist. The ocean is not just full of plain water (H_2O) though but rather the somewhat mysterious saltwater (H_2O plus *many other substances*) that you will read more about throughout this book. Another unique fact about the ocean is that it is always moving, which may be challenging or helpful to organisms living on or below the surface. Additionally, resources such as light and oxygen are in limited supply, something that land dwellers do not need to consider.

Earth's oceans are home to an extraordinary variety of living organisms adapted to the special conditions of the sea. The characteristics of these organisms and the variety of marine life itself are consequences of the many properties of the ocean habitat. This chapter provides a survey of the developmental history and present structure of the ocean basins. Adaptations to these properties and oceanographic processes have molded the ocean's inhabitants through their very long history of evolutionary development. It is thought that life first evolved in the ocean several billion years ago, so, in essence, living conditions in the ocean helped shape all living organisms that evolved later on some level, even those currently living on land.

As students of the Earth's ocean, gaining a new perspective will help in our understanding of this nonterrestrial environment. Humans naturally tend to see the world from a human point of view, with human scales of time and distance, with land under our feet and air surrounding us. To begin to understand the marine environment of our home planet and how it and its inhabitants evolved to their present forms, we must broaden our perspective to include very different time and distance scales. Terms such as "young" and "old" or "large" and "small" have limited meaning unless placed in some useful context. **Figure 1.1** compares size scales for a few common oceanic inhabitants, and **Figure 1.2** includes time scales for the Earth, ocean, and living organisms. Throughout this book, these scales are revisited, and others are introduced to help you develop a practical sense of the time and space scales experienced by

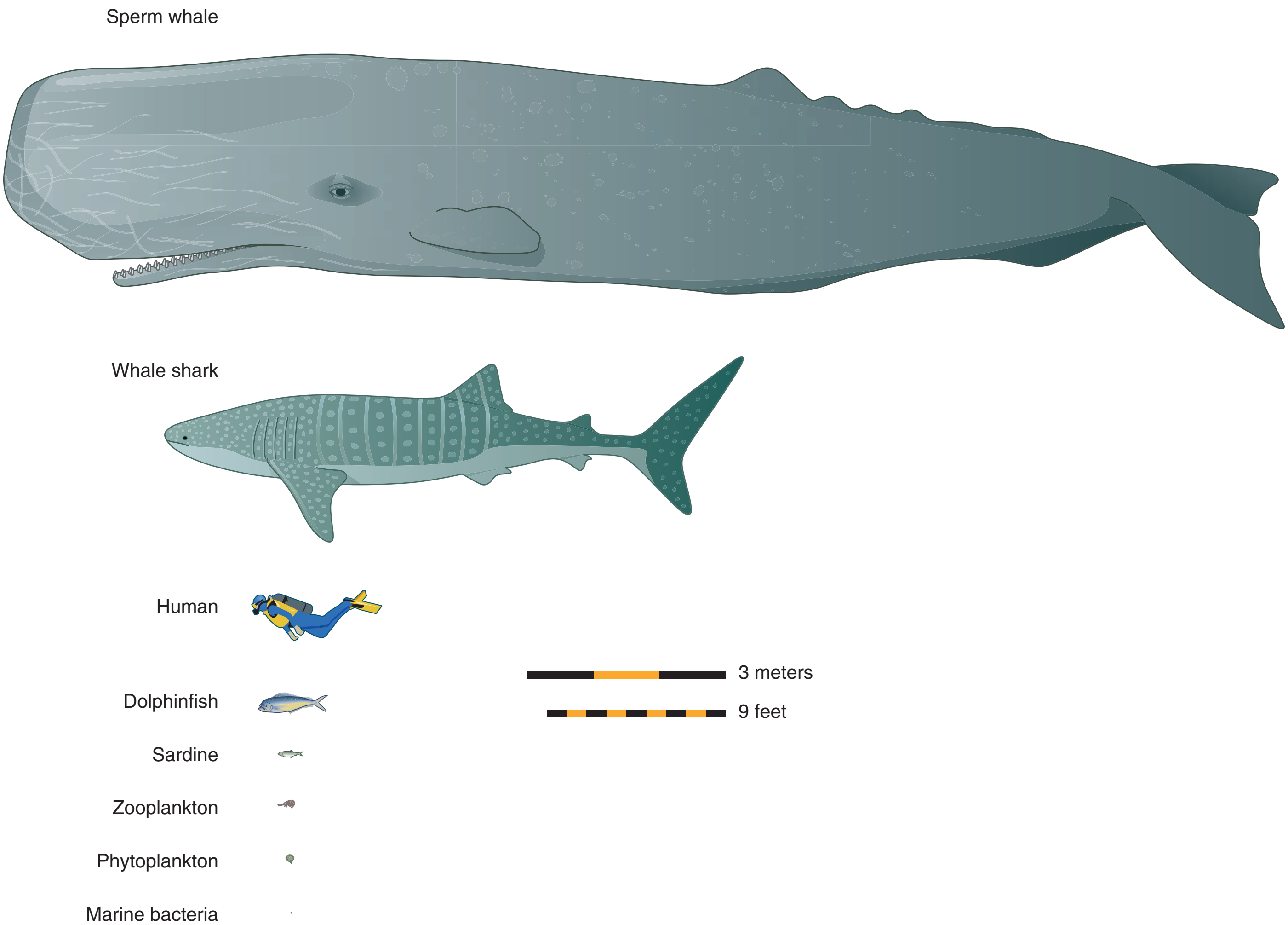

Figure 1.1 A size comparison of common marine organisms and a human. Images are to scale for the sperm whale, whale shark, human, dolphinfish, and sardine. The zooplankton, phytoplankton, and marine bacteria images are magnified approximately 10 times so that they are visible on the page.

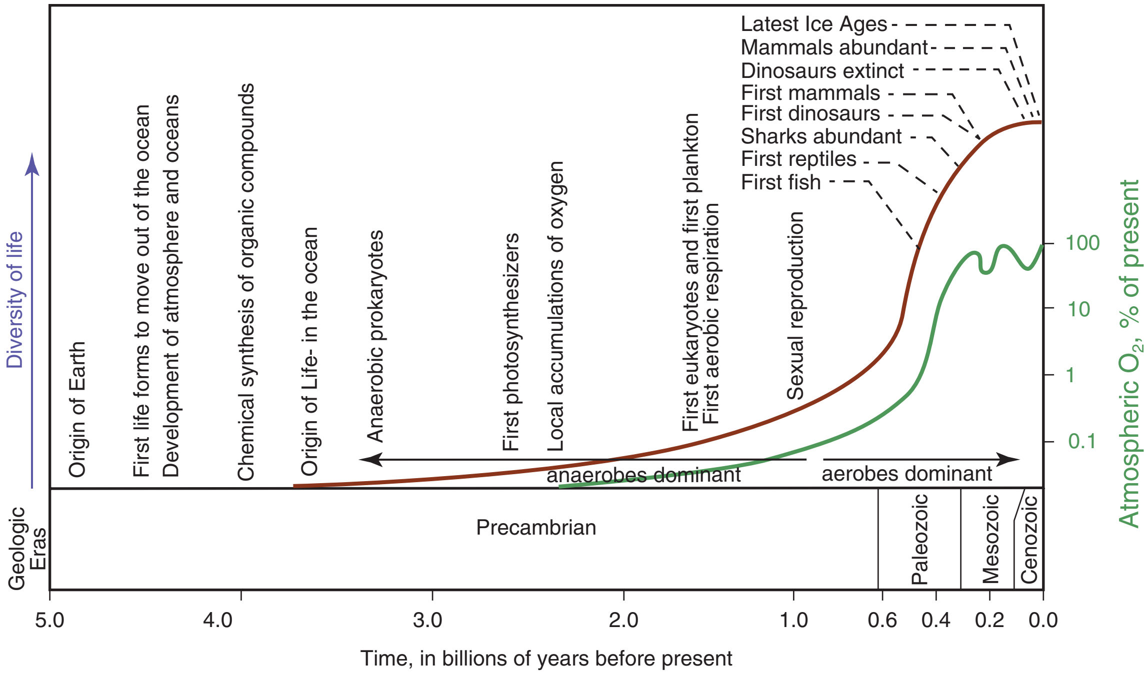

Figure 1.2 A summary of some biological and physical milestones in the early development of life on Earth. The brown curve represents the relative diversity of life; the green curve represents the O_2 concentration of the atmosphere.

marine organisms. As you read about the marine environment, attempt to think in terms of these scales.

1.1 History of Earth and the Sea

Our Earth is thought to have been formed about 4.6 billion years ago. Although some disagreement exists over the exact mechanism of the formation of the solar system and Earth, the most widely accepted explanations of the origin of our solar system indicate that the planets aggregated from a vast cloud of cold gas and dust particles into clusters of solid matter. These clumps continued to grow as gravity attracted them together. As Earth grew in this manner, pressure from the outer layers compressed and heated Earth's center. Aided by heat from decay of radioactive elements, the planet's interior melted. Iron, nickel, and other heavy metals settled to the core, whereas the lighter materials floated to the surface and cooled to form a density-layered planet with a relatively thin and rigid crust (**Figure 1.3**).

Early in Earth's history, volcanic vents poked through the crust and tapped the upper mantle for liquid material and gases that were then spewed out over the surface of the young Earth, and a primitive atmosphere developed. Thick water vapor was certainly present. As it condensed, it fell as rain, accumulated in low places on Earth's surface, and formed primitive oceans. Additional water may have arrived as "snowballs" from space in the form of comets colliding with the young Earth. Atmospheric gases dissolved into accumulating seawater, and other chemicals, dissolved from rocks and carried to the seas by rivers, added to the mixture, eventually creating that complex brew of water, ions, and molecules that we call seawater.

Since their initial formation, the ocean basins have experienced considerable change. New material derived from Earth's mantle has extended the continents so that they are now larger and stand higher than at any time in the past. The oceans have kept pace, getting deeper with accumulations of new water from volcanic gases and from the chemical breakdown of rock. Earth's early life forms (represented by marine bacterial fossils that are

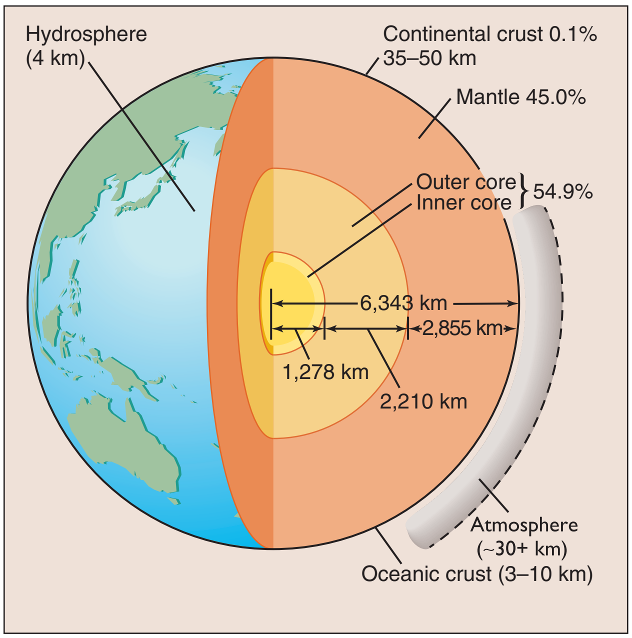

Figure 1.3 A section through the Earth representing the density-layered interior structure and the thickness of each layer. The Earth's crust is so thin that it is represented by a black line.

Figure 1.4 An artist's depiction of life forms present during the Cambrian Explosion.

around 3.5 billion years old) also had a significant impact on the character of the physical environment. Whether the earliest life forms originated at alkaline vents on the deep-sea floor or in warm pools at the sea's edges is a matter of continuing speculation and research. What is clear, however, is that life on this planet requires water; in fact, all living organisms are composed mostly of water.

Early in life's history on Earth, molecular oxygen (O_2) began to be produced in increasing amounts by microscopic photosynthetic **prokaryotes**, as they converted carbon dioxide (CO_2) and water into sugars and O_2. The O_2 content of the atmosphere 600 million years ago was probably about 1% of its present concentration. It was not much, but it was an important turning point, the time when organisms that could take advantage of O_2 in aerobic respiration became dominant and organisms not using O_2 (anaerobes) became less prevalent.

The **evolution** of more complex life forms using increasingly efficient and variable methods of energy utilization set the stage for an explosion of marine species. During the Cambrian period (542 to 488 million years ago) the diversity of life increased dramatically, so much so that this period is referred to as the *Cambrian Explosion*. Most major groups of marine organisms made their appearance during this time. Worms, sponges, corals, fishlike creatures, and the distant ancestors of terrestrial animals and plants were abundant, but life at that time could exist only in the sea, where a protective blanket of seawater shielded it from intense solar radiation (**Figure 1.4**). How do we know about the diversity of life during the Cambrian period, or any other time in the distant past? Fossil evidence provides us with most of the information we have, and various advanced dating techniques allow for estimates of the ages of fossils. The most interesting fossils discovered from the Cambrian period are from areas containing shale material. Shale is very fine material that allows for rapid fossilization of soft or hard body parts, and an increased amount of fine details are preserved from specimens.

As O_2 became more abundant in the upper atmosphere, some of it was converted to **ozone** (O_3). The process of forming ozone absorbed much of the lethal ultraviolet radiation coming from the sun and prevented the radiation from reaching Earth's surface. The O_2 concentration of the atmosphere 400 million years ago is estimated to have reached 10% of its present level and achieved its current concentration in the Mesozoic era (about 200 million years ago). The additional ozone screened out enough ultraviolet radiation to permit a few life forms to abandon their sheltered marine home and colonize the land. Only recently have we become aware that industrialized society's increasing use of aerosols, refrigerants, and other atmospheric pollutants is gradually depleting this protective layer of ozone. Figure 1.2 provides a general timeline for some of the major events in the early development of life on Earth.

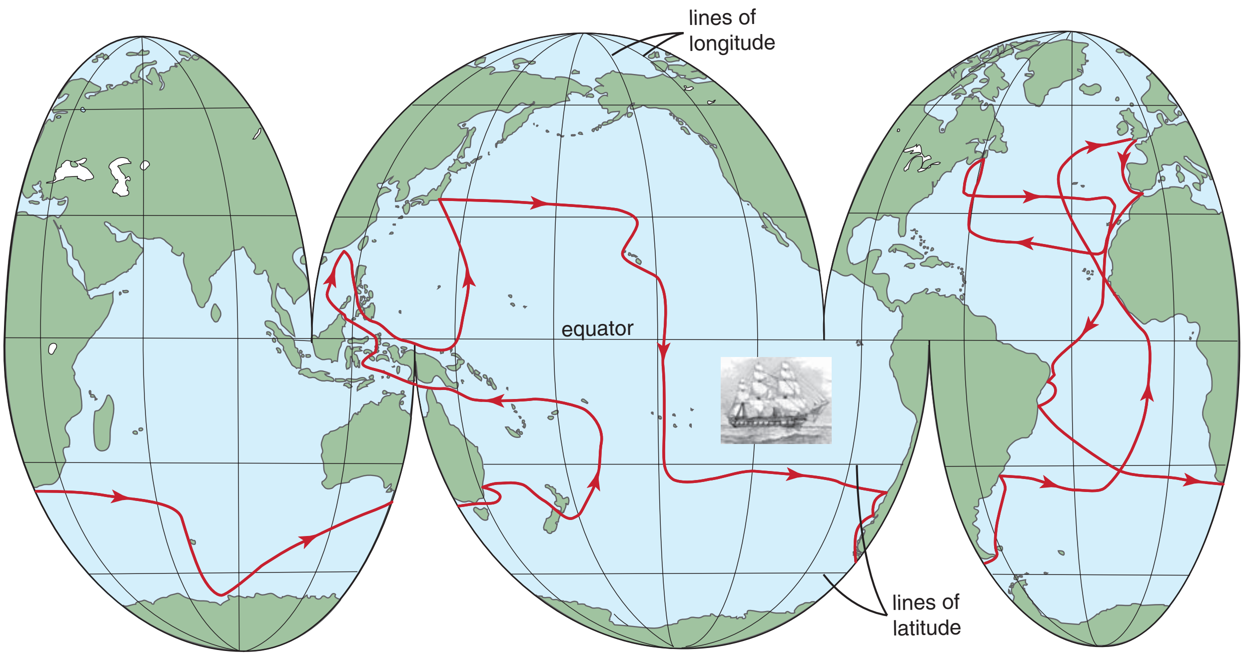

Figure 1.5 An "orange peel" projection of the Earth's surface with latitude and longitude lines at 30-degree intervals. The red line tracks the voyage of HMS *Challenger* (inset).
Courtesy of Steve Nicklas, NOS, NGS/NOAA.

DID YOU KNOW?

Geological periods are marked by large changes such as major extinction events. If even one of the major extinction events in Earth's history had not taken place, then life as we know it today would not exist. Extinction events remove some species from existence, making room for new species to evolve and take over previously occupied areas. The mass extinction of almost all dinosaurs at the end of the Cretaceous period made room (and a much safer environment) for large mammals to thrive.

Charting the Deep

As fascinated as people are with the sea, it can be assumed that people must have explored their local coastal environments very early in their history, but few early discoveries were recorded. By 325 B.C., Pytheas, a Greek explorer, had sailed to northwestern Europe and developed a method for determining **latitude** (**Figure 1.5**). About a century later, Eratosthenes of Alexandria, Egypt, provided the earliest recorded estimate of Earth's size, its first dimension. His calculated circumference of 39,690 km was only about 1% less than today's accepted value of 40,008 km. During the Middle Ages, Vikings, Arabians, Chinese, and Polynesians sailed over major portions of Earth's oceans. By the 15th century, all the major inhabitable land areas were occupied; only Antarctica remained unknown to and untouched by humans. Even so, precise charting of the ocean basins had to await several more voyages of discovery.

Between 1768 and 1779, James Cook, an English navigator, conducted three exploratory voyages, mostly in the Southern Hemisphere. He was the first to cross the Antarctic Circle and to understand and conquer scurvy (a disease caused by a deficiency of vitamin C). He is best remembered as the first global explorer to make extensive use of the marine chronometer developed by John Harrison, a British inventor. The chronometer, a very accurate shipboard clock, was necessary to establish the **longitude** of any fixed point on the Earth's surface. Together with Pytheas's 2,000-year-old technique for fixing latitude, reasonably accurate positions of geographic features anywhere on the globe could be established for the first time, and our two-dimensional view of Earth's surface was essentially complete. Today, coastal Long Range Navigation (LORAN) stations and satellite-based global positioning systems (GPSs) enable individuals to determine their position to within a few meters anywhere on Earth. With GPS technology currently available on most cellular phones, it is difficult to imagine a time when navigation was a complicated task.

DID YOU KNOW?

Captain Cook's voyages were not for the faint of heart. Over the 25 years he led expeditions, many sailors died, food was scarce, dates of arrival back home were anything but certain, and the pay was minimal. Only the most dedicated or desperate of men dared join an expedition. In fact, during one expedition to Australia the trip turned into somewhat of a disaster as navigation near what would later be called the Great Barrier Reef led to a grounded ship. Yet Captain Cook himself was a determined man, and he did all he could to keep his men alive. His passions were exploration and navigation, and he needed brave and competent men to join him.

In 1872, a century after Cook's voyages, the first truly interdisciplinary global voyage for scientific exploration of the seas departed from England. The HMS *Challenger* was converted expressly for this voyage. The voyage lasted over 3 years, sailed almost 69,000 **nautical miles** in a circumnavigation of the globe (Figure 1.5), and returned with such a wealth of information that 10 years and 50 large volumes were required to publish the findings. During the voyage, 492 depth soundings were made. These soundings traced the outlines of the Mid-Atlantic Ridge under 2 km of ocean water, plumbed the Mariana Trench to a depth of 8,185 m, and filled in rough outlines globally of the third dimension of the world ocean, its depth. The data collected during the HMS *Challenger* expedition contributed greatly to our knowledge of the marine environment during the infancy of the field of marine science.

A Different View of the Ocean Floor

Early in the 20th century, Alfred Wegener proposed that the oceans were slowly changing in enormous ways and had been since they arose. Wegener developed a detailed hypothesis of what eventually became known as **continental drift** to explain several global geologic features, including the remarkable jigsaw-puzzle fit of some continents (especially the west coast of Africa and the east coast of South America). He proposed that our present continental masses had drifted apart after the breakup of a single supercontinent, **Pangaea**. His evidence seemed ambiguous at the time, though, and most scientists remained unconvinced. It was not until the early 1960s that new evidence compelled two geophysicists to independently, and almost simultaneously, propose the closely related concepts of **seafloor spreading** and **plate tectonics**. In hindsight, these related concepts seem completely obvious—that the Earth's crust is divided into giant irregular plates (**Figure 1.6**). These rigid crustal plates float on the denser and slightly more plastic mantle material. Each plate edge is defined by oceanic trench or ridge systems, and some plates include both oceanic and continental crusts. New oceanic crustal material is formed continually along the axes of oceanic ridges and rises. As crustal plates grow on either side of the ridge, they move away from the ridge axis in opposite directions, carrying bottom sediments and attached continental masses with them (**Figure 1.7**).

In 1968, a new and unusual ship, the *Glomar Challenger*, was launched to probe Earth's history as recorded in sediments and rocks beneath the oceans. Equipped with a deck-mounted drilling rig, the *Glomar Challenger* was capable of drilling into the seafloor in water over 7,000 m deep. Within 2 years, the *Glomar Challenger* recovered vertical sediment core samples from enough sites on both sides of the Mid-Atlantic Ridge to finally and firmly confirm the hypotheses of seafloor spreading and continental drift. Before being decommissioned in 1983, the *Glomar Challenger* traveled almost 700,000 km and drilled 318,461 m of seafloor in 1,092 drill holes at 624 sites in all ocean basins. Subsequent analyses of microscopic marine fossils recovered from this tremendous store of marine sediment samples have led to refined estimates of the ages and patterns of evolution of living organisms in all the major ocean basins. The *JOIDES Resolution*, named after the HMS *Resolution* commanded by Captain Cook, continued the work that the *Glomar Challenger* had begun and is still in operation today (**Figure 1.8**). Data from core samples collected from this vessel add to our continued understanding of the history of Earth and our world ocean.

The changes that seafloor spreading and plate tectonics have wrought on the shapes and sizes of the oceans have been and will continue to be quite impressive. Currently, the African continent is drifting northward on a collision course with Europe, relentlessly closing the Mediterranean Sea. The Atlantic Ocean is becoming wider at the expense of the Pacific Ocean. Australia and India continue to creep northward, slowly changing the shapes of the ocean basins they border. Occasional violent earthquakes are only incidental tremors in this monumental collision of crustal plates. The rates of seafloor

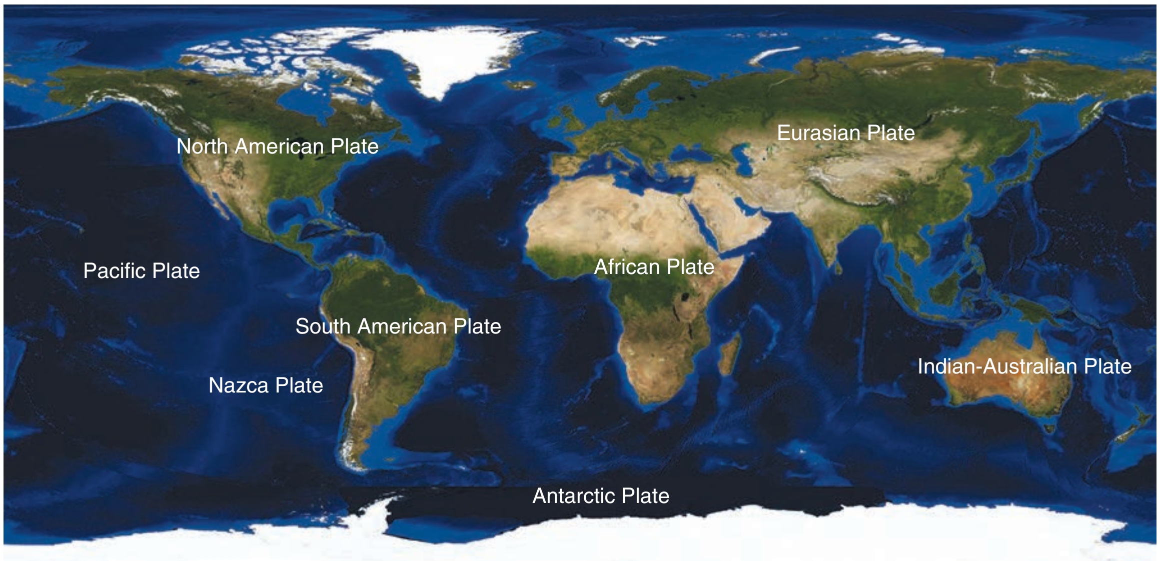

Figure 1.6 The major plates of Earth's crust. Compare the features of the map with those of Figure 1.12.
Courtesy of Reto Stockli, NASA Earth Observatory.

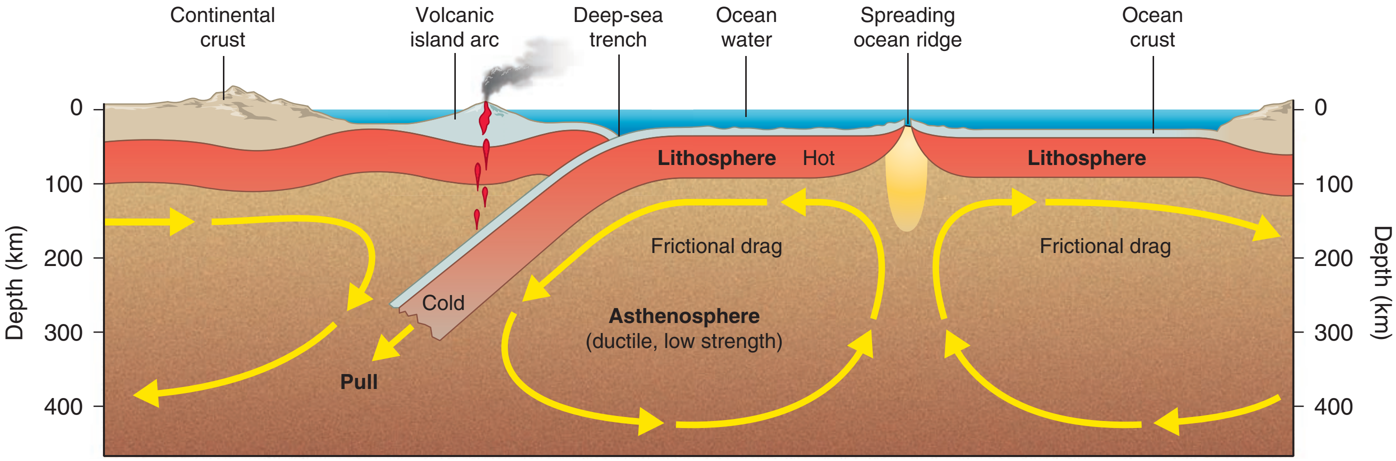

Figure 1.7 Side view of a spreading ocean floor, illustrating the relative motions of oceanic and continental crusts. New crust is created at the ridge axis, and old crust is lost in deep-sea trenches.

spreading have been determined for some oceans, and they vary widely. The South Atlantic is widening about 3 cm each year (or approximately your height in your lifetime). The Pacific Ocean is shrinking somewhat faster. The fastest seafloor spreading known, 17.2 cm/yr, was measured along the East Pacific Rise, a mid-oceanic ridge at the meeting point of five plates.

The breakup of the megacontinent Pangaea produced ocean basins where none existed before. The seas that existed 200 million years ago have changed size or have disappeared altogether. Some of the past positions of the continents and ocean basins, based on our present understanding of the processes involved, are reconstructed in **Figure 1.9**. Excess crust produced by seafloor spreading folds into mountain ranges (the Himalayas are a dramatic example) or slips down into the mantle and remelts (Figure 1.7). Consequently, most marine fossils older than about 200 million years can never be studied; they, too, have been carried to destruction by the "conveyor belt" of subduction, the sinking of seafloor crust at trench locations to be remelted in the mantle. Ironically, the only fossil evidence we can find for the first 90% of the evolutionary history of marine life is found in landforms that were once ancient seabeds.

Figure 1.8 The ocean drill ship, *JOIDES Resolution*.

On much shorter time scales, other processes have been at work to alter the shapes and sizes of ocean basins. During the past 200,000 years, our planet has experienced two major episodes of global cooling associated with extensive continental

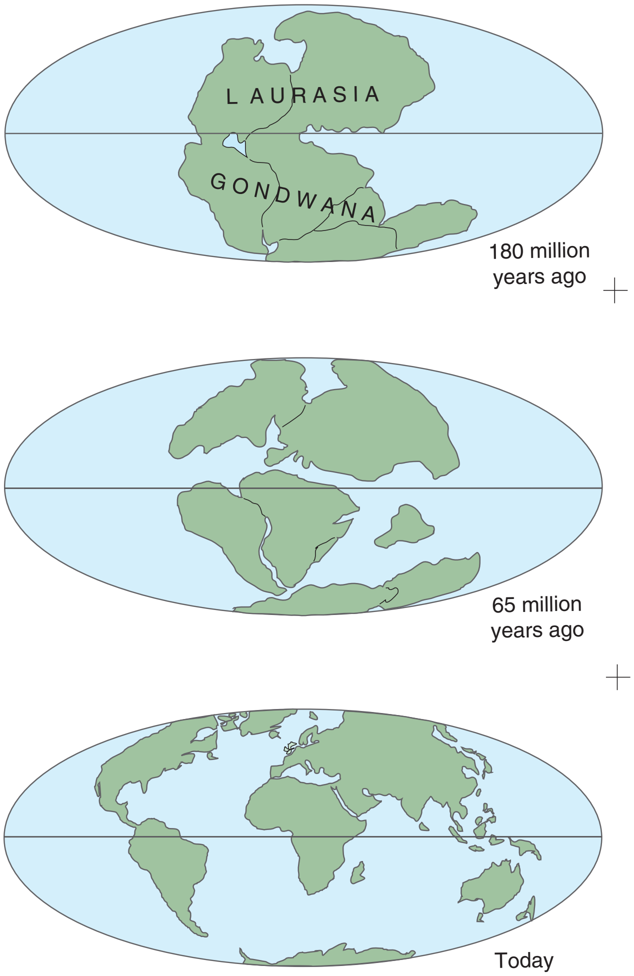

Figure 1.9 About 200 million years ago, the megacontinent, Pangaea, separated into two large continental blocks, Laurasia and Gondwana. Over time, these blocks fragmented into the smaller continents that we see today, and they continue to drift apart.

Data from Dietz and Holden 1970.

glaciation. Just 18,000 years ago, northern reaches of Europe, Asia, and North America were frozen under the grip of the most recent ice age, or the **last glacial maximum (LGM)**. The massive amount of water contained in those glaciers lowered the sea level about 150 m below its present (and also its preglacial) level. Between 18,000 and 10,000 years ago, melting and shrinking of these continental glaciers were accompanied by a 150-m rise in global sea level and the flooding of land exposed during the LGM. Coral reefs, estuaries, and other shallow coastal habitats were modified extensively during this flooding. Currently, warmer summer temperatures around Antarctica are creating real concern about the potential for melting glaciers to cause another rise in global sea levels of a few meters. Another concern for sea level rise is increasing ocean temperatures in general, which would lead to an expansion of water, a rise in sea level, and temperature challenges for many marine organisms. Current estimates indicate a continuous sea level rise of greater than 0.3 cm/yr worldwide.

1.2 The World Ocean

Based on our current knowledge, Earth is the only planet in our solar system that has liquid water at its surface. Unlike the faces of any planet we can see from Earth, from space our Blue Planet stands apart from all others because 70% of our planet's solid face is hidden by water too deep for light to penetrate. Our world ocean has an average depth of about 3,800 m (2.4 miles). This may seem like a lot of water, but when compared with Earth's diameter of 12,756 km, the world ocean is actually a relatively thin film of water filling the low places of Earth's crustal surface. On the scale of the standard view of Earth seen from space, the average ocean water depth is represented by a distance of about 0.04 mm (about 1/1,000 of an inch). Although shallow on a planetary scale, these water depths of several thousand meters easily dwarf the largest of the plants or animals living there.

Visualizing the World Ocean

Being so vast in depth, volume, and area, it can be difficult to obtain a grasp of the ocean as one large entity. Yet the waters of the world's ocean are all interconnected, and one can attempt to visualize Earth's marine environment in this way, as shown in **Figure 1.10**. The Antarctic continent is surrounded by a "Southern Ocean," which has three large embayments extending northward. These three oceanic extensions, partially separated by continental barriers, are the Atlantic, Pacific, and Indian Oceans. Other smaller oceans and seas, such as the Arctic Ocean and the Mediterranean Sea, project from the margins of the larger ocean basins. These broad connections between major ocean basins permit exchange of both seawater and the organisms living in it, reducing and smoothing out differences between adjacent ocean basins.

Figure 1.11 represents a more conventional view of the world ocean, showing separations into four major ocean basins—the Atlantic, Pacific, Indian, and Arctic—and without the emphasis on the extensive southern connections apparent in Figure 1.10. The format of Figure 1.11 is often more useful because our interest in the marine environment has been focused on the temperate and tropical regions of Earth.

The equator is a very real physical boundary extending across the tropical center of the large ocean basins. The curvature of Earth's surface causes areas near the equator to receive more concentrated radiant energy from the sun than equal-sized

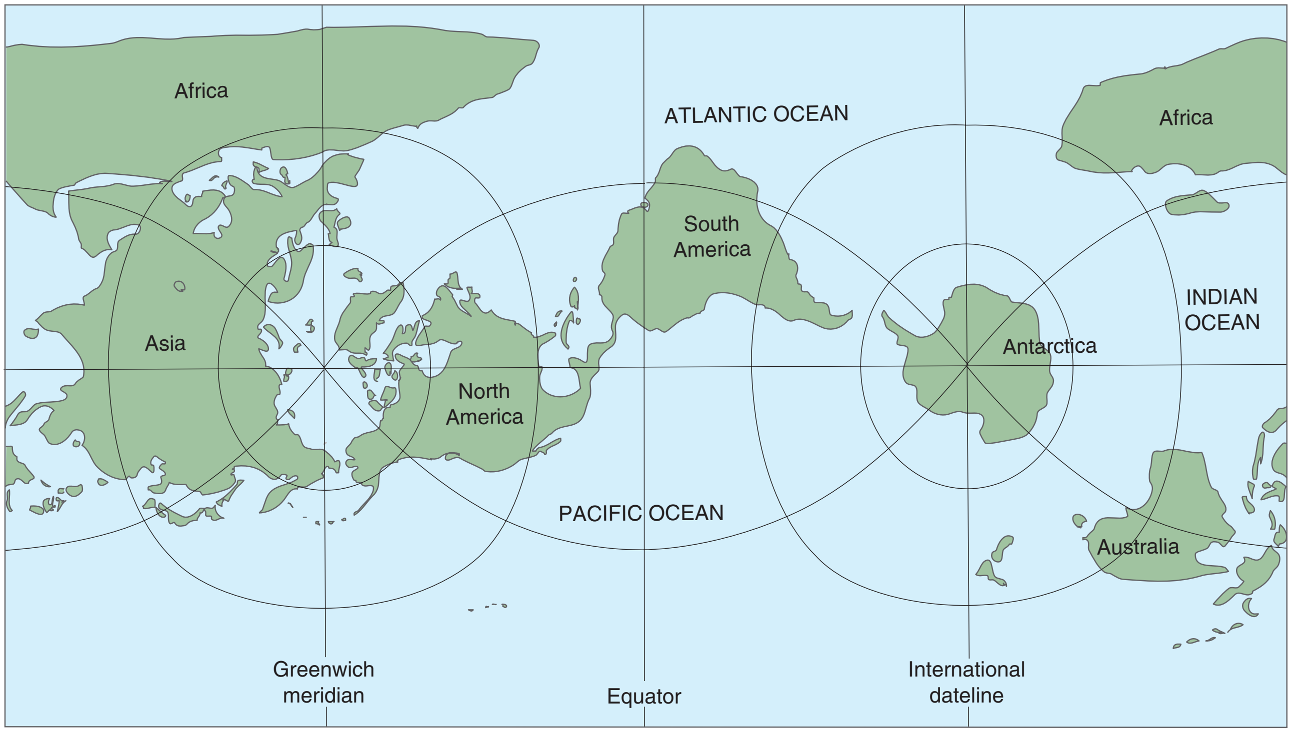

Figure 1.10 A modified polar view of the world ocean, emphasizing the extensive connections between major ocean basins in the Southern Hemisphere.

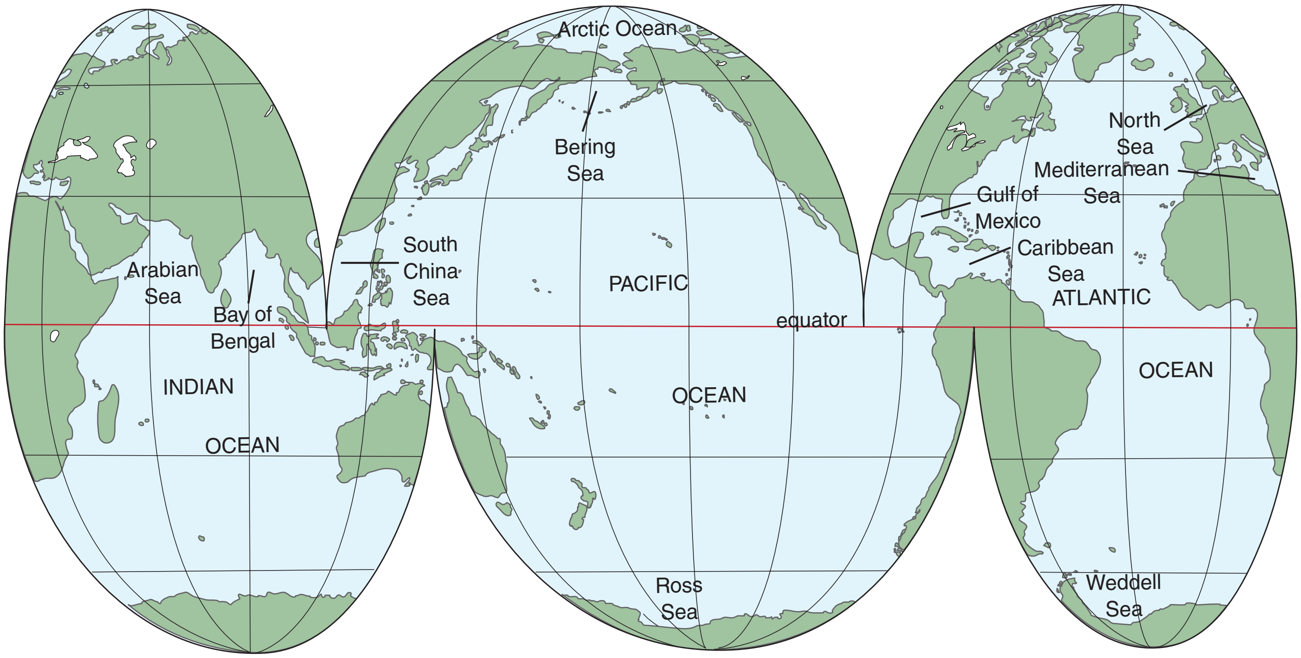

Figure 1.11 An "orange peel" equatorial view of the world ocean.

areas in polar regions where the sun's energy is spread out. The resultant heat gradient from warm tropical to cold polar regions establishes the basic patterns of atmospheric and oceanic circulation. Surface ocean current patterns display a nearly mirror-image symmetry in the northern and southern halves of the Pacific and Atlantic Oceans. This symmetry establishes it as a natural, although intangible, focus for the graphic representation of these features and of the life zones they define.

Nearly two thirds of our planet's land area is located in the Northern Hemisphere. The Southern Hemisphere is an oceanic hemisphere, with 80% of its surface covered by water. The Pacific Ocean alone accounts for nearly one half of the total ocean area. A few descriptive measurements for features of the six largest marine basins are listed in **Table 1.1**.

Maximum oceanic depths extend to over 11,000 m, but most of the ocean floor lies shallower, at depths between 3,000 and 6,000 m below the sea surface. As a terrestrial comparison, the maximum height of a mountain above land is Mount Everest, measuring 8,848 m tall. The tallest mountain is Mauna Kea in Hawaii, which reaches a total of 10,205 m high from a submarine base underwater in the Hawaiian trough. Only 4,205 m of the mountain are visible above water, which is why Mount Everest is considered the tallest peak. An image of the northern and central parts of the Atlantic Ocean (**Figure 1.12**) illustrates some of the larger scale features of the ocean floor. The **continental shelf**, which extends seaward from the shoreline and is actually a structural part of the continental landmass, would not be considered an oceanic feature if sea level were lowered by as little as 5% of its present average depth. The width of continental shelves varies, from being nearly absent off southern Florida to over 800 km wide in the Arctic Ocean north of Siberia. Continental shelves account for 8% of the ocean's surface area; this is equivalent to about one sixth of Earth's total land area.

Most continental shelves are relatively smooth and slope gently seaward. The outer edge of the shelf, called the **shelf break**, is a vaguely defined feature that usually occurs at depths between 120 and 200 m. Beyond the shelf break, the bottom steepens slightly to become the **continental slope**. Continental slopes reach depths of 3,000 to 4,000 m and form the boundaries between continental masses and the deep ocean basins.

TABLE 1.1 Some Comparative Features of the Major Ocean Basins

Ocean or Sea	Area (km²)	Volume (km³)	Average Depth (m)	Maximum Depth (m)
Pacific	165.2	707.6	4,282	11,033
Atlantic	82.4	323.6	3,926	9,200
Indian	73.4	291.0	3,963	7,460
Arctic	14.1	17.0	1,205	4,300
Caribbean	4.3	9.6	2,216	7,200
Mediterranean	3.0	4.2	1,429	4,600
Other	18.7	17.3		
Totals (average)	*361.1*	*1,370.3*	*(3,795)*	

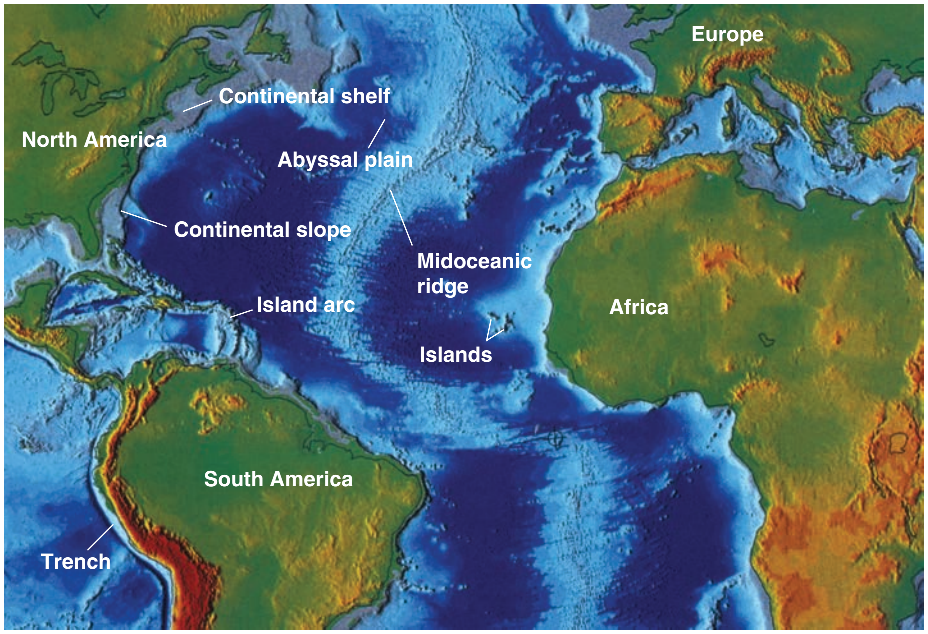

Figure 1.12 Some large-scale features of the North Atlantic seafloor. Compare these large features to some of those depicted in Figure 1.14.
Courtesy of National Geophysical Data Center/NOAA.

A large portion of deep ocean basins consists of flat sediment-covered areas called **abyssal plains**. These plains have almost imperceptible slopes, much like those of eastern Colorado. The sediment blanket over abyssal plains often completely buries smaller crustal elevations, called *abyssal hills*. Most abyssal plains are situated near the margins of the ocean basins at depths between 3,000 and 5,000 m.

Oceanic **ridge and rise systems**, such as the Mid-Atlantic Ridge and East Pacific Rise, occupy over 30% of the ocean basin area. The ridge and rise systems are rugged, more or less linear features that form a continuous underwater mountain chain encircling Earth. The Mid-Atlantic Ridge actually resembles a 20- to 30-km-wide canyon like the East African Rift Valley, sitting atop a broadly elevated seafloor aligned down the center of the Atlantic Ocean. The top of the Mid-Atlantic Ridge may extend 4 km above the surrounding abyssal hills, and isolated peaks occasionally extend above sea level to form islands such as Iceland and Ascension Island. The East Pacific Rise is much lower and broader, with a barely perceptible rift about 2 km wide.

Trenches are distinctive ocean-floor features, with depths usually extending deeper than 6,000 m. Most trenches, including the seven deepest, are located along the margins of the Pacific Ocean. The bottom of the Challenger Deep, in the Mariana Trench of the western North Pacific, is 11,033 m deep, the greatest ocean depth found anywhere. This is as far below sea level as commercial jets typically fly above the sea surface. The enormous depths of trenches impose extreme conditions of high water pressure and low temperature on their inhabitants. Although trenches account for less than 2% of the ocean bottom area, they are integral parts in the processes of seafloor spreading and plate tectonics, acting as sites where crustal plates tens or hundreds of millions of years old are finally subducted back into the mantle to be remelted.

Most oceanic islands, seamounts, and abyssal hills have been formed by volcanic action. Oceanic **islands** are volcanic mountains that extend above sea level; **seamounts** are volcanic mountains whose tops remain below the sea surface. Most of these features are located in the Pacific Ocean where volcanic activity is common. Islands in tropical areas are often submerged and capped by coral atolls or fringed by coral reefs. These reefs form some of the most beautiful and complex animal communities found anywhere.

Seeing in the Dark

Humans are visual beings; we have relatively good vision and continually examine our surroundings through the clarity of air. In the oceans, however, the opacity of seawater has long thwarted our ability to examine its depths in detail. Fortunately, the opacity of seawater to light is compensated by its transparency to sound. The early ancestors of dolphins capitalized on this feature of water about 20 million years ago by evolving sophisticated biosonar systems capable of high-resolution target discrimination. Biosonar is based on the production of sharp sounds, detecting the echo as it bounces off a target, and then measuring the time delay between sound production and echo return. In a technologic sense, we are catching up with dolphins with the development of various types of electronic **sonar** (*so*und *na*vigating *r*anging) systems. Without going into the history of the development of sonar, it is sufficient to note that several different types of sonar systems with different resolutions have been central to obtaining detailed pictures of the deep ocean floor. Although sonar technically uses sound information, we use computer software to convert sounds into visual signals we can easily examine and relate to.

The most widespread and familiar type of sonar is operated from surface ships. You may be familiar with commercial versions of these as fish finders or depth finders on personal boats. At sea, surface sonar systems operate from a single ship-based transmitter to produce a single line or track of sequential depth measurements below the ship as it is under way. This system provides an acoustic view of the seafloor in two dimensions, with poor resolution of small structures or fine detail.

Multibeam sonar systems also are operated from surface vessels but with an array of numerous sound transmitters and receivers arranged from bow to stern. The many overlapping sound beams return much more information about the seafloor, information that would be a useless jumble of data without computers to decipher it. Multibeam sonar can map a swath of ocean bottom several kilometers wide in a single pass and with much higher resolution than single-transmitter systems. The result is the acoustic equivalent of a continuous strip of aerial photographs of the ocean floor (**Figure 1.13**).

Side-scan sonar systems are variants of the multi-beam technique. As its name implies, side-scan sonar directs sound beams to the sides of the ship's track. Images obtained with side-scan sonar show in rich detail the fine texture of the seafloor, equivalent to close-up photographs of the ocean floor. The method of sonar used by scientists will vary depending on the specific research question. For studies with large survey areas, multibeam systems are ideal. For studies requiring finer details of the ocean floor, side-scan sonar is sometimes a better option. Regardless of the sonar method used, the resulting picture of the seafloor is clearer and provides more information when seas are calm during the survey period. Although computer software can correct for some ship movements, the corrections that can be made are limited.

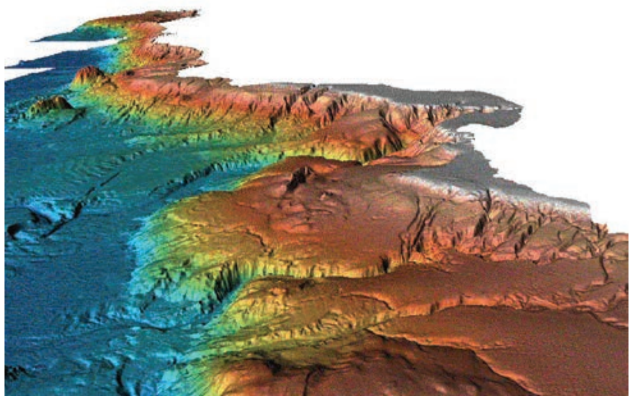

Figure 1.13 A multibeam sonar image of the coastal margin of southern California. Variegated colors depict varying depths.

Courtesy of National Oceanic and Atmospheric Administration.

1.3 Classification of the Marine Environment

The large size and enormous complexity and variability of the marine environment make it a difficult system to classify. Many systems of classification have been proposed, each reflecting the interest and bias of the classifier. A scientist interested in marine worms living within the sediments will classify the environment using a much finer scale than a scientist studying the migration patterns of sea turtles across hundreds or thousands of kilometers of ocean. The system presented here is a modified version of a widely accepted scheme proposed by Hedgpeth over a half-century ago, appropriate for large-scale classifications of the marine environment. The terms used in **Figure 1.14** designate particular zones of the marine environment. These terms are easily confused with the names of groups of organisms that normally inhabit these zones. The boundaries of these zones are defined on the basis of physical characteristics such as water temperature, water depth, and available light.

Working downward from the ocean surface, the limits of **intertidal zones** are defined by tidal fluctuations of sea level along the shoreline. The splash, intertidal, and inner shelf zones occur in the **photic** (lighted) **zone**, where the light intensity is great

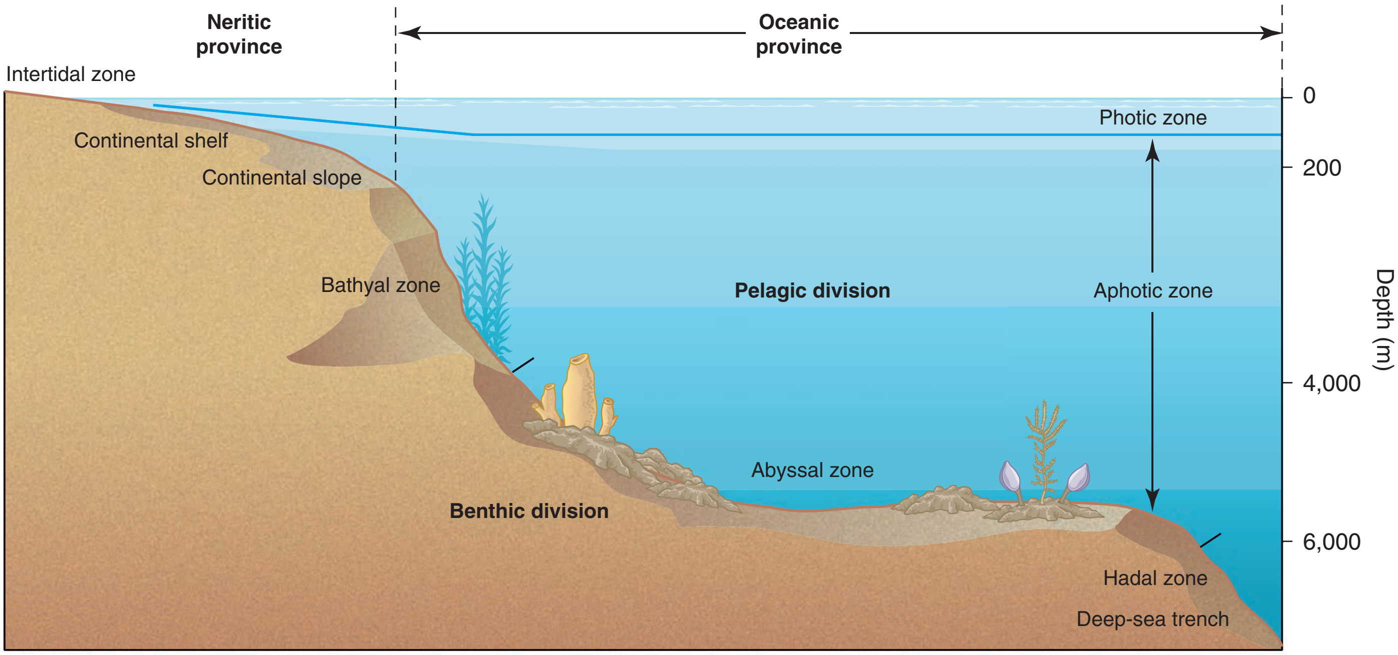

Figure 1.14 A system for classifying the marine environment.

Data from J. W. Hedgpeth, ed., *Treatise on Marine Ecology and Paleoecology* (Geological Society of America, 1966).

RESEARCH in Progress

Mapping the Seafloor

The earliest investigations of the seafloor involved extremely basic methods such as the use of ropes and lead weights dropped to the bottom to gain a sense of depth and very rough seafloor bathymetry. These methods were time-consuming and not as accurate as one would like, but at the time they offered bits and pieces of information about the seafloor that were previously completely unknown. As technology improved, oceanographers seeking finer details of the seafloor and marine biologists hoping to gain more information about the available seafloor habitat for organisms took great interest in advanced seafloor mapping methods. The development of sonar techniques opened up the seafloor to observation by scientists and mariners. Surprisingly, despite advances in sonar technology, until very recently only a small fraction of the ocean seafloor had been mapped to any extent because sonar is costly and time-consuming. Sonar requires a ship to navigate very slowly over the area to be mapped while sending and receiving sound wave signals to and from the seafloor, a process commonly known as "mowing the lawn." Because the ocean is so vast, only areas of high interest such as the coastlines, marine reserves, shipping channels, and known shipwreck areas have been mapped with sonar (**Figures A** and **B**).

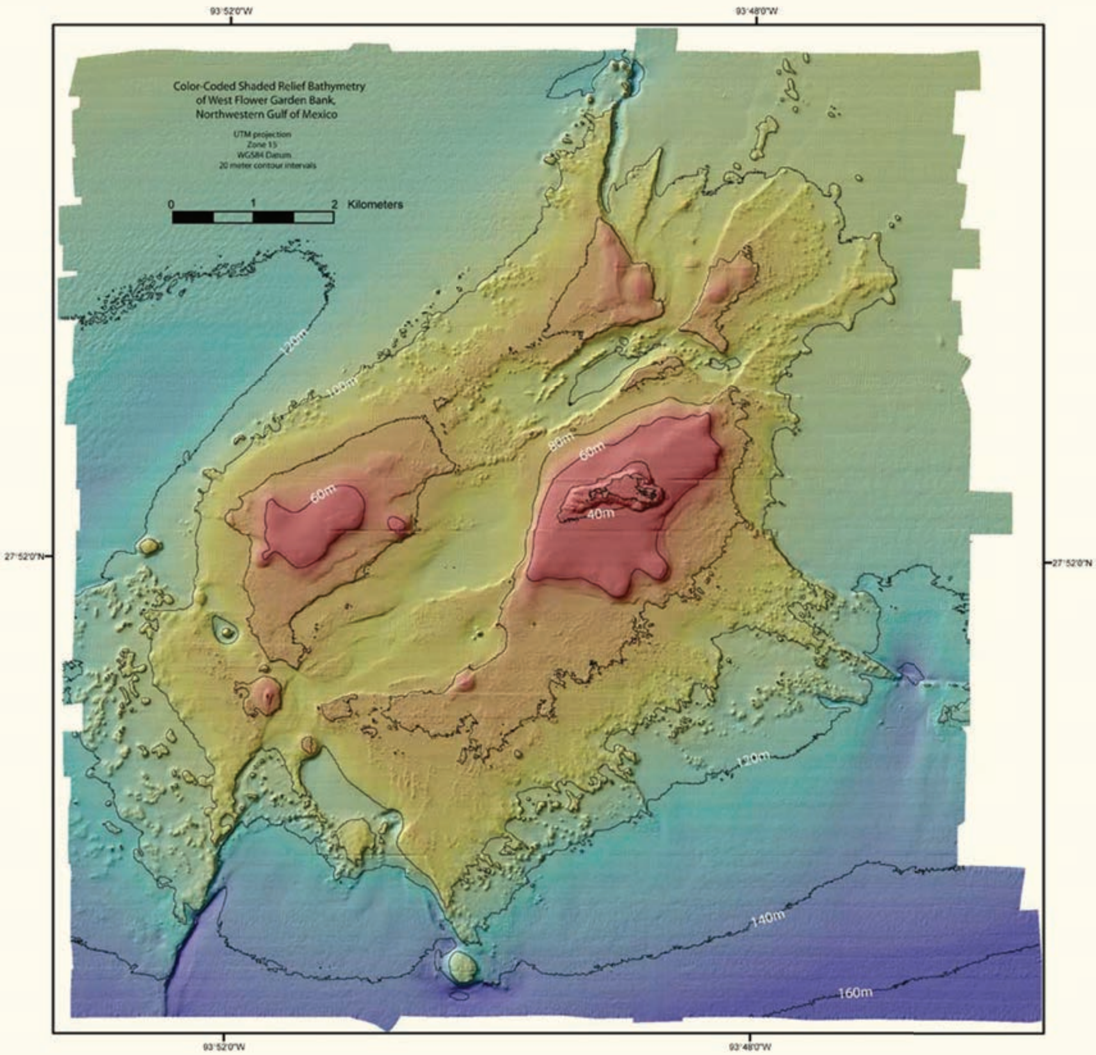

Figure A Multibeam imaging of West Flower Garden Bank, a marine reserve in the Gulf of Mexico. Colors and bathymetry lines (20-m contours) indicate depths.
Courtesy of U.S. Geological Survey.

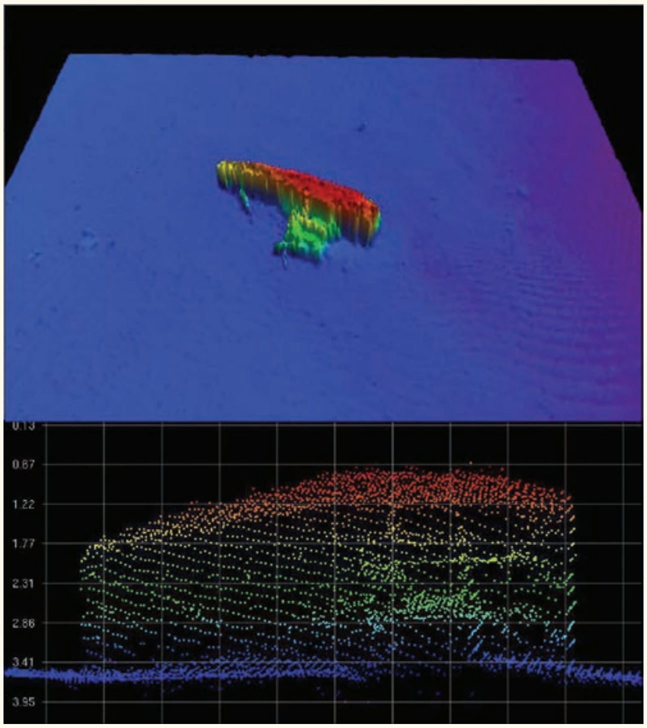

Figure B Multibeam imaging of a shipwreck in Kachemak Bay, Alaska.
Courtesy of National Oceanic and Atmospheric Administration.

Satellite data can provide some seafloor characteristic information on very large scales. Satellites cannot penetrate the sea surface, but they can detect the minor differences in sea level height caused by large features on the seafloor. These minor differences provide a signal and reveal features such as ocean trenches, seamounts, and large oceanic ridges. A recent project aimed at mapping the entire ocean bottom using satellite data provided maps at a resolution of 5 km. This means that objects 5 km or larger can be detected, so large trenches or ridges are visible, but anything smaller than 5 km is not. The results of these mapping efforts revealed around 20,000 previously unknown seamount features, which are underwater mountains that rise 1 km or more from the seafloor. Although these results are exciting to geologists and provide information about important deep-sea features, 5-km resolution is not fine enough detail to be useful to address many marine research questions.

Maps made using sonar data provide higher resolution, and these exist for only about 10% to 15% of the seafloor at a resolution of 100 m. Maps with even finer resolution that can display features several meters in size exist for less than 1% of the seafloor! These finer resolution maps are what many mariners and marine scientists are interested in, because it is at these finer resolutions that smaller features become visible to reveal a more realistic view of the seafloor. Why is it so interesting, and in some cases critical, to reveal the fine-scale features of the seafloor? From a safety perspective, mariners attempting to navigate the seas safely and to avoid potentially dangerous obstacles benefit from detailed seafloor maps. Some features are tall but narrow and pose the risk of a ship strike if their locations are unknown. From a marine science perspective, knowledge of seafloor features provides insight into the available habitat, or homes, for the many sea creatures interacting closely with their seafloor environments. Some larger marine animals appear to use seafloor features for navigation, so scientists attempting to piece together migration routes find detailed seafloor features essential for studies of migratory behaviors.

Many benthic organisms require specific seafloor features for their lifestyles, whether it be hiding between rocks or using underwater landmarks to meet up with a mate. For example, the endangered white abalone is found only on or very near rocks where it is able to blend in with the environment, feed on drift kelp, and encounter other individuals while releasing eggs or sperm into the water. Scientists studying white abalone use detailed multibeam sonar maps to determine where they should focus their research efforts to search for abalone (**Figure C**). Knowledge of seafloor features saves scientists invaluable time because searching in areas of barren sand or rocks with very high relief will yield no abalone to study.

Detailed maps of seafloor characteristics are becoming increasingly valuable to scientists as the many associations of organisms with specific bottom features are discovered. Over time a larger area of the world ocean will be mapped with higher accuracy, but presently most of the sea remains a mystery.

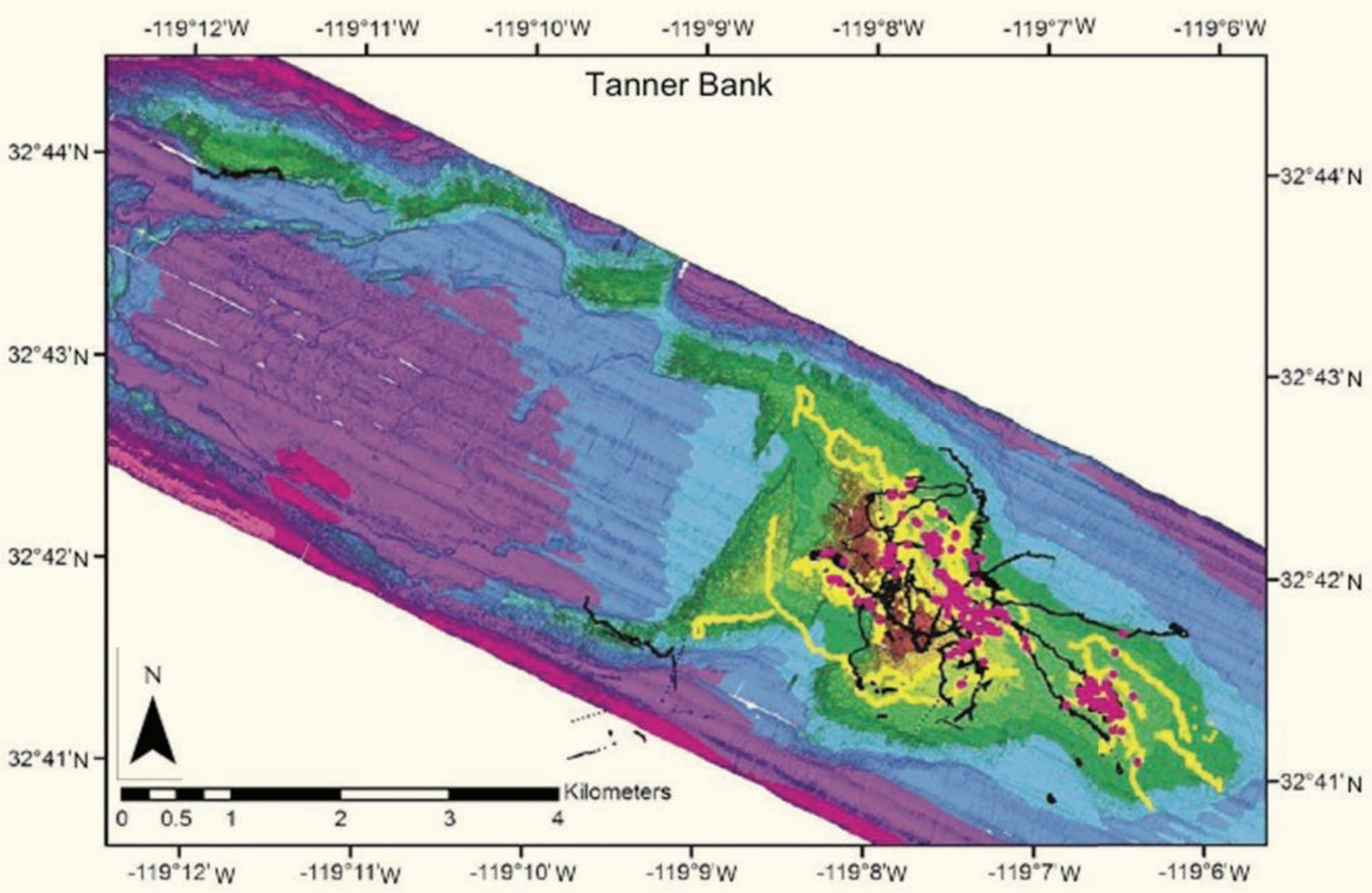

Figure C Results of white abalone population surveys (pink dots) overlaid onto multibeam bathymetry survey data (variegated colors indicate depth). Details of the seafloor are visible, as are ship tracks (horizontal lines).

Courtesy of National Oceanic and Atmospheric Administration. Adapted from Butler, J., M. Neuman, D. Pinkard, R. Kvitek, and G. Cochrane. 2006. The use of multibeam sonar mapping techniques to refine population estimates of the endangered white abalone *(Haliotis sorenseni). Fishery Bulletin* 104:521–532.

Critical Thinking Questions

1. Think of some requirements organisms have for life in the sea. Which of these requirements may include features of the seafloor that are visible with high-resolution sonar? How might revealing seafloor features aid biologists in their studies of marine benthic organisms?
2. Why are marine geologists and marine biologists interested in different levels of seafloor details? Try to think of a research topic that could make use of both broad-scale maps with less detail and fine-scale maps with many details.

For Further Reading

Afonso, P., N. McGinty, and M. Machete. 2014. Dynamics of whale shark occurrence at their fringe oceanic habitat. *PLoS ONE* 9(7):e102060. doi:10.1371/journal.pone.0102060.

Butler, J., M. Neuman, D. Pinkard, R. Kvitek, and G. Cochrane. 2006. The use of multibeam sonar mapping techniques to refine population estimates of the endangered white abalone (*Haliotis sorenseni*). *Fishery Bulletin* 104:521–532.

Sandwell, D. T., R. Dietmar Muller, W. H. F. Smith, E. Garcia, and R. Francis. 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science* 346(6205):65–67.

enough to accommodate photosynthesis. The depth of the photic zone depends on conditions that affect light penetration in water, extending much deeper (up to 200 m) in clear tropical waters than in murky coastal waters of temperate or polar seas (sometimes less than 5 m). The rest of the ocean volume is the perpetually dark **aphotic** (unlighted) **zone**, where the absence of sunlight prohibits photosynthesis.

The **benthic division** refers to the environment of the sea bottom. The inner shelf includes the seafloor from the low-tide line to the bottom of the photic zone. Beyond that, to the edge of the continental shelf, is the outer shelf. The **bathyal zone** is approximately equivalent to the continental slope areas. The abyssal zone refers to abyssal plains and other ocean-bottom areas between 3,000 and 6,000 m in depth. The upper boundary of this zone is sometimes defined as the region where the water temperature never exceeds 4°C. The hadal zone is that part of the ocean bottom below 6,000 m, primarily the trench areas. Deep-sea trenches are located within the hadal zone and sometimes extend very deep.

The **pelagic division** includes the entire water mass of the ocean. For our purposes, it is sufficient to separate the pelagic region into two provinces: the **neritic province**, which includes the water over the continental shelves, and the **oceanic province**, the water of the deep ocean basins. Each of these subdivisions of the ocean environment is inhabited by characteristic assemblages of marine organisms.

DID YOU KNOW?

The deepest parts of the ocean include deep-sea trenches that are formed by subduction, a process that includes two of Earth's plates colliding and one dropping below the other, causing the seafloor to bend. Life exists even in these deep regions of extreme conditions and no light. The deepest known part of the ocean, the Challenger Deep, is part of the Mariana Trench and is approximately 11 km deep! Only two manned expeditions have successfully explored the Challenger Deep: the first was over 50 years ago, and the second was in 2012. It looks like marine biologists have some more exploring to do in deep-sea trenches.

1.4 An Introduction to Evolution

The physical classification scheme described in the previous section is useful for us to make sense of the vast ocean realm from a physical perspective. From a biological perspective, the classifications are useful to distinguish different areas available for organisms to reside and all of the environmental conditions in these areas, known as **habitats**. Each marine organism is adapted to live in certain conditions, and as a result each life zone around the globe is represented by a suite of organisms adapted to live there. Once **eukaryotic** life evolved there was an explosion of diversity as organisms moved into the many habitat areas available in the sea. Many new species arose, some species were not well adapted for life and became extinct, and the species we see today evolved from earlier ancestral forms.

The main mechanism of evolution is **natural selection**. Organisms best suited for their environments will survive to reproduce and pass on their genes. If this continues over many generations there will be a higher proportion of genes coding for favorable features in the **population**. Eventually, the favorable features will become more common in the population, and the unfavorable features will become less common or even entirely absent. Because the environment is constantly changing there is no perfect state for an organism, and evolution is not goal oriented. The best state for survival is really a moving target as unpredictable environmental changes occur. The combination of the changing environment and the ability of species to adapt or become extinct has led to the great diversity of life that we see today. The ocean realm is no exception; marine organisms are well adapted for life in their unique environments, and changes in physical oceanographic conditions (e.g., temperature or ocean chemistry), or changes to the availability of resources (e.g., food) often lead to differential survival rates. The description of evolution presented above is a very basic introduction to the topic; we will examine the unique adaptations for survival and the evolution of marine organisms as one of the major themes discussed throughout this book.

Case Study

Earth's Earliest Life Forms

One of the most intriguing questions scientists have pondered for decades is exactly how and when the first life forms evolved on Earth. It is estimated that the Earth is 4.5 billion years old, and it was long assumed that the Earth was uninhabitable for about a billion years. Early Earth was thought to be extremely hot, with frequent volcanic activity and an abundance of chemicals that did not support life. Atmospheric oxygen levels were likely low, prohibiting life from flourishing until photosynthetic bacteria (microbes) transformed the atmosphere. Recent evidence indicates that early Earth may not have been so inhospitable, as fossils from miniature microbial communities that flourished along coasts 1 billion years after the Earth formed have been discovered.

For many years the primary evidence of early life forms was in the form of stromatolites, relatively large structures formed by cyanobacteria that fossilize well and can be dated (**Figure A**). The oldest known stromatolites are dated at approximately 3.45 billion years and are found at the Strelley Pool formation in Australia. Other fossilized microbial formations found at the same location in Australia include 3.4-billion-year-old sulfur-eating microbes.

In 2013, a scientist was exploring the geology of a study location in Australia and noticed some interesting wavy-looking formations in the rocks (**Figure B**). Although many scientists had walked over the same area and likely seen the wavy rocks, their importance had not been recognized. It turns out that the wavy formations are evidence of microbial life, and these microbes have been dated to 3.5 billion years, the oldest

(*continues*)

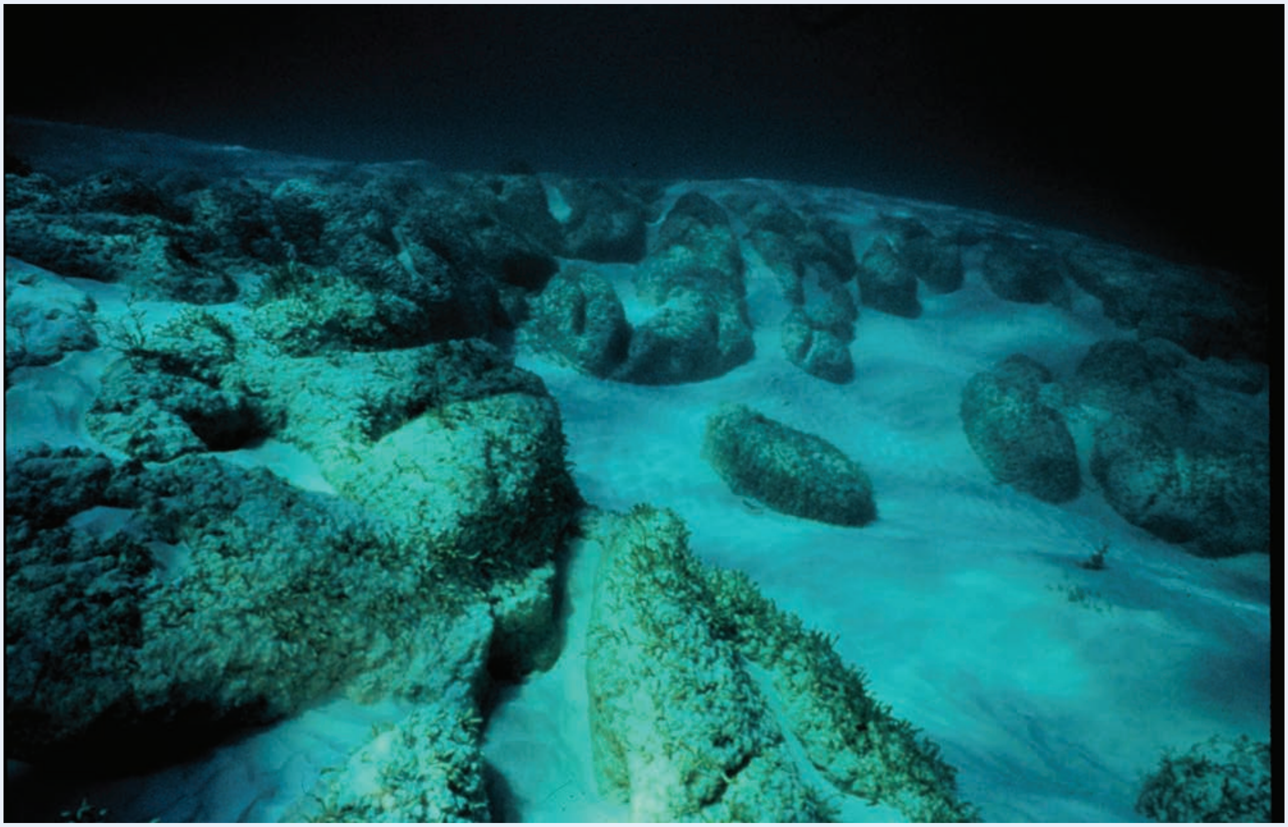

Figure A Stromatolites.
Courtesy of National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, National Undersea Research Program.

fossilized life forms known to exist. Under the microscope the wavy forms appear as thin black filaments in between sand grains, which is a characteristic formation of microbial mats. Due to their location along the ancient shoreline, it is presumed that the microbes were photosynthesizing rather than using minerals from the rocks as their energy source. This new information suggests that photosynthesis began at least 3.5 billion years ago, which is earlier than previously thought.

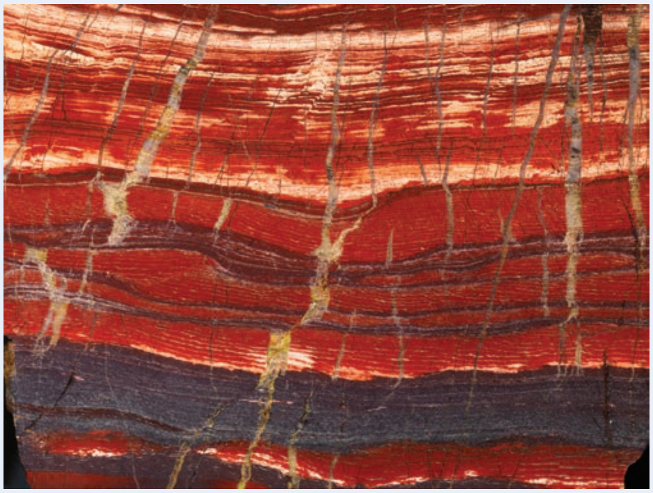

Figure B Microbial mat fossils that extend the fossil record of the earliest life forms by 300 million years.
© RGB Ventures/SuperStock/Alamy Stock Photo.

Is it likely that these 3.5-billion-year-old fossils provide evidence of the absolute first life forms? No, it is not likely. These microbial mats were made up of photosynthetic bacteria, and it is more likely that nonphotosynthetic bacteria evolved first. The challenge with detecting early life forms is that they must leave behind evidence in the form of fossils or in carbon isotopes. In 2015, 4.1-billion-year-old zircon was discovered that potentially once harbored life, but these results have not been verified. The search for the first life forms is ongoing and always will be, as there is no way to know with certainty when life first evolved, and any new evidence is just one more piece of the early life puzzle. What is certain is that we will continue to be amazed by new discoveries and information that will paint a clearer picture of what the young Earth and seas were like.

Critical Thinking Questions

1. Why can it be assumed that life evolved earlier than 3.5 billion years ago even though the oldest fossils are from this time?
2. What is the importance of discovering early life? What information do early life forms provide for scientists studying life today?

For Further Reading

Bell, E., and M. Harrison. 2015. Potentially biogenic carbon preserved in a 4.1 billion-year-old zircon. *Proceedings of the National Academy of Science* 112(47):14518–14521.

Nofke, N., D. Christian, D. Wacey, and R. M. Hazen. 2013. Microbially induced sedimentary structures recording an ancient ecosystem in the ca. 3.48 billion-year-old Dresser Formation, Pilbara, Western Australia. *Astrobiology* 13(12):1103–1124.

STUDY GUIDE

TOPICS FOR DISCUSSION AND REVIEW

1. Volcanic activity, earthquakes, and the distribution of continents on Earth today are all due to a single process. State what this process is, and describe how it is responsible for these phenomena.
2. Label a diagrammatic cross-section of the North Atlantic Ocean with all benthic features (such as trenches and shelf breaks) presented in this chapter. Then discuss whether this is the best way to categorize the seafloor.
3. What is sonar, and why is it perhaps the best way to determine the dimensions of ocean basins?
4. What is the photic zone, and what zones occur within the photic zone?
5. Why is classifying the marine environment useful and important?
6. What is the most basic definition of evolution by natural selection?

KEY TERMS

abyssal plains 10
aphotic zone 15
bathyal zone 15
benthic division 15
continental drift 6
continental shelf 9
continental slope 9
eukaryotic 15
evolution 4
habitat 15
intertidal zone 11
island 10
last glacial maximum (LGM) 8
latitude 5
longitude 5
natural selection 15
nautical mile 6
neritic province 15
oceanic province 15
ozone 4
Pangaea 6
pelagic division 15
photic zone 11
plate tectonics 6
population 15
prokaryote 4
ridge and rise system 10
seafloor spreading 6
seamount 10
shelf break 9
sonar 10
trench 10

REFERENCES

Broad, W. J. 1997. *The Universe Below: Discovering the Secrets of the Deep Sea*. New York: Simon & Schuster.

Clark, P. U., N. G. Pisins, T. F. Stocker, and A. J. Weaver. 2002. The role of the thermohaline circulation in abrupt climate change. *Nature* 415:863–869.

Cloud, P. 1989. *Oasis in Space: Earth History from the Beginning*. New York: W. W. Norton.

Detrick, R. 2004. The engine that drives the earth. *Oceanus* 42(2):6–12.

Dietz, R. S., and J. C. Holden. 1970. Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to present. *Journal of Geophysical Research* 75(26):4939–4956.

Duxbury, A. C., and A. B. Duxbury. (1991). *An Introduction to the World's Oceans*. Dubuque: Wm. C. Brown Publishing.

Earle, S. 2001. *National Geographic Atlas of the Ocean: The Deep Frontier*. Washington, DC: National Geographic.

Ellis, R. 2000. *Encyclopedia of the Sea*. New York: Knopf.

Geist, E. L., V. V. Titov, and C. E. Synolakis, 2006. Tsunami: Wave of change. *Scientific American* 294:56–63.

Hogg, N. 1992. The Gulf Stream and its recirculation. *Oceanus* 35:28–37.

Janin, H., and S. A. Mandia. (2012). *Rising Sea Levels: An Introduction to Cause and Impact*. Jefferson, NC, and London: McFarland & Company, Inc. Publishers.

Jenkyns, H. C. 1994. Early history of the oceans. *Oceanus* 36:49–52.

Keleman, P. B. 2009. The origin of the land under the sea. *Scientific American* 300(2):42–47.

Kunzig, R. 1999. *The Restless Sea: Exploring the World Beneath the Waves*. New York: W. W. Norton.

Leier, M. 2001. *World Atlas of the Oceans: More Than 200 Maps and Charts of the Ocean Floor*. Richmond Hill, Ontario: Firefly Books.

Mann, M. E. 2007. Climate over the past two millennia. *Annual Review of Earth and Planetary Sciences* 35:111–136.

McDonald, K. C., and P. J. Fox. 1990. The mid-ocean ridge. *Scientific American* 262:72–79.

Melville, W. K., and P. Matusov. 2002. Distribution of breaking waves at the ocean surface. *Nature* 417:58–63.

Satake, K., and A. F. Atwater. 2007. Long-term perspectives on giant earthquakes and tsunamis at subduction zones. *Annual Review of Earth and Planetary Sciences* 35:349–374.

Tarduno, J. 2008. Hot spots unplugged. *Scientific American* 298(1):87–93.

Weller, R. A., and D. M. Farmer. 1992. Dynamics of the ocean's mixed layer. *Oceanus* 35:46–55.