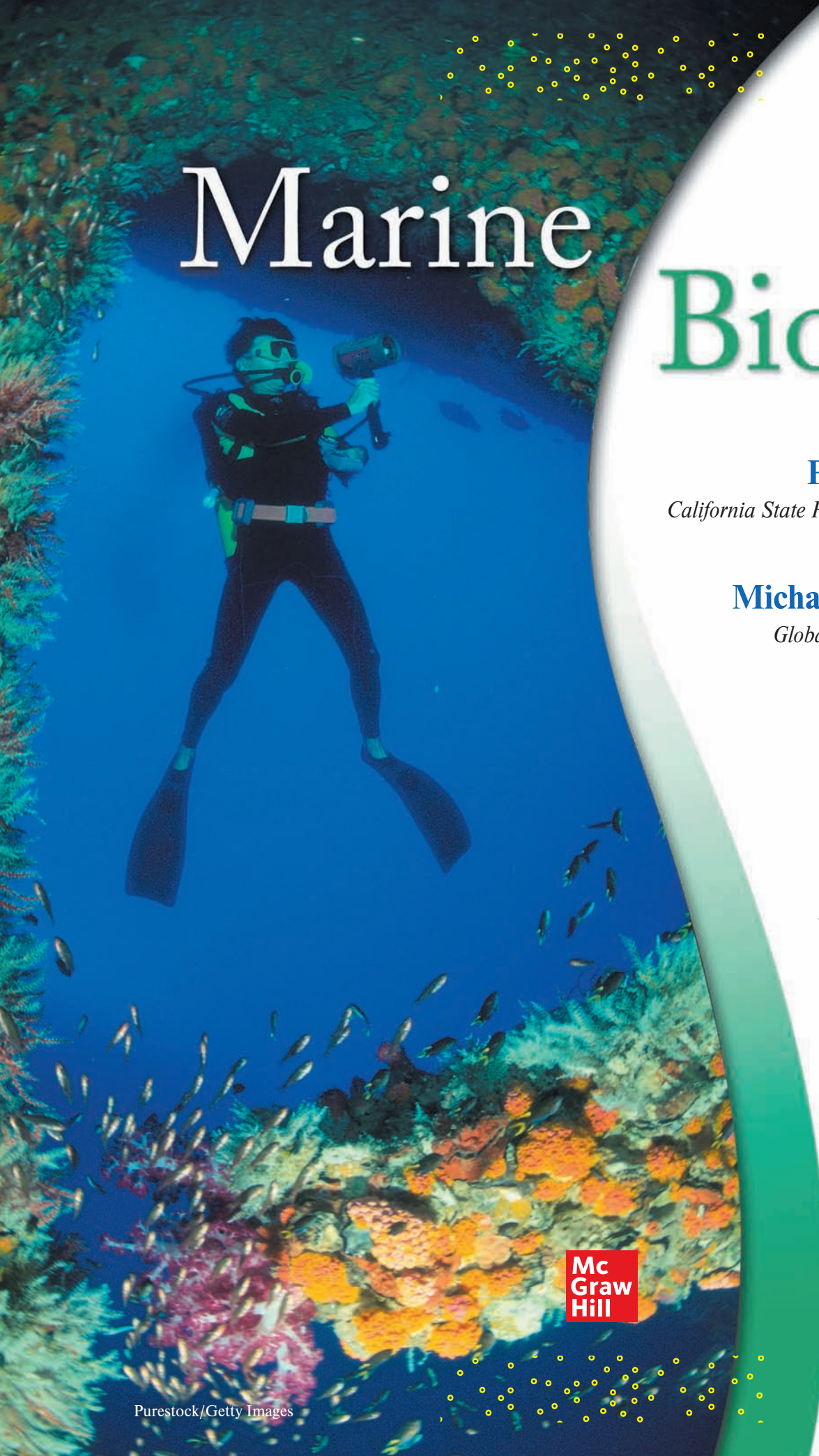


Twelfth Edition

Marine Biology

**Peter Castro
Michael Huber**

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An underwater photograph of a scuba diver in a black wetsuit and mask, holding a camera, swimming over a vibrant coral reef. The water is clear blue, and the reef is covered in various colorful corals and small fish. A large, curved white graphic element separates the image from the text on the right.

Marine

Twelfth Edition

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MARINE BIOLOGY

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Dedication

To all future marine biologists

—Peter Castro—

To Mason and Erin

—Michael Huber—

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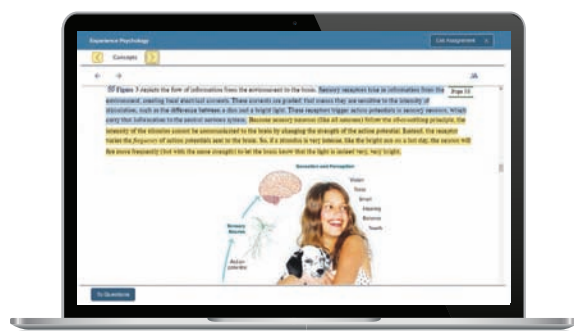
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About the Authors



Peter Castro, Ph.D.

Peter Castro realized that he had to become a marine biologist during a high school field trip to the coral reefs in his native Puerto Rico. He obtained a B.S. in biology from the University of Puerto Rico, Mayagüez, but left the warm Caribbean for warm Hawai'i to obtain a Ph.D. in marine zoology from the University of Hawai'i, Mānoa. His first experience with cold water was a year of post-doctoral research at Hopkins Marine Station of Stanford University in Monterey Bay, California. He is currently Professor Emeritus at California State Polytechnic University, Pomona. He also holds a B.A. in history and art history from his home institution, something that took him 18 years to accomplish as a part-time student. He is fluent in four languages and has taught marine biology (in English and Spanish) as a Fulbright Scholar at Odessa State University in the former Soviet Union. His research specialty is the biology of crustaceans symbiotic with reef corals and other invertebrates, research that has taken him anywhere where the water is warm enough to dive. He has also been doing research for almost the last two decades on the systematics of deep-water crabs, mostly, of all places, in Paris, France. Dr. Castro has so far published 70 peer-reviewed papers on his research. He is currently editor-in-chief of the *Journal of Crustacean Biology*.

Michael Huber, Ph.D.

Michael became fascinated by aquatic organisms when he caught his first trout on an Alaskan lake at age 2. His interest



in marine biology grew, and he went on to obtain B.S. degrees in both zoology and oceanography from the University of Washington. He received his doctorate from Scripps Institution of Oceanography for research on a group of symbiotic coral crabs. After his Ph.D., he worked at Scripps on the genetics and cell biology of unicellular algae and bioluminescence in midwater organisms. In 1988 he moved to the Biology Department at the University of Papua New Guinea, where he had the opportunity to work on some of the world's most spectacular coral reefs and was Head of the University's Motupore Island Research Station. He also became increasingly involved in marine environmental science. This interest continued to grow when he left Papua New Guinea in 1994 to become the Scientific Director of James Cook University's Orpheus Island Research Station on Australia's Great Barrier Reef. In 1998 he became a full-time environmental advisor, providing scientific information and advice on marine environmental protection to international agencies, governments, and private industry. Much of his work has been in marine environmental protection at the global level, while regionally much of his work has been in the Asia-Pacific region. He has worked on a wide range of environmental issues including pollution control and waste management, underwater noise, habitat conservation and restoration, marine invasive species, endangered species management, long-term environmental monitoring, effects of mariculture, and deep-sea mining. Dr. Huber is a past Chairman of GESAMP, a United Nations scientific body that advises international agencies on marine environmental issues. Currently, he is helping coordinate GESAMP's role in the United Nations of Ocean Science for Sustainable Development. Mike has worked in more than 40 countries.

Mike lives in Brisbane, Australia. His hobbies are fishing, diving, swimming, listening to and attempting to play music, reading, and gardening.

Preface

We are absolutely delighted to introduce *Marine Biology, twelfth edition*. When we first start working on the very first edition back in 1988, our focus was on getting through that task—and the book on shelves somewhere—and never dreamed we would find ourselves introducing a twelfth edition. We are profoundly grateful to the many instructors, reviewers, and most of all students who have carried us to this point.

Whether their interest originated from visiting the shore, scuba diving, recreational fishing, sailing, aquarium keeping, viewing television documentaries and movies, or just dreaming about the ocean, we hope this book reinforces, enhances, and informs the fascination of readers all over the world with the ocean. And, of course, we have tried in *Marine Biology* to provide a rigorous introduction to marine biology as a science.

Marine Biology is used by undergraduate, graduate, high school, and adult-education students, as well as by interested laypersons not enrolled in formal courses. We are gratified that many professional marine biologists use the book. The book is used in many countries outside the United States, and has been translated into six other languages. While keeping this range of users in mind, we have written the text primarily for lower-division, non-science majors at colleges and universities. For many of these students, marine biology will be their only tertiary science course, often taken to satisfy a general education requirement. We have therefore been careful to provide solid basic science coverage, including principles of the scientific method, the physical sciences, and basic biology. Our aim has been to integrate this basic science content with a stimulating, up-to-date overview of marine biology. We hope this approach demonstrates the relevance of the physical sciences to biology and makes all sciences less intimidating. To this end, we use an informal writing style that emphasizes an understanding of concepts over rigorous detail and terminology.

Not all marine biology courses, of course, are intended to fulfill a basic science requirement, and in many the students already have a science background. To balance the needs of instructors teaching courses with and without prerequisites in biology or other sciences, we have designed the book to provide as much flexibility as possible in the use of the basic science material, the order in which topics are presented, and overall emphasis and approach. We have tried to meet the needs and expectations of a wide variety of students, from the scuba-diving philosophy major to the biology major considering a marine science career. We hope a variety of readers other than university students also find the book useful and enjoyable.

Four major themes run through *Marine Biology*. One is the above-mentioned coverage of basic science applied to the marine environment. Another is a focus on the organisms themselves, and

their vast diversity not only in taxonomic terms but also in structure, function, and ecology. The third theme is an ecosystem approach that integrates this organismal diversity with the challenges imposed by the surrounding environment, both physical and biological. A final theme that, unfortunately, becomes more urgent with each passing year is the impact of humans on the marine environment.

Marine Biology, twelfth edition, adopts a global perspective to emphasize that the world's oceans and seas are an integrated system that cannot be understood by looking in any one person's own backyard. For many students this is a new perspective. One aspect of our global approach is the deliberate inclusion of examples from many different regions and ecosystems so that as many students as possible, not just in North America but around the world, will find something relevant to their local areas or places they have visited. We hope this will stimulate them to think about the many relationships between their own shores and the one world ocean that so greatly influences all our lives.

CHANGES IN THE TWELFTH EDITION

Like all new editions of *Marine Biology*, we have made extensive revisions to the twelfth edition to correct errors, incorporate new information, and improve readability. In many cases, our revisions reflect comments by reviewers, whose suggestions we greatly appreciate. Unfortunately, perhaps the dominant theme of this revision reflects the inescapable reality of the existential threat of climate change to both the health of the ocean and human society. Even in the last edition, our coverage of global climate change reflected some scientific uncertainty, and tended to point to impacts in the future. Since then, the uncertainty has vanished and it is clear that climate change is happening *now*, at a faster rate and with more dire consequences than we thought. Other aspects of global change have also become more urgent. We have reflected this throughout our revision, in every chapter, to reflect that negative global change is not something that *might* happen, *in future decades*, but is happening now and urgently needs to be addressed to avert catastrophe. This theme carries into the other aspects of global change described in *Special Report: Our Changing Planet*.

Aspects of this overarching theme included in the revision include:

- A new Box 1.1 on the 2019–2020 *Polarstern* expedition to study changes in Arctic Sea ice
- A new section in Chapter 6 on the economic importance of seagrass, saltmarsh, and mangrove communities

- A new Box 10.3 on carbon sinks and blue carbon, introducing both terms and including two new figures, and further discussion of blue carbon sinks in other relevant sections throughout the book
- The addition in Chapter 14 of a new section on Human Impact on Coral Reefs, consolidating and updating coverage that was previously spread across multiple chapters
- New coverage of illegal, unreported, unregulated fishing in Chapter 17

There are many other changes, throughout the book, that update information on the health of the oceans.

Of course, as in every edition, we have updated the information in the book to reflect new research and recent data, to incorporate suggestions from reviewers, and especially to make the book more user-friendly. There are too many changes to fully list here, but examples include:

- Significant revision of the line art in every chapter to improve accessibility for readers with visual challenges
- Line art in many chapters was updated to include the latest available data
- Significant revision of the explanation of the Coriolis Effect—something we have always struggled to explain on the written page. We hope this time we made it better.
- A new Figure 3.36 showing part of an actual tide table
- New coverage of the importance non-coding (“junk”) DNA and epigenetic markers, including their heritability
- Added information on the importance of glycoproteins
- Updated coverage of the shortcomings of the traditional “biological species concept,” especially in light of prokaryote reproduction, horizontal gene transfer, and hybridization
- New Box 5.1 on the origins of eukaryotes
- New Figure 6.13 comparing marine seaweeds and flowering plants
- New Box 7.3 on mantis shrimp eyes
- Information on “predator fear” effects—ecological effects of predator avoidance by prey species
- Updated examples of transplantation, caging, and removal experiments in marine ecology
- New Figure 17.13 comparing marine and freshwater capture fisheries with aquaculture production

As in every revision, there are many smaller changes throughout the book to include corrections, updates, and clarifications. We have also included a number of new photographs, in our continuing effort to make the book more visually appealing.

ORGANIZATION

Marine Biology is organized into four parts. **Part one** (*Chapters 1 through 4*) introduces students to marine biology and the basic sciences that underpin it. *Chapter 1* describes the history of marine biology. It also explains the fundamentals of the scientific method. This feature emphasizes that science is a process, an ongoing human endeavor. We think it is critical that students understand how and why science works, that science has limitations, and that there is still much to be learned. *Chapters 2 and 3* are a basic introduction to marine geology, physics, and chemistry. *Marine Biology* includes more information on these subjects, and places greater stress on their importance to understanding marine ecosystems, than other texts but we have kept *Chapters 2 and 3* as short as possible and have covered many abiotic aspects of the marine environment in the chapters where they are most relevant to biology. Wave refraction, for example, is described in conjunction with intertidal communities (*Chapter 11*) and estuarine circulation is discussed as part of the ecology of estuaries (*Chapter 12*). This approach emphasizes the importance of the physical and chemical environment to the organisms of the sea throughout the book. At the same time, it provides flexibility for instructors to make best use of the material in light of general education requirements, course prerequisites, and students’ backgrounds. *Chapter 4*, “Fundamentals of Biology,” briefly reviews some essential biological concepts. In covering basic biology we have tried to balance the needs of a spectrum of students ranging from those with no prior university-level instruction to those who have taken a number of biology courses. Depending on the level of their students, instructors may choose to cover *Chapter 4* in class, assign it as review reading, or omit it and rely on the in-text glossary entries in later chapters to remind students of the definitions of key terms.

Part Two (*Chapters 5 through 9*) surveys the diversity of marine life from the perspective of organismal biology. As in Part One, we provide introductory information that is reviewed and expanded upon in later chapters. In discussing the various taxa we emphasize functional morphology, ecological and physiological adaptations, and economic importance or other significance to humanity. Classification and phylogeny are not stressed, though we do present cladograms illustrating widely accepted phylogenetic schemes for invertebrates and vertebrates. As in the rest of the book we have selected organisms from around the world for photographs, line drawings, and color paintings, but organisms from the coasts of North America are emphasized. Organisms are referred to by their most widely accepted common names. One or two common or important genera are noted in parentheses the first time a group is mentioned in a chapter, but we have not attempted to provide comprehensive lists of genera.

Part Three of the book (*Chapters 10 through 16*) presents an ecological tour of the major environments of the world ocean, commencing with an introduction to some fundamental principles of marine ecology in *Chapter 10*. As in *Chapter 4*, important concepts

presented here are reviewed elsewhere in the in-text glossary boxes. The remaining six chapters of Part Three proceed from nearshore to offshore and from shallow to deep water, describing the physical characteristics of each environment and the adaptations and interactions of the organisms that live there. This admittedly arbitrary sequence follows the teaching sequence of the greatest number of our reviewers, but the chapters are designed so that they can be covered in any sequence according to instructors' preferences and needs. Most chapters include generalized food webs with standardized color coding to indicate the nature of the trophic relationships. Part Three also contains the *Special Report: Our Changing Planet*, a feature on anthropogenic global change that was introduced in the seventh edition.

Finally, **Part Four** looks at the many ways in which humans interact with the world ocean: our use of and impact on the marine environment and the influence of the ocean on the human experience. The section presents an up-to-date, comprehensive view of issues and concerns shared by many students. The chapter on resource utilization (*Chapter 17*) looks not only at traditional uses, such as fisheries, aquaculture, and oil and gas extraction but also at more modern aspects, such as the emerging technologies to generate energy from the sea, the pharmacological use of marine natural products, and the application of genetic engineering and other technologies in aquaculture. *Chapter 18* discusses human-induced degradation of the marine environment, balanced by an examination of marine conservation and habitat restoration.

The *Special Report: Our Changing Planet*, lying roughly in the middle of the book, presents some of the global-scale threats to the ocean resulting from human activities. Much of the material in the *Special Report* could appear in chapters where it is most relevant to specific ecosystems or species. In our opinion, bringing this material together in a single section emphasizes both the global nature of human-induced change in the ocean and the multiple stresses we are imposing. Placing the *Special Report* in the middle

of the book results in important related material being covered in later chapters. We think the current placement gives prominence to this critically important issue even if the *Special Report* has to look forward to later chapters.

ACKNOWLEDGMENTS

Bill Ober and Claire Garrison have again done a superb job of bringing new life to the illustrations, including new ones. We also thank the many contributors of photographs that add so much to the book. Most of all we thank the students, friends, colleagues, former teachers, and reviewers who answered questions, pointed out errors, and made suggestions that have greatly improved the book. We take full credit, however, for any errors or shortcomings that remain.

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The following people reviewed the eleventh edition and have provided valuable comments and suggestions for preparing the twelfth edition:

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Part One Principles of Marine Science



CHAPTER

The Science of Marine Biology



Kilili Yuyan

Researchers from the tribally managed Alutiiq Pride Marine Institute in Alaska collect clams, an important food for local indigenous people, to test for harmful toxins.

Marine biology is the scientific study of life in the sea. The ocean is vast, home to countless strange and wonderful creatures. The beauty, mystery, and variety of sea life often attract students to marine biology courses. This same sense of adventure and wonder is what leads marine biologists to their profession.

There are also many practical reasons to study marine biology. Life on Earth probably originated in the sea, so the study of marine organisms teaches us about all life on Earth, not just marine life. Many medical advances, for example, have been underpinned by research on marine organisms, such as studies of the animal immune system in sea anemones and sea star larvae, the fertilization of sea urchin eggs, nerve conduction in squids, and barnacle muscles.

Marine life is also a vast source of human wealth. It provides food, medicines, and raw materials, offers recreation to millions,

and supports tourism all over the world. Marine organisms can also cause problems. Some marine organisms harm humans directly by causing disease or attacking people. Others harm us indirectly by injuring or killing other marine organisms that we value for food or other purposes. Marine organisms can erode piers, sea walls, and other structures in the ocean, foul ship bottoms, and clog pipes.

At a much more fundamental level, marine life is vital to the very nature of our planet. Marine organisms produce around half the oxygen we breathe and help regulate Earth's climate. Our shorelines are shaped and protected by marine life, and some marine organisms even help create new land. In economic terms, the ocean's living systems are worth *trillions* of dollars every year.

To make full and wise use of the sea, to solve the problems that marine organisms create, and to predict the effects of human

activities on the ocean, we must learn all we can about marine life. In addition, marine organisms provide valuable clues to Earth's past, the history of life, and even our own bodies. This is the challenge, the adventure, of marine biology.

1.1 THE SCIENCE OF MARINE BIOLOGY

Marine biology is really the more general science of biology applied to the sea rather than a separate science. All the disciplines of biology are represented in marine biology. There are marine biologists who study the basic chemistry of living things, for example. Others are interested in whole organisms: how they behave, where they live and why, and so on. Other marine biologists adopt a global perspective and look at the way entire oceans function as systems. Marine biology is thus both part of a broader science and itself made up of many different disciplines, approaches, and viewpoints.

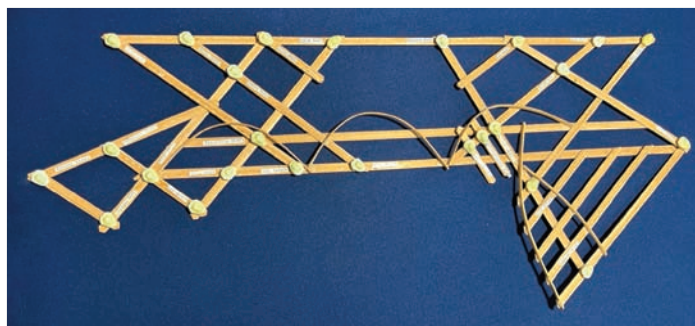
Marine biology is closely related to oceanography, the scientific study of the oceans. Like marine biology, oceanography has many branches. Geological oceanographers, or marine geologists, study the sea floor. Chemical oceanographers study ocean chemistry, and physical oceanographers study waves, tides, currents, and other physical aspects of the sea. Marine biology is most closely related to biological oceanography, so closely, in fact, that the two are difficult to separate. Sometimes they are distinguished on the basis that marine biologists tend to study organisms living relatively close to shore, whereas biological oceanographers focus on life in the open ocean, far from land. Another common distinction is that marine biologists tend to study marine life from the perspective of the organisms (for example, studying what an organism eats), while biological oceanographers tend to take the perspective of the ocean (for example, studying how food energy cycles through the system). In practice there are so many exceptions to these distinctions that most marine scientists don't worry about the difference.

A marine biologist's interests may also overlap broadly with those of biologists who study terrestrial organisms. Many of the basic ways in which living things make use of energy, for example, are similar whether an organism lives on land or in the sea. Nevertheless, marine biology does have a flavor all its own, partly because of its history.

The History of Marine Biology

People have been living by the sea since the dawn of humanity, and seafood was crucial to early humans. The earliest known stone blades, from 165,000 years ago, were discovered in a seaside cave in South Africa, along with piles of shells from Stone Age clam-bakes and the earliest traces of ochre pigment, thought to be used for symbolic body painting and decoration. Ancient bone or shell harpoons and fishhooks have also been found, as well as the earliest known jewelry in the form of shell beads from as long as 110,000 years ago. There is evidence that even more ancient peoples voyaged across the sea.

One of the paths of early human migration from Africa into Europe probably followed the coast, with its abundant seafood. Humans also probably migrated down the west coast after arriving



Michael E. Huber

FIGURE 1.1 A stick chart of the Marshall Islands, in the Western Pacific Ocean. The shells represent island groups, and the sticks represent prevailing wind and wave patterns. Pacific Islanders navigated over vast distances between tiny islands using such charts.

in the Americas. That migration seems to have been very rapid and may have been by boat.

The use of marine resources improved peoples' knowledge of marine organisms and drove improvements in seamanship and navigation. Ancient Pacific Islanders had detailed knowledge of marine life, which their descendants still retain. They were consummate mariners (Fig. 1.1), using clues such as wind, wave, and current patterns to navigate over vast distances, perhaps as far as South America.

The Phoenicians were the first accomplished Western navigators. By 2000 BCE (Before Common Era, that is, before year 1 in the Gregorian calendar that we use today), they were sailing around the Mediterranean Sea, Red Sea, eastern Atlantic Ocean, Black Sea, and Indian Ocean.

The ancient Greeks had considerable knowledge of nearshore organisms in the Mediterranean region. The Greek philosopher Aristotle is often considered to be the first marine biologist. He described many forms of marine life and recognized, among other things, that gills are the breathing apparatus of fish.

During the Dark Ages, scientific inquiry, including the study of marine life, came to a grinding halt in most of Europe. Much of the knowledge of the ancient Greeks was lost or distorted. Not all exploration of the ocean stopped, however. During the ninth and tenth centuries CE, or Common Era, the Vikings continued to explore the North Atlantic. In 995 CE a Viking party led by Leif Eriksson discovered Vinland, what we now call North America (Fig. 1.2). Arab traders were also active in the Middle Ages, voyaging to eastern Africa, Southeast Asia, and India. In the Far East and the Pacific, people also continued to explore and learn about the sea.

During the Renaissance, spurred in part by the rediscovery of ancient knowledge preserved by the Arabs, Europeans again began to investigate the world around them, and several undertook voyages of exploration. Christopher Columbus rediscovered the "New World" in 1492—word of the Vikings' find had never reached the rest of Europe. In 1519 Ferdinand Magellan led the first expedition to sail around the globe. Other epic voyages increased our knowledge of the oceans. Fairly accurate maps began to appear for the first time, especially for places outside Europe.

Explorers soon became curious about what lived in the ocean they sailed. An English sea captain, James Cook, was one of the

FIGURE 1.2 Viking explorers reached North America in ships like this reconstruction, *Sea Stallion*, centuries before Columbus.



PA Images/Alamy Stock Photo

first to make scientific observations and to include a full-time naturalist among his crew. In a series of three great voyages, beginning in 1768, he explored all the oceans. He and his crew were the first Europeans to see the Antarctic ice fields and to land in Hawai'i, New Zealand, Tahiti, and a host of other Pacific islands. Cook was the first to use a chronometer, an accurate timepiece that enabled him to determine his longitude precisely, and therefore prepare reliable charts. From the Arctic to the Antarctic, from Alaska to Australia, Cook extended and reshaped the European conception of the world. He brought back specimens of plants and animals and tales of new lands previously unimagined by Europeans. Cook was generally respectful and appreciative of indigenous cultures by the standards of the day, but not always. He was killed in 1779 in a fight after a dispute with native Hawaiians at Kealahou Bay, Hawai'i.

By the nineteenth century, taking a naturalist along on expeditions was commonplace. Perhaps the most famous of these shipboard naturalists was Charles Darwin, also from England. Beginning in 1831, Darwin sailed around the world on HMS *Beagle* for five years, horribly seasick most of the time. *Beagle*'s primary mission was to map coastlines, but Darwin made detailed observations of all aspects of the natural world. This set off a train of thought that led him, years later, to propose the theory of evolution by natural selection (see "Natural Selection and Adaptation," in 4.5). Though best known for the theory of evolution, Darwin made many other contributions to marine biology. He explained the formation of the distinctive rings of coral reef called atolls (see "Atolls," in 14.2). He used nets to capture the tiny, drifting organisms known as plankton, which marine biologists still do today (Fig. 1.3). Darwin's many interests also included barnacles, crustaceans that attach to surfaces (see Fig. 7.33). Specialists still refer to his treatise on them.

In the United States the most important early exploratory voyage was the United States Exploring Expedition of 1838–42, often

called the "Wilkes Expedition" after its leader, Lt. Charles Wilkes of the U.S. Navy. The expedition included 11 naturalists and scientific illustrators. Wilkes was by all accounts a vain and cruel man who promoted himself to Captain as soon as he left port and was later court-martialed for flogging his crew to excess. Only two of the expedition's six ships made it home. Nevertheless, the Wilkes Expedition's achievements are impressive. The expedition charted 2,400 km (1,500 mi) of the coast of Antarctica, confirming it as a continent, as well as the coast of the Pacific Northwest of North America. It explored some 280 islands in the South Pacific, collecting information about peoples and cultures as well as flora and fauna. The 10,000 biological specimens included some 2,000 previously unknown species (Fig. 1.4). The expedition, the first international survey sponsored by the U.S. government, also laid a foundation for government funding of scientific research.

The Challenger Expedition By the mid-nineteenth century, a few lucky scientists were able to make voyages specifically to study the oceans, instead of having to tag along on ships doing other jobs. One was Edward Forbes, who in the 1840s and 1850s carried out extensive trawling of the sea floor, mostly around his native Britain but also in the Aegean Sea and other places. Forbes died prematurely in 1854, at age 39, but was the most influential marine biologist of his day. He discovered many previously unknown organisms and recognized that sea-floor life varies at different depths (see Box 16.2, "Biodiversity in the Deep Sea"). Perhaps his most important contribution, however, was to inspire new interest in life on the sea floor.

Forbes's contemporaries and successors, especially from Britain, Germany, Scandinavia, and France, carried on his studies of sea-floor life. Their ships were poorly equipped and the voyages short, but their studies produced many valuable results. They were so successful, in fact, that British scientists managed to convince their government to fund the first major oceanographic expedition, under the scientific leadership of Charles Wyville Thompson. The British navy supplied a light warship to be fitted out for the purpose. The ship was named HMS *Challenger*.

Challenger underwent extensive renovations in preparation for the voyage. Laboratories and quarters for the scientific crew were added, and gear for collecting samples in deep water was installed. Though primitive by modern standards, the scientific equipment on board was the best of its day. Finally, in December 1872, *Challenger* set off.

FIGURE 1.3 These marine scientists are hauling in a net known as a "bongo net" used to capture minute marine plankton. One is signaling instructions to the winch operator.



Michael E. Huber



robertharding/Alamy Stock Photo

FIGURE 1.4 Peale's dolphin (*Lagenorhynchus australis*), named after the Wilkes Expedition naturalist who first described it, is one of 2,000 marine and terrestrial species discovered by the expedition.

Over the next three and a half years, *Challenger* and her crew sailed around the world, gathering information and collecting water, sediment, and biological samples (Fig. 1.5). The sheer volume of data gathered was enormous—it took 19 years to publish the results, which fill 50 thick volumes. *Challenger* brought back more information about the ocean than had been recorded in all previous human history.

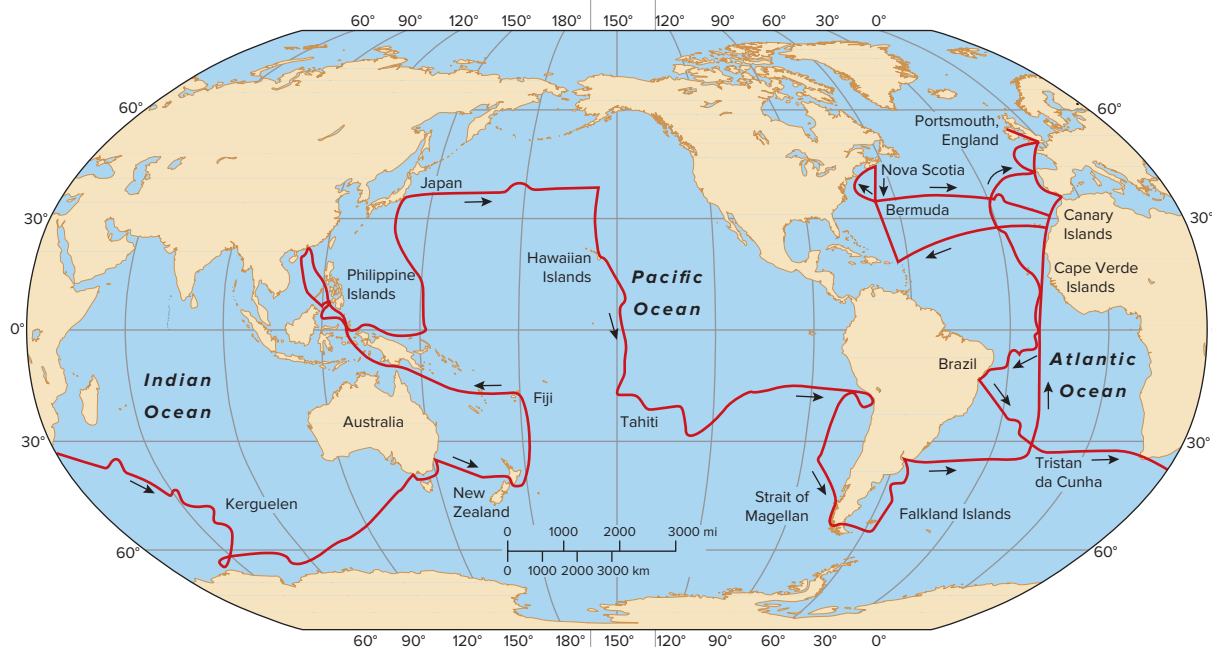
It was not just the duration of the voyage or the amount of information collected that set the *Challenger* expedition apart

from earlier efforts. The expedition set new standards for ocean research. *Challenger's* scientists collected data in a more systematic way than previous expeditions and kept meticulous records. For the first time, scientists began to get a coherent picture of what the ocean was like. They also learned about the enormous variety of marine life, for *Challenger* brought back thousands of previously unknown species. Thus, the *Challenger* expedition laid the foundations of modern marine science.

Other expeditions continued the work begun by *Challenger*, and major oceanographic cruises continue to this day. In many ways, though, the voyage of the *Challenger* remains one of the most important in the history of marine science.

The Growth of Marine Labs Even before *Challenger* set off, biologists were excited about the organisms brought back by ocean expeditions. Unfortunately, the ships had quarters for only a few scientists. Most biologists only got to see the preserved specimens the ships brought back to port. Such specimens revealed much about marine life around the world, but biologists wanted to know how the organisms actually lived: what they did and how they functioned. Living specimens were essential for this, but ships usually stayed in one place for only a short time, making long-term observations and experiments impossible.

As an alternative to ships, biologists began to work at the seashore. Among the first were two French biologists, Henri Milne



Source: Bill Ober

FIGURE 1.5 The route of the *Challenger* expedition, which from 1872 to 1876 conducted the first systematic survey of the world ocean.

Edwards and Victor Andouin, who around 1826 began making regular visits to the shore to study marine life. Others soon followed suit. These excursions offered the opportunity to study live organisms, but there were no permanent facilities and only a limited amount of equipment could be taken along. Eventually, biologists set up permanent laboratories where they could keep organisms alive and work over long periods. The first such laboratory was the Stazione Zoologica, founded in Naples, Italy, in 1872—the same year *Challenger* embarked. The laboratory of the Marine Biological Society of the United Kingdom was founded at Plymouth, England, in 1879.

The first major American marine laboratory was the Marine Biological Laboratory at Woods Hole, Massachusetts. It is hard to pinpoint the exact date when this laboratory was established. The first marine laboratory at Woods Hole was started by the United States Fish Commission in 1871, but didn't flourish. Several other short-lived laboratories later appeared in the area. Harvard biologist Louis Agassiz, who also studied many of the specimens collected by the Wilkes Expedition, established a laboratory on nearby Cape Ann in 1873. In 1888 this lab moved to Woods Hole and officially opened its doors as the Marine Biological Laboratory. It is still one of the world's most prestigious marine labs.

After these early beginnings, other marine laboratories were established. Among the earliest in the United States were Hopkins Marine Station in Pacific Grove, California (Fig. 1.6), Scripps Institution of Oceanography in La Jolla, California, and Friday Harbor Marine Laboratory in Friday Harbor, Washington. More laboratories appeared all over the world, and new ones are being established even today.

World War II had a major effect on the development of marine biology. A new technology, **sonar**, or *sound navigation and ranging*, was developed for submarine warfare. Sonar is based on detecting underwater echoes (Fig. 1.7). The ocean, long thought of as a silent realm, was suddenly found to be full of sound, much of it made by animals. During wartime, learning about these animals was no longer the casual pursuit of a few interested marine biologists but a matter of national security. As a result of this urgency, several marine laboratories, such as Scripps and the Woods Hole Oceanographic Institution (established in 1929), grew rapidly. When the war ended, these labs not only remained vital research centers, but continued to grow.

The years immediately after World War II saw the refinement of the first practical **scuba**, or self-contained underwater breathing apparatus. The basic technology was developed in occupied France by the engineer Émile Gagnan to allow automobiles to run on compressed natural gas. After the war, Gagnan and fellow Frenchman Jacques Cousteau modified the apparatus, using it to breathe compressed air under water. Cousteau went on to devote his life to scuba diving and the oceans.



FIGURE 1.6 An early marine biology class at Stanford University's Hopkins Marine Station. The station, established in 1892, is the third-oldest in the United States.

Using scuba, marine biologists could, for the first time, go under water for more than a few minutes at a time to observe marine organisms in their natural environment (Fig. 1.8). They could work comfortably in the ocean, collecting specimens and performing experiments, though still limited to relatively shallow water, generally less than 50 m (165 ft).

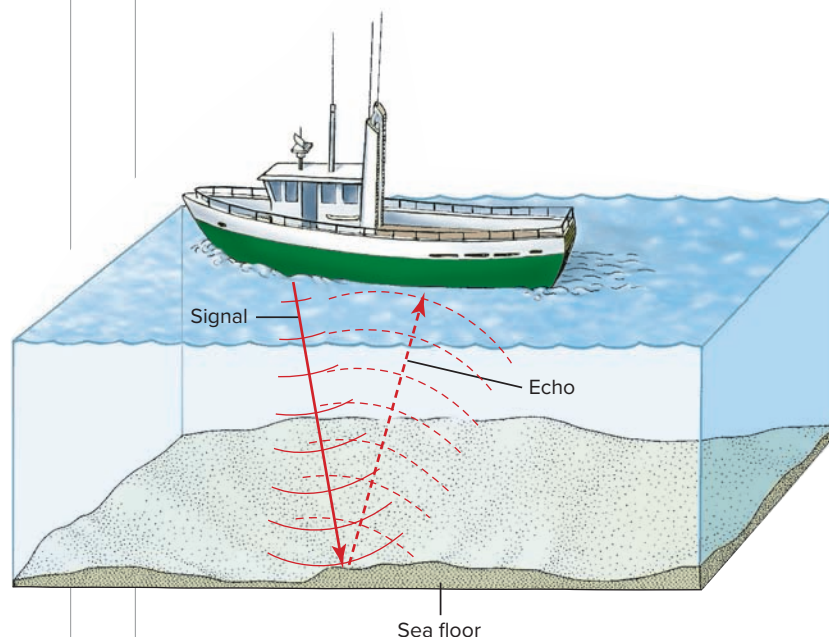


FIGURE 1.7 A ship uses sonar by "pinging," or emitting a loud pulse of sound, and timing how long it takes the echo to return from the sea floor. The water depth can be determined from the return time. This, the most common form of sonar, is called "active sonar" because the sounds used are actively generated by the equipment.

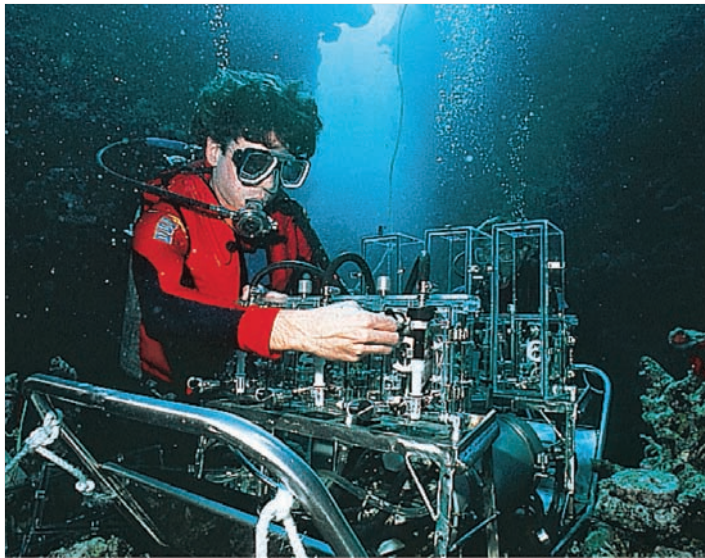


FIGURE 1.8 Scuba is an important tool for many marine biologists. This one is using an apparatus called a respirometer to measure the production and consumption of oxygen by organisms on a coral reef.

Courtesy of Australian Institute of Marine Science; <http://www.aims.gov.au/docs/cc-attribution.html>

Marine Biology Today

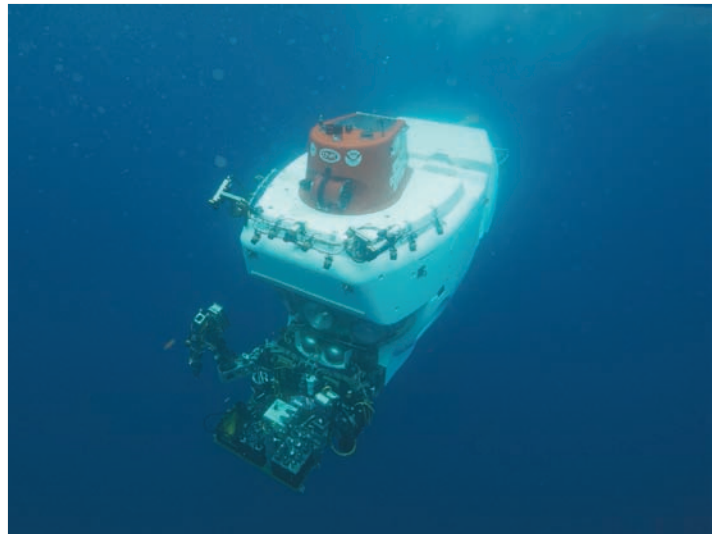
Oceanographic ships and shore-based laboratories are as important to marine biology now as ever. Today many universities and other institutions operate research vessels (Fig. 1.9). Modern ships are equipped with the latest technology for navigation, sampling, and studying marine life. Many, like *Challenger*, were originally built for other uses, but more and more research vessels are purpose-built for marine science.

In addition to ships as we normally think of them, some remarkable craft are used to study the marine world. High-tech

FIGURE 1.9 The R/V *Thomas G. Thompson*, operated by the University of Washington, was the first of a new generation of dedicated research vessels that offer more work space and can travel to research sites faster and stay there longer than earlier research ships.



Robert Hinton, University of Washington



Woods Hole Oceanographic Institution

FIGURE 1.10 *Alvin*, a deep-sea submarine operated by the Woods Hole Oceanographic Institution, is one of the most famous vessels in the history of marine science.

submarines descend to the deepest parts of the ocean, revealing a once-inaccessible world (Fig. 1.10). Various odd-looking vessels ply the oceans, providing specialized research platforms (Fig. 1.11).

Marine laboratories, too, have come a long way since the early days. Today labs dot coastlines around the world and are used by an international community of scientists. Some are equipped with the most up-to-date facilities available. Others are simple field stations, providing “bed, breakfast, and boats” in remote locations. Often the scientists even have to bring their own breakfasts! There are undersea habitats where scientists can live for weeks at a time, literally immersed in their work (Fig. 1.12). Marine labs are important not only for research but also for education. Many offer hands-on undergraduate courses for students to study marine biology firsthand, and most provide facilities where graduate students begin their careers in marine science.

We all know technology is exploding. Even today’s elementary school students have lived through major changes that have affected all of society—our personal lives, business, even politics. Needless to say, technology has and continues to transform marine science. Satellites peer down at the ocean and this **remote sensing** technology has revealed much of what we know about large-scale features like ocean currents and the geographic distribution of marine life (Fig. 1.13). Satellites only see the surface of the ocean, however, and a lot of the action is a long way down. Submarines are one way to penetrate the depths, but scientists increasingly use underwater robots, including remotely operated vehicles (ROVs), which are controlled from the surface, and autonomous underwater vehicles (AUVs; see Fig. 16.23), which operate independently of direct human control. Marine scientists continue to develop an array of instruments that sit on the bottom, float in place, drift with the currents, or are even attached to



EYE ON SCIENCE

Box 1.1 The Best Laid Plans

The plan was audacious. For millennia, mariners venturing into polar waters feared being trapped in the ice, starving while their vessels were crushed by massive icebergs. But one group of researchers decided to deliberately wedge their research vessel, *RV Polarstern* in the Arctic ice and spend a year drifting with the floating icepack. The Arctic is warming much faster than the rest of our planet (see Special Report, Climate Change), and scientists are desperate to better understand the implications. An entire year of measurements and experiments would vastly improve our knowledge.

Over 10 years of careful planning and preparation—not to mention fundraising—went into the expedition, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC), the largest Arctic research expedition ever. But things don't always go according to plan. *Polarstern*, a converted icebreaker that can withstand the tremendous pressure of the ice, sailed from Norway in September 2019. A few weeks later, she was wedged in the ice and the scientists got to work.

To prevent their measurements from being effected by the operations of the ship itself, they set up much of the equipment on the surrounding ice up to 50 km (30 mi) away, getting around with snowmobiles and helicopters. As Arctic winter set in, the researchers had to learn to cope with constant darkness and temperatures down to -50°C (-60°F). They weren't expecting to encounter polar bears within days of their arrival, and scientists had to take turns away from their studies to stand watch. The bears also had an irritating habit of chewing the power and communication cables linking the various instruments. Despite their planning,



MOSAiC researchers drill through the ice.

dpa picture alliance archive/Alamy Stock Photo

severe storms sometimes disrupted their instruments. But overall the expedition was going more or less as planned, and data on the Arctic air, ice and water, and the things living in them, started flooding in.

Then the world changed. When the coronavirus hit, hundreds of scientists scheduled to rotate for a stint on *Polarstern* were faced with cancelled flights, travel restrictions, quarantine, expired visas, and closed borders. And the prospect of an outbreak onboard ship, in the remote Arctic, was unthinkable. It became essentially impossible to conduct resupply and crew swaps by air as planned. As the expedition's logistics coordinator said "there you have a plan B, C, D, and X, and then a virus like this comes along and just thwarts all the plans."

The project leaders were forced into the difficult decision to break free of the ice and head to the edge of the ice pack, where crew swap and resupply could be done by ships lacking *Polarstern's* icebreaking capability. They left much of the research facility on the ice, hoping to return as soon as possible

but not knowing for sure when. New logistics plans and coronavirus procedures were frantically developed. Other oceanographic expeditions were cancelled due to coronavirus, but almost miraculously *Polarstern* was able to return to its base camp after only two weeks! In the end, the expedition spent over a year in the ice pack, moving from the constant darkness of winter to the unending days of summer, before returning to port in October 2020. In all, nearly 500 scientists from 20 countries participated.

Unfortunately, MOSAiC brought bad news. Results show that Arctic ice is thinning faster, and more ice is lost in summer, than was expected. Researchers were surprised to see fishes from the North Atlantic, indicating that marine species are moving northward as their normal home waters warm. Such rapid changes in the Arctic are a worrying harbinger of what is in store for the rest of our planet.

For more information, explore the links provided in the Marine Biology Online Learning Center.

animals (see "Observing the Ocean," below). Space technology has a role to play here as well; many oceanographic instruments relay their data through satellites.

Marine biologists use every available tool to study the sea, even some decidedly low-tech ones (Fig. 1.14), and information about the ocean pours in at an ever-increasing pace.

The Census of Marine Life With all of these advances, marine biologists are equaling if not surpassing milestones from past centuries such as the *Challenger* expedition. Despite the achieve-

ments of the past, at the turn of the twenty-first century less than 1% of the oceans had been explored, and we had probably discovered an even smaller fraction of marine species. We knew hardly anything about most species that had been discovered. To make a dent in this ignorance, marine scientists launched the 10-year Census of Marine Life (COML) in the year 2000. COML was a massive undertaking, involving some 2,700 scientists, at nearly 700 institutions in 81 countries. It included some 24 projects focused on a particular region, a specific group of organisms, or individual ecosystem types. The individual scientists and research groups involved



(a)



(b)

FIGURE 1.11 R/V *FLIP*, short for *floating instrument platform*, operated by Scripps Institution of Oceanography, provides a stable platform for research at sea. (a) Most of the hull consists of a hollow tube that floats while the vessel is towed into position. When the hull is flooded and sinks, *FLIP* swings into a vertical position (b) in which it is largely unaffected by the rise and fall of waves.

Scripps Institution of Oceanography, UC San Diego

Scripps Institution of Oceanography, UC San Diego

would have done their research anyway, but through networking, data sharing, and cooperation, their work was greatly magnified.

COML found an amazing amount of undiscovered marine biodiversity, discovering nearly two new species a day. Genetic studies, analysis of historical records and other investigations established that past populations of some species exploited by humans (for example, some whales and fishes) were much larger before exploitation than previously thought, and that they declined earlier. For example, fishing reduced the Nova Scotian cod population by 96% as early as 1850. This established new understanding of what constitutes “healthy” baseline populations. From a global decline in phytoplankton to evidence that most harvested fish species have become fewer and smaller, COML painted a picture of oceans even more profoundly affected by human activities than we thought. But COML also documented that populations can recover with sound conservation measures.

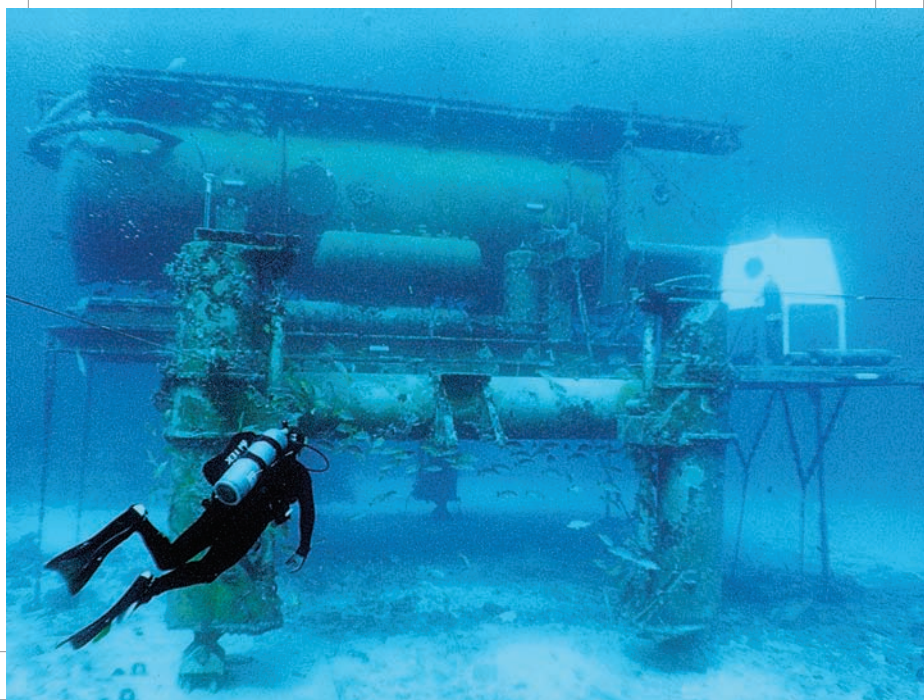
COML officially ended in 2010 but created a lasting legacy. New technologies were developed, the networks for international cooperation continue, and data platforms that were created provide free access to data by not only scientists but also the general public. The Ocean Biogeographic Information System (OBIS) makes the vast amount of information COML collected about what species live where not only continues to operate but is growing. You can still follow online the movements of tagged sharks, seals, and sea turtles on systems developed by COML. Some COML results are even on Google Earth.

1.2 THE SCIENTIFIC METHOD

Marine biology is an adventure, for sure, but it is still a science. Scientists, including marine biologists, share a certain way of looking at the world. Students of marine biology need to be familiar with this approach and how it affects our understanding of the natural world.

FIGURE 1.12 A diver swims outside *Aquarius*, the world’s only underwater marine science laboratory. *Aquarius* is located in the Florida Keys Marine Sanctuary at a depth of about 20 m (60 ft). The living quarters are in the large cylinder at the upper left, which, fortunately for the crew, is larger than it appears here because it is further away than the diver.

Mark E. Ward



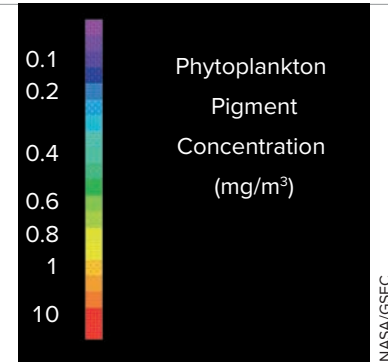
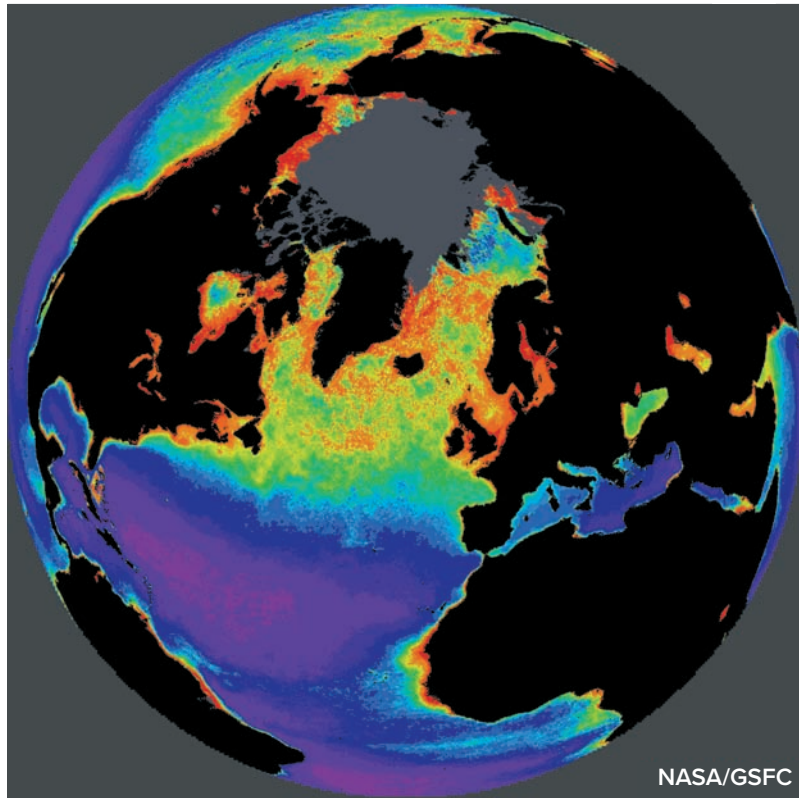


FIGURE 1.13 A satellite image showing the abundance of photosynthetic organisms in the ocean, as indicated by the amount of pigment in the water. This photo was taken by the Coastal Zone Color Scanner (CZCS), which was mounted on the *Nimbus-7* satellite. It is actually a composite of information gathered over nearly an eight-year period. Advances in computer and space technology made this image possible.

spite of these minor differences, most scientists do agree on the basic principles of the scientific method, which should be seen as a flexible framework guiding the study of nature and not a rigid set of rules.

Observation: The Currency of Science

We live in an age of science. Advertisers boast of “scientific” improvements to their products. News sites regularly report new breakthroughs, and many media outlets have dedicated science reporters. Governments and private companies spend billions of dollars a year on scientific research and education. Why does science have such prestige in our society? The answer, quite simply, is that it works! Science is among the most successful of human endeavors. Modern society could not exist without the knowledge and technology produced by science. Everyone’s lives have been enriched by scientific advances in medicine, agriculture, industry, communication, transportation, art, and countless other fields.

Much of the practical success of science results from the way it is done. Scientists do not see the world as a place where things just happen for no reason. They assert instead that the universe can be explained by physical laws. Scientists don’t go about discovering these laws haphazardly; they proceed according to time-tested procedures. The set of procedures that scientists use to learn about the world is called the **scientific method**.

Scientists may disagree over the fine points of the scientific method and may apply the method in slightly different ways. In

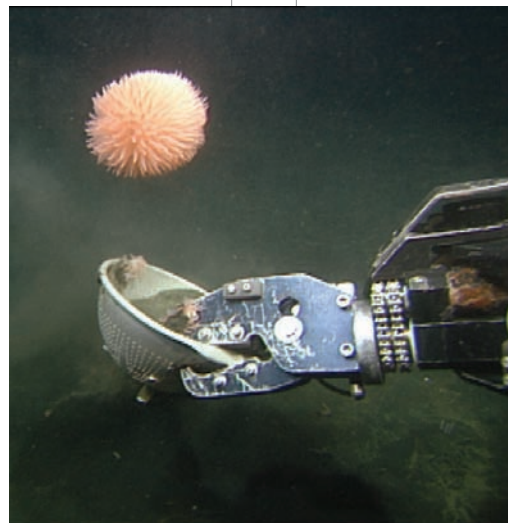


FIGURE 1.14 High-tech meets low-tech: The robotic arm of the ROV *Ventana* captures a pom-pom anemone (*Liponema brevicornis*) in an ordinary kitchen colander.

same object. Sensory perception may be imperfect, and scientists, like anyone else, are not always impartial, but the object is there for all to see and measure. Thus, there is a way to check and validate any one person’s observations.

Observation is critical to all phases of the scientific method. To begin with, it allows us to describe the natural world. The only way to learn what organisms live in a particular part of the ocean, how many of them there are, how fast and how large they grow, when

The goal of science is to discover facts about the natural world and principles explaining these facts. At the heart of the scientific method is the conviction that we can learn about the world only through our senses or with tools that extend our senses. Microscopes, for example, extend our vision to help us see what is otherwise too small to see. Thus, scientific knowledge is fundamentally derived from the observation of nature. Science is based on observations, and not on preexisting ideas of how the world is or should be.

Relying on observations means that others can verify the observations. A person’s thoughts, feelings, and beliefs are internal. No one has access to the minds of others. On the other hand, the world studied by scientists is external to any one person. Different people can look at the

Box 1.2 Observing the Ocean

Most of the ocean is incredibly remote, and difficult and expensive to get to. The ocean is also a vast, interconnected network, and conditions at one place are affected by events far away. To cap things off, events such as storms and earthquakes—not to mention the interactions and movements of marine organisms—occur suddenly, so that being in the right place at the right time to observe them is often a matter of luck. Ships, submarines, scuba diving, and studies in the laboratory and on the shore are essential in marine science, but they can't provide the continuous coverage of broad areas of the ocean, throughout its depths, that is needed to really understand the sea. Satellites do observe vast areas of the ocean (see "Marine Biology Today," above), but only at the surface.

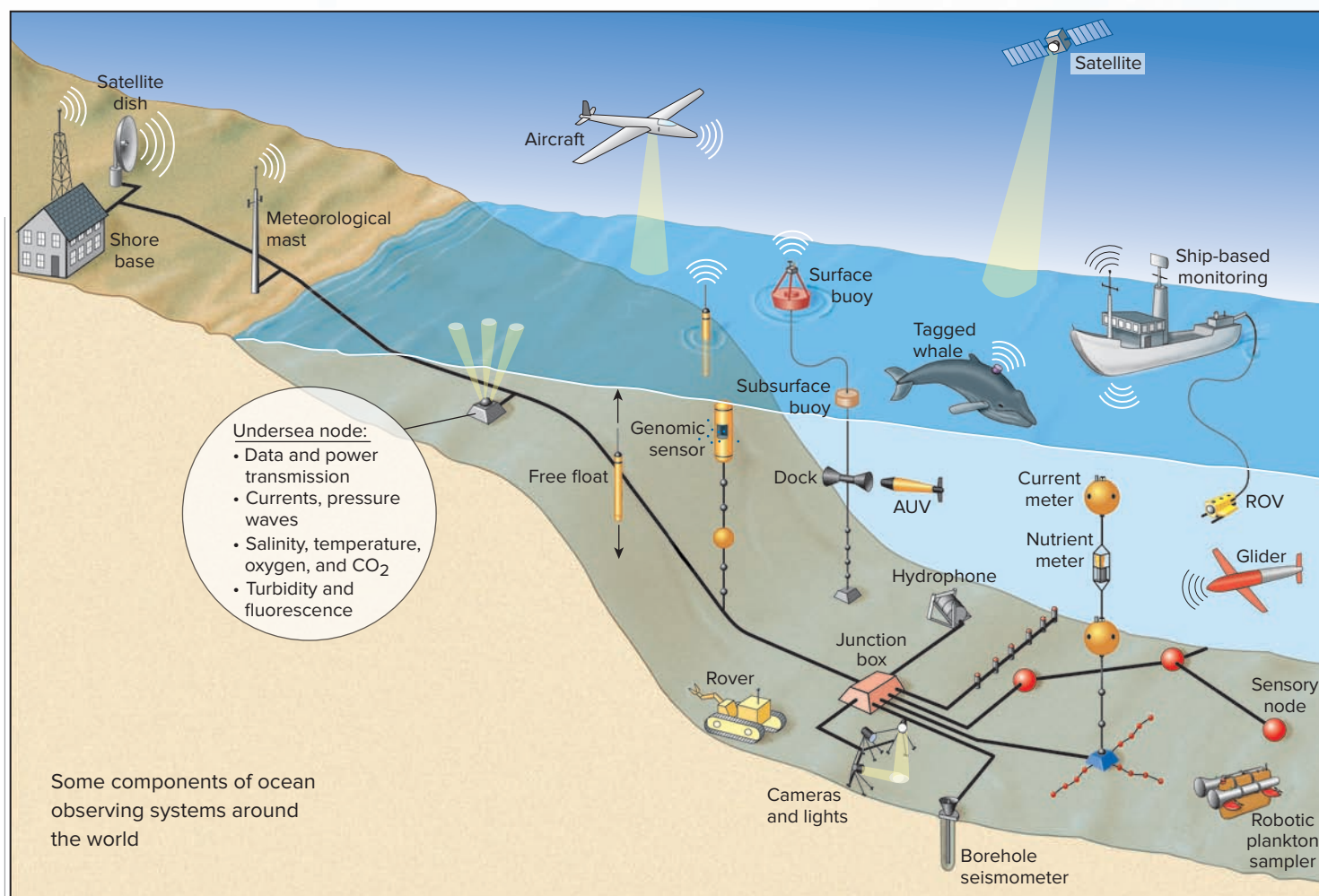
Technologies are allowing scientists—and the general public—to observe the oceans in ways that would have seemed like science fiction not long ago. In the Argo system, for example, some 3,800 automated floats, looking a bit like torpedoes turned on end, drift throughout the ocean. Each float continuously bobs between the surface and a depth of 2,000 m (6,600 ft), over about 10 days, measuring ocean properties and sending their data and position via satellite when they surface. Argo floats provide huge amounts of information at the scale of the entire global ocean. Robotic gliders cruise across the oceans for years at a time, like Argo floats, collecting data and surfacing to relay it by satellite.

Oceanographers have also wired parts of the sea floor, providing power and communications for an amazing array



Marine biologists fit a southern elephant seal (*Mirounga leonina*) with electronic instruments.

of instruments that measure currents and water chemistry, detect sea-floor tremors, and track biological activity. The first such system in the United States was the Long-term Ecosystem Observatory (LEO), installed off the New Jersey coast in 1996. LEO, now known as the Coastal Ocean





Observation Lab (COOL), includes underwater gliders, shore-based radar, ship measurements, and moored instruments, and is being integrated with similar systems into a single network covering the United States from Maine to Florida. In the Pacific, the Victoria Experimental Network Under the Sea (VENUS) has operated in coastal waters in British Columbia since 2006. The affiliated North East Pacific Time-integrated Undersea Networked Experiments (NEPTUNE) Observatory, which extends off the coast from British Columbia to Oregon, has operated since 2008. The Monterey Accelerated Research System (MARS) has also operated since 2008, off the coast of northern California. Science and Technology University Research Network (SATURN) Collaboratory (marine scientists on the west coast of North America seem to like naming their networks after planets) was established to measure interactions between the Columbia River in the Pacific northwest and the coastal ocean. The Ocean Observatories Initiative (OOI) has instrument arrays at locations around the Americas, from Antarctica to the North Pacific and Atlantic oceans. There are similar networks in Europe, Japan, the Gulf of Mexico, and the Arctic Ocean. The vision is to integrate all these networks into a single Global Ocean Observing System (GOOS), but so far such observing systems cover only a small fraction of the ocean, mostly near the coast.

Many exciting devices have been developed for these networks, such as genomic sensors that identify plankton DNA and measure toxins, and free-ranging autonomous underwater vehicles (AUVs)

that move across the seabed or in the water making measurements and collecting samples. Some networks include docking stations for AUVs to recharge batteries and upload data.

Like all cutting-edge endeavors, developing these observing networks has its challenges. High-tech electronics can be fickle even in the laboratory, much less the depths of the sea. A NEPTUNE scientist once said, “We’re learning a lot, which is another way of saying that things are breaking.” But more and more the networks are reliably collecting data and transmitting photos, audio, and video that are freely available online, often in real time. An Internet search can take you to some amazing places in the ocean depths.

The networks have also brought unexpected benefits, in part because they are used by scientists from widely varying disciplines. For example, marine geologists use the NEPTUNE network to monitor for earthquakes, but the endangered fin whale (*Balaenoptera physalus*) sings at a sound frequency that interferes with the earthquake measurements. Scientists developed software tools to identify and filter out fin whale songs to track the whales.

Not all ocean observing systems are inanimate—marine animals are recruited. Seals, sea lions, sharks, and other large marine animals move underwater faster than we can ever hope and are unlikely to behave naturally when humans are present. To get a firsthand look at what these animals do beneath the surface, scientists developed “crittercam,” a compact underwater video camera attached to animals including

sea turtles, sharks, whales, seals, and sea lions, and it provided the first underwater views of feeding humpback whales using curtains of bubbles to herd herring, social diving behavior in Adélie (*Pygoscelis adeliae*) and chinstrap (*P. antarctica*) penguins, and the movements of endangered sea turtles in Mexico. A crittercam attached to a sperm whale (*Physeter catodon*) provided new views of life in the deep sea.

Scientists use animals to study the ocean as well as the animals themselves. An “Autonomous Underwater Sampler” is another name for an animal, such as an elephant seal, with a sensor glued to its back. Originally the transmitters, which measure temperature, depth, and salinity, were used to record the diving behavior of the animals, but oceanographers realized that the sensors also provide valuable data on ocean currents, as the animals can go places scientists can’t access otherwise.

Marine scientists are also finding ways to capitalize on equipment installed for other purposes. For example, using signal processing software an undersea cable installed by Google can measure deep-sea earthquakes and ocean waves.

Ocean observing systems aren’t just for science. They bring concrete benefits to society. They help track storms, warn of tsunamis, (see Box 3.3, “Waves That Kill”) track the effects of climate change, monitor fish populations, and make shipping more efficient. Ocean observatories will save lives and money and help humanity make wiser use of the oceans—and indeed the entire ocean planet.

and how they reproduce, what they eat, how they behave, and so on, is to observe that part of the ocean and the organisms living there. Exploration and description are vitally important parts of marine biology, constantly revealing new information. Previously unknown species, for example, are discovered almost every week. New technologies, such as underwater cameras that reveal the behavior of whales (see Box 1.2, “Observing the Ocean”) or genetic techniques that have uncovered vast numbers of previously unknown marine microbes (see Box 5.2, “Tiny Cells, Big Surprises”), regularly improve our ability to observe the sea and make new discoveries. Each finding leads to new observations. The discovery of completely unknown and unexpected ecosystems at deep-sea hot springs, for example, led biologists to look for—and find—similar ecosystems in other parts of the ocean (see 16.4).

As they observe more and more about the world, scientists inevitably seek to explain their observations—*why is that*

species of seaweed found only in a certain depth range?—and to make predictions—*will the fishing be good next year?* The desire to explain and predict in turn guides yet more observation.

Two Ways of Thinking

To describe, explain, and make predictions about the natural world, scientists use two basic ways of thinking. In **induction**, they use observations to arrive at general principles. Conversely, reasoning from general principles to specific conclusions is called **deduction**. Scientists once argued about which way of thinking is acceptable, but now generally agree that both induction and deduction are indispensable.

Induction In induction, a scientist starts with a series of observations. Ideally, they have no goal or preconceptions about the



FIGURE 1.15 The Atlantic sailfish (*Istiophorus albicans*) attacking a school of sardines. The long projection on the snout is called the bill.

outcome and are completely objective. The scientist then uses these observations to reach a general conclusion. For example, suppose a marine biologist examined a sailfish (Fig. 1.15), a shark (Fig. 1.16), and a tuna (Fig. 1.17) and found they all had gills. Because sailfishes, sharks, and tunas are all fishes, he might conclude *All fishes have gills*. This is an example of induction.

In the process of induction, general conclusions are made on the basis of specific observations.

Scientists must be careful when using induction. The step from isolated observations to general conclusions critically depends on the number and quality of the observations and on recognizing their limitations. If our biologist stopped after examining the sailfish, which happens to have a bill, induction might lead to the false conclusion *All fishes have bills*. Even after examining all three fishes, he might have concluded *All marine animals have gills* instead of just *All fishes have gills*. This is where deduction comes into play.

Deduction In deduction, scientists start with a general statement about nature and predict what the specific consequences would

FIGURE 1.16 A tiger shark (*Galeocерdo cuvier*). The five vertical gill slits can be seen just in front of the pectoral fins.



FIGURE 1.17 The southern bluefin tuna (*Thunnus maccoyii*) has two plates on each side of the head that cover its gills.

be if that statement is true. The general statement might be based on hunch or intuition, but is usually based on observations. If our marine biologist used induction to make the general statement *All marine animals have gills*, knowing whales are marine animals he might reason that whales must have gills. Thus, a general statement about all marine animals was used to make a statement about a particular kind of marine animal.

In deduction, specific predictions are made by applying general principles.

Testing Ideas

Scientists are never content to simply make statements about the world and let it go at that. Instead, they are obsessed with testing the statements to see if they are, in fact, true. Both induction and deduction lead the scientist to make statements about the world, based on available information or even an “educated guess,” that *might* be true but requires further testing. A statement that might be true is called a **hypothesis**. A crucial feature of the scientific method is that all hypotheses are tested, usually again and again. This insistence on testing is one of the great strengths of the scientific method. Incorrect hypotheses are usually quickly weeded out and discarded.

Constructing the Hypothesis Scientific hypotheses must be stated in a way that allows them to be critically tested. What this means is that it must be possible, at least potentially, to *disprove* the hypothesis if it is false. Sometimes this is simple. For example,

the hypothesis that whales have gills is easy to test. All the biologist has to do is examine a whale to see if it has gills, and he would find that whales have lungs, not gills (Fig. 1.18). He would have proven the hypothesis *Whales have gills* false. This would also disprove the more general hypothesis *All marine animals have gills*. The steps our marine biologist used to construct and test these hypotheses are illustrated in Figure 1.19. This line of reasoning is not entirely imaginary. Aristotle used similar logic in the fourth century BCE, observing not only that whales breathe with lungs and not gills but also that unlike most fishes they give birth to live young instead of laying eggs. Unfortunately, Aristotle's recognition that whales and other marine mammals are not fishes was lost to Western science for more than two millennia.

Hypotheses are often much more complicated than whether or not an animal has gills. Marine organisms are affected by weather and current patterns, the abundance of food and predators, natural cycles of reproduction and death, human activities, and a host of other factors.

People sometimes make the mistake of proposing hypotheses that cannot actually be tested. Someone might say *There are mermaids in the ocean*. The problem with this hypothesis is that it could never be *proved* to be false. An army of marine biologists could spend their entire careers looking for a mermaid without finding one, but the true believer could always say *The mermaids are there, you just didn't find them*. No matter how hard they looked, the biologists could never prove that there are no mermaids. Therefore, the statement *There are mermaids in the ocean* is not a valid scientific hypothesis because it is not **testable**.

A scientific hypothesis is a statement about the world that might be true and is testable. A testable hypothesis is one that at least potentially can be proved false.

The Nature of Scientific Proof It must be possible to disprove a hypothesis, at least in principle, before the hypothesis is a scientific one. But how can a hypothesis be proved true? This question has always troubled scientists, and the answer may trouble you too. In general, no scientific hypothesis can be absolutely proved true. For example, consider the hypothesis that all fishes

The term *fish* is used for a single individual or for more than one individual of the same species.

The term *fishes* is used to refer to more than one species of fish.



FIGURE 1.18 A sperm whale (*Physeter catodon*) exhales bubbles of air from its lungs through the blowhole on top of its head.

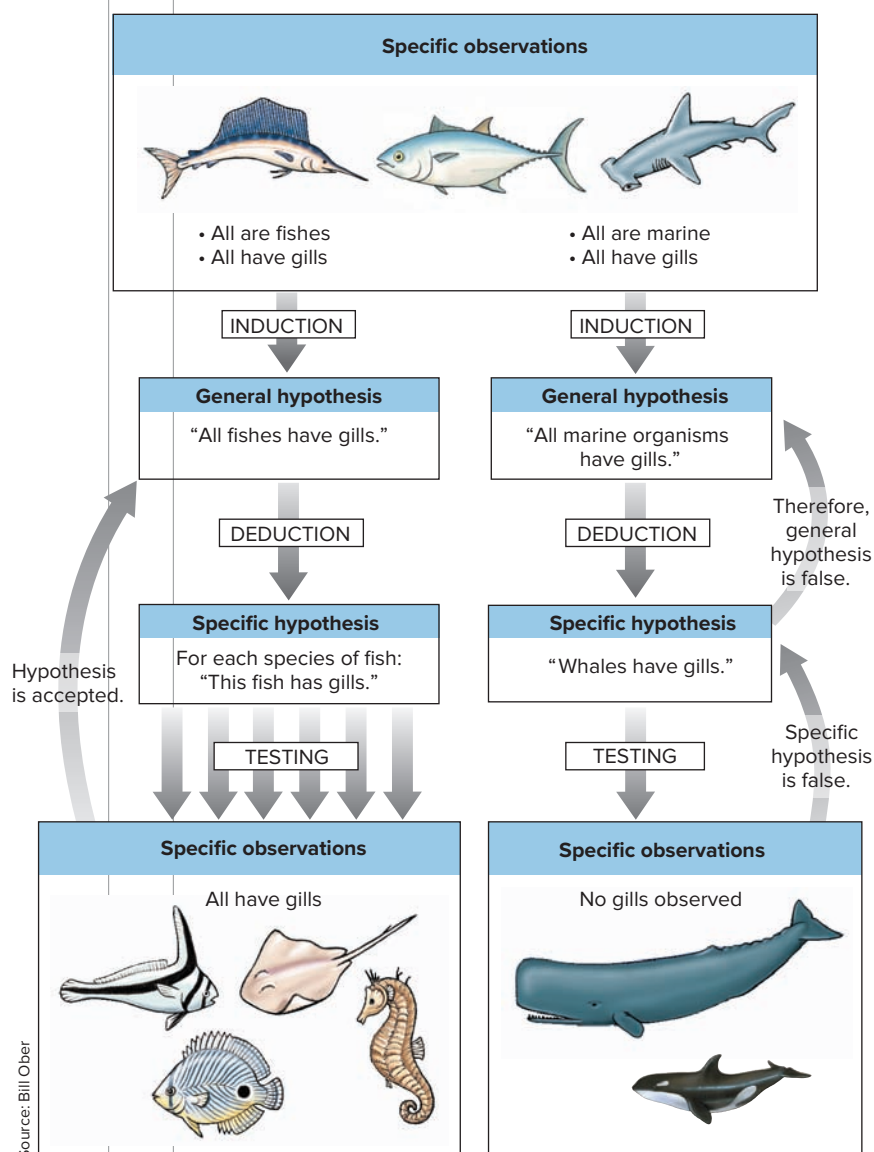


FIGURE 1.19 An example of the scientific method. Two hypotheses were derived from the same observations. When tested by further observations, one hypothesis (left) is accepted and one (right) is rejected.

have gills. It is easy to see that this hypothesis can be proved false by finding a fish without gills. But even though every fish so far examined has gills, this does not prove that *all* fishes have gills. Somewhere out there may lurk a fish without them. Just as it cannot be proved that there are no mermaids, it can never be proved that all fish have gills.

In science, then, there are no absolute truths. Knowing this, scientists could throw up their hands and look for another line of work. Fortunately, most scientists have learned to accept and deal with the lack of absolute certainty that is inherent in science by making the best of the available evidence. All scientific hypotheses are examined and tested, poked, and prodded, to see if they agree with actual observations of the world. When a hypothesis withstands all these tests, it is conditionally accepted as “true” in the sense that it is consistent with the available evidence. Scientists speak of *accepting* hypotheses, not *proving* them. They accept the hypothesis that all fish have gills because every attempt to reject it has failed. At least for now, the hypothesis fits the observations. The good scientist, however, never quite forgets that any hypothesis, even a personal favorite, could be thrown out the window by new information. No hypothesis is exempt from testing, or immune to being discarded if it conflicts with the evidence. The bottom line in science is observation of the world, *not* our preconceived ideas and beliefs.

No hypothesis can be scientifically *proved* to be true. Instead, hypotheses are *accepted* as long as they are supported by the available evidence.

Testing the Hypothesis Because hypotheses generally can’t be proved true, scientists, somewhat surprisingly, spend their time trying to disprove, not prove, hypotheses. They have more confidence in hypotheses that have stood up to critical testing than in untested ones. Thus, the role of the scientist is to be a skeptic.

Often scientists are trying to decide among two or more **alternative hypotheses**. After looking at the sailfish, shark, and tuna, our imaginary marine biologist advanced two possible hypotheses: that all fish have gills and that all marine animals have gills. Both hypotheses were consistent with the observations to that point. After examining a whale, our biologist rejected the second hypothesis and, in doing so, strengthened the first one. He arrived at the best hypothesis by a process of elimination.

Real marine biologists rarely have it as easy as our imaginary one, who was able to construct and then test his hypotheses about gills with just a few simple observations. Hypothesis testing usually requires carefully planned, painstaking observations. Occasionally a new observation or set of observations leads to the complete rejection of an accepted hypothesis, which has been termed a “scientific revolution.” Such discoveries make headlines, but most of the time the scientific process is a gradual one in which hypotheses are continually refined and modified, and new alternatives proposed, as more information becomes available.

Hypotheses can often be tested by making the right kind of observations of the natural world, at the right time and place.

Improved observing systems (see “Observing the Ocean,” above) and continuing ocean exploration are constantly revealing more of the ocean’s secrets.

Sometimes, however, the conditions needed to test a hypothesis do not occur naturally and scientists must manipulate nature, that is, perform an **experiment**, to make the necessary observations.

In experiments, scientists create artificial situations to test hypotheses because they cannot make the necessary observations under natural conditions.

Suppose another marine biologist observes that the same species of mussel is smaller at a location that has generally warmer water than at a colder spot. She wants to know if that size difference is due to the temperature difference. But the temperature at both locations changes all the time with seasons, weather, and so forth. The difference in temperature between locations would never stay the same. Even if it did, there would be many other differences between the two places. The mussels might be different strains, for example. They might be eating different foods or different amounts of food. There might be pollution or an outbreak of disease at one place or another, or stronger currents or waves. Or people could be harvesting the mussels at one location, so the mussels there are younger on average. In any natural situation, there are countless factors other than temperature that might explain the difference in mussel size. Factors that might affect observations are called **variables**.

Faced with all these variables, the biologist decides to perform an experiment. She collects mussels from a single location and divides them at random into two groups. This means the two groups of mussels in the experiment are pretty much the same. She places the two groups into separate tanks where she can control the water temperature. She grows one group in warm water, the other in cold. She feeds all the mussels the same amounts of the same food at the same time, protects the mussels from pollution and disease, supplies both holding tanks with seawater from the same source, and keeps all the other living conditions exactly the same for both groups. Because all these variables are the same for both groups, the biologist knows that they cannot be responsible for any differences observed in mussel growth. The only difference between the two groups is temperature.

To prevent a variable from affecting the experiment, the scientist has two options. One is to artificially keep the variable from changing—for example, by giving all the mussels exactly the same food. The other is to make sure that any changes that do occur are identical for both groups. By supplying both tanks with seawater from the same source, for example, our biologist ensures that any changes in the quality of the water affect both groups of mussels equally. Variables that are prevented from affecting an experiment are said to be **controlled**, and the experiment is called a **controlled experiment** (Fig. 1.20). Since the biologist has controlled the effects of other variables while growing the mussels at different temperatures, she can be confident that differences in growth between the two groups are due to temperature.

In this imaginary experiment, our biologist found that temperature was in fact the factor causing the observed size difference. But

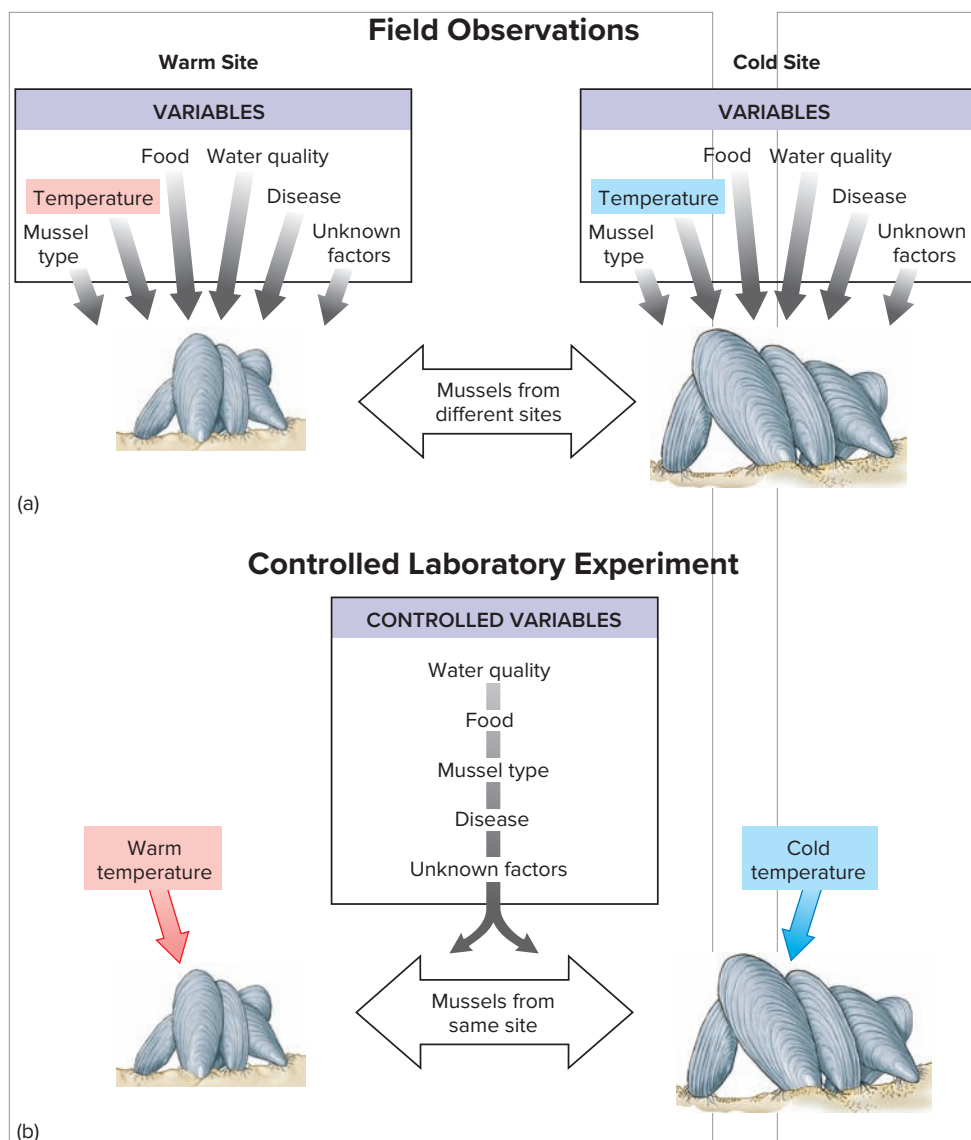


FIGURE 1.20 (a) Many different variables might produce differences between groups of mussels at different locations. (b) Controlling the variables in an experiment allows the effects of a single factor—in this case, temperature—to be tested, confirming that the size difference between the sites is due to temperature. This example describes a laboratory experiment, but experiments are often performed in the field.

why? Perhaps the higher temperature increased the mussels' metabolism so they burned more energy and grew slower (a weight-watcher's dream). Or maybe the temperature was near the upper extreme that the mussels can tolerate, so they were stressed. More often than not, good science raises as many questions as it answers, which is why science continually progresses. This example is particularly relevant because Earth is warming (see "Climate Change," in Special Report: Our Changing Planet) and understanding the effects on organisms both in the sea and on land is increasingly urgent.

The way that variables interact can also be studied. The mussels could be maintained in different *combinations* of temperature and food supply, for example, to see how the effects of temperature depend on food supply. That would help answer the question of whether the smaller size in warmer water is an effect of higher metabolism.

Experiments aren't just for the laboratory—many (some would say most) important controlled experiments are done out in the real world (see Box 11.1, "Transplantation, Removal, and Caging Experiments").

Not all experiments are designed, much less controlled. Marine scientists are hungry for knowledge however they get it, and capitalize whenever they can on accidental and natural experiments. When a ship accidentally dumped a cargo of tennis shoes in a North Pacific storm, plotting where the floating shoes washed up on beaches improved our understanding of surface currents. Monitoring the recovery of a coral reef smashed by a cyclone provided information about how fast damaged reefs can recover.

Marine scientists often try to capture what they think they know in the form of models. These may start as very simple sketches along the lines of "the water flows from here to there, this eats that." Even such simple "models" help crystallize and communicate our understanding. They also help identify errors in our thinking and point to where more information is needed. If numbers can be attached—how much water flows, how much they eat—more sophisticated models are developed to predict what might happen in a particular situation. If the prediction doesn't bear out, what did we miss or were our measurements wrong: back to the drawing board. This cycle of capturing and testing our knowledge is another, powerful form of experiment.

Source: Bill Ober

The Scientific Theory Most of us have heard people ridicule some idea or other because it was "only theoretical." The public usually reserves such scorn for controversial or unpopular theories. The theory of gravity, for instance, is rarely criticized for being "only a theory" even though physicists have no accepted explanation of why gravity exists. People often say "theory" in everyday conversation to mean a guess, speculation, or just one of several possible explanations for something, but scientists don't use the term **scientific theory** to refer to a controversial or provisional hypothesis. A hypothesis is not considered a scientific theory until all reasonable alternatives have been ruled out and the hypothesis has passed every possible test. A scientific theory is supported by overwhelming evidence and represents the best comprehensive explanation of our observations of how the world works. It is an established scientific principle that guides the search for new knowledge by leading to new, testable hypotheses.

Box 1.3 John Steinbeck and Ed Ricketts

People mostly know the American writer John Steinbeck as the author of such beloved works as *The Grapes of Wrath*, *Of Mice and Men*, and *East of Eden*. Less well known are Steinbeck’s contributions to marine biology, which resulted largely from his close friendship with a man named Ed Ricketts.

Steinbeck and Ricketts first met in 1930—by Steinbeck’s account, in a dentist’s office in Pacific Grove, California. Steinbeck had a long-standing interest in marine biology and had wanted to meet Ricketts for some time. Ricketts owned the Pacific Biological Laboratory, located near the Hopkins Marine Station and the present site of the Monterey Bay Aquarium. Ricketts collected specimens of marine life along the Pacific coast and sold them to universities and museums. He was immensely popular in the area and knew more about marine biology than anyone around.

The two men became close friends almost immediately. Before long Steinbeck, then struggling as a writer, was spending a lot of time hanging around his friend’s laboratory, going on collecting trips, and assisting in day-to-day operations. Steinbeck got so involved in this work that he could even get excited about a microscope:

*My dream for some time in the future is a research scope with an oil immersion lens, but that costs about 600 dollars and I'm not getting it right now.... Oh boy! Oh boy! Sometime I'll have one.*¹

John Steinbeck would eventually credit Ricketts with shaping his views of humanity and the world, and characters in at least six of Steinbeck’s novels were based on Ricketts. The most famous is Doc, the main character of *Cannery Row*, who runs the “Western Biological Laboratory”:

It sells the lovely animals of the sea, the sponges, tunicates, anemones, the stars and buttlestars [sic], the sunstars,

*the bivalves, barnacles, the worms and shells, the fabulous and multiform little brothers, the living moving flowers of the sea, nudibranchs and tectibranchs, the spiked and nobbed and needly urchins, the crabs and demi-crabs, the little dragons, the snapping shrimps, the ghost shrimps so transparent that they hardly throw a shadow.... You can order anything living from Western Biological and sooner or later you will get it.*²

The friendship was beneficial to marine biology as well as to literature. Their expedition to Mexico produced *The Sea of Cortez*, a scientific report that is also part literature and part travelogue. The book lists the more than 600 species collected by the pair, including some 60 that were new to science. The trip was not all work, however: The authors report taking “2,160 individuals of two species of beer.”

Ed Ricketts’s most enduring contribution to marine biology was the 1939 publication *Between Pacific Tides*. Written with Jack Calvin, a friend of Ricketts and Steinbeck, *Between Pacific Tides* is a comprehensive guide to the seashore life of the Pacific coast of North America. Revised and updated, it is still used by amateurs and professionals alike.

Though Ricketts was an able biologist and was largely responsible for the content of *Between Pacific Tides*, he had difficulty getting his observations and ideas down on paper. Steinbeck almost certainly helped him write the book and get it published. When Ricketts felt that the publisher, Stanford University Press, was dragging its feet, Steinbeck fired off this sarcastic letter:

*Gentlemen:
May we withdraw certain selected parts of Between Pacific Tides which with the passing years badly need revision. Science advances but Stanford Press does not.*



Vicki Buchsbaum Pearse

Ed Ricketts.

There is the problem also of the impending New Ice Age.

Sometime in the near future we should like to place our order for one (1) copy of the forthcoming (1948, no doubt) publication, The Internal Combustion Engine, Will it Work?³
Sincerely,
John Steinbeck
Ed Ricketts

P.S. Good Luck with A Brief Anatomy of the Turtle.

Ed Ricketts was killed in a train accident in 1948. Steinbeck, saddened at the death of his friend, wrote, “There died the greatest man I have ever known and the best teacher.”

¹Source: “2/17/1948 to Gwyndolyn Steinbeck” by John Steinbeck and Ed Ricketts and “12/15/1939 letter to Elizabeth Otis” by John Steinbeck, from *Steinbeck: A Life in Letters* edited by Elaine A. Steinbeck and Robert Wallsten.
²Source: “Chapter 5” from *Cannery Row* by John Steinbeck, 1945.
³Source: “2/17/1948 to Gwyndolyn Steinbeck” by John Steinbeck and Ed Ricketts and “12/15/1939 letter to Elizabeth Otis” by John Steinbeck, from *Steinbeck: A Life in Letters* edited by Elaine A. Steinbeck and Robert Wallsten.

It must be remembered, however, that a theory is still a hypothesis, albeit a well-tested one. As with other hypotheses, theories cannot be absolutely proved and are accepted as true only as long as they are supported by evidence. Good scientists accept theories only as long as the best available evidence supports them, and they recognize that any theory could be overturned by new evidence.

A scientific theory is a hypothesis that has been so extensively tested that it is generally regarded as true. Like any hypothesis, however, it is subject to rejection if enough evidence accumulates against it.

Limitations of the Scientific Method

No human enterprise, including science, is perfect. Just as it is important to understand how and why the scientific method works, it is important to understand the limitations of the scientific

method. For one thing, remember that scientists are people too: they have the same human shortcomings as anyone else. Scientists may be attached to favorite theories even when confronted with contradictory evidence—being wrong can be hard to accept. Like anyone else, they may let personal biases affect their thinking. No one can be completely objective all the time. Fortunately, factual errors are usually corrected because hypotheses are tested not just by one person but by many. The practical success of science is evidence that the self-checking nature of the scientific method does work most of the time.

Science also has some built-in limitations. Ironically, these limitations arise from the same features that give the scientific method its power: the insistence on direct observation and testable hypotheses. This means that science cannot make judgments about values, ethics, or morality. Science can reveal how the world is, but not how it should be. Science cannot decide what is beautiful. Science can't even tell humanity how to use the knowledge and technology it produces. These things all depend on values, feelings, and beliefs, which are beyond the scope of science.



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Critical Thinking

1. Most of the major advances in marine biology have come in the last 200 years. What do you think are the reasons for this?
2. Recall that the statement “There are mermaids in the ocean” is not a valid scientific hypothesis. Can the same be said of the statement “There are *no* mermaids in the ocean?” Why?
3. Imagine you are a marine biologist and you notice that a certain type of crab tends to be larger in a local bay than in the waters outside the bay. What hypotheses might account for this difference? How would you go about testing these hypotheses?
4. Many species of whale have been hunted to the brink of extinction. Many people think that we do not have the right to kill whales and that all whaling should cease. On the other hand, in many cultures whales have been hunted for centuries and still have great cultural importance. People from such cultures argue that limited whaling should be allowed to continue. What is the role that science can play in deciding who is right? What questions cannot be answered by science?

For Further Reading

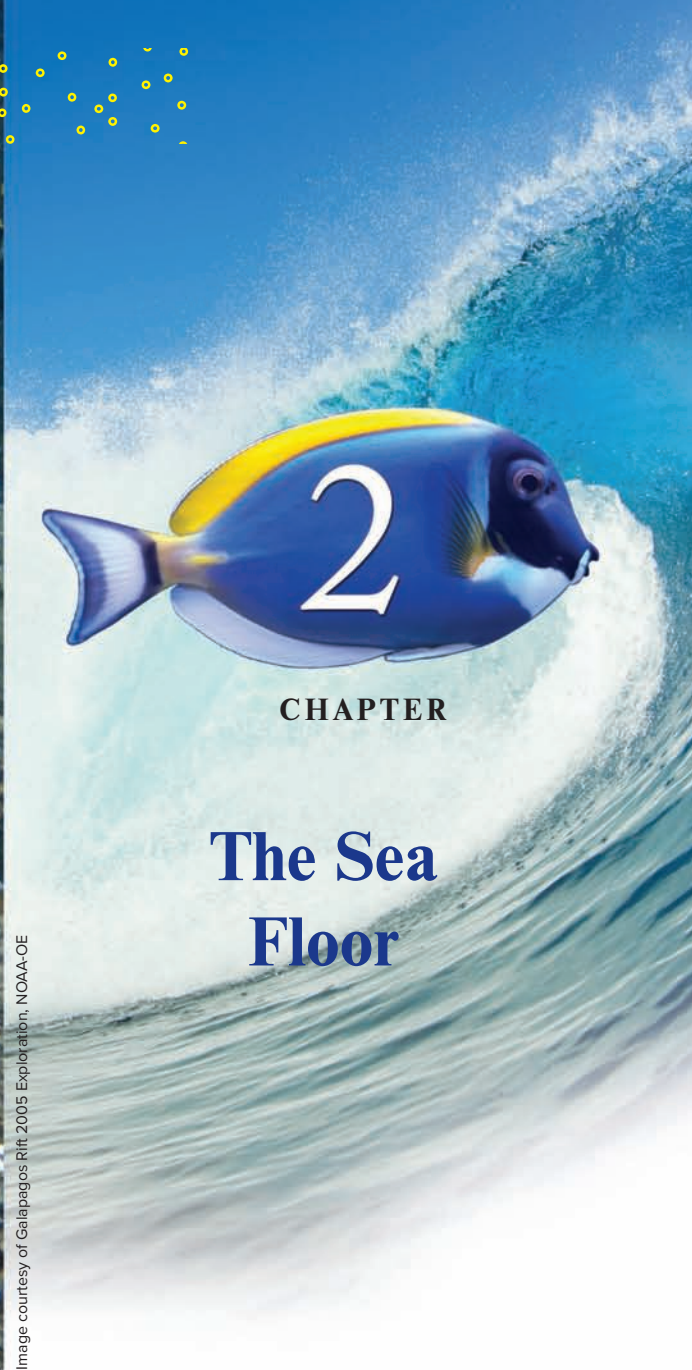
Some of the recommended reading may be available online. Look for live links on the *Marine Biology* Online Learning Center.

General Interest

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CHAPTER

The Sea Floor

Image courtesy of Galapagos Rift 2005 Exploration. NOAA-OE

Submarine eruptions produce fresh sea floor like this “pillow basalt,” which formed as lava slowly oozed out of a fissure on the sea floor. The new sea floor has already been colonized by vent clams (*Calyptogena magnifica*) and other animals.

The oceans are not just places where the land happens to be underwater. Most of the sea floor is geologically distinct from the continents. It is locked in a perpetual cycle of birth and destruction that shapes the oceans and controls much of the geology of the continents. Marine geological processes affect not only the oceans but also dry land.

Many of the processes that mold ocean basins occur slowly, over hundreds of millions of years. On this timescale, where a human lifetime is but the blink of an eye, solid rocks flow like liquid, entire continents move across the face of the Earth, and mountains grow from flat plains. To understand the sea floor, we must learn to adopt the unfamiliar perspective of geological time.

At first glance geology might not seem to have much to do with marine biology, but geological processes profoundly influence marine

habitats, the natural environments where marine organisms live. Geological processes sculpt the shoreline, determine the water depth, control whether the bottom is muddy, sandy, or rocky, create new islands and undersea mountains for organisms to colonize, and determine the nature of marine habitats in countless other ways. Much of the history of life in the oceans has been determined by geological events.

2.1 THE WATER PLANET

Our planet is very much a water planet, unique in having large amounts of liquid water—the oceans—on its surface. The oceans not only cover 71% of the globe but also regulate its climate and atmosphere.

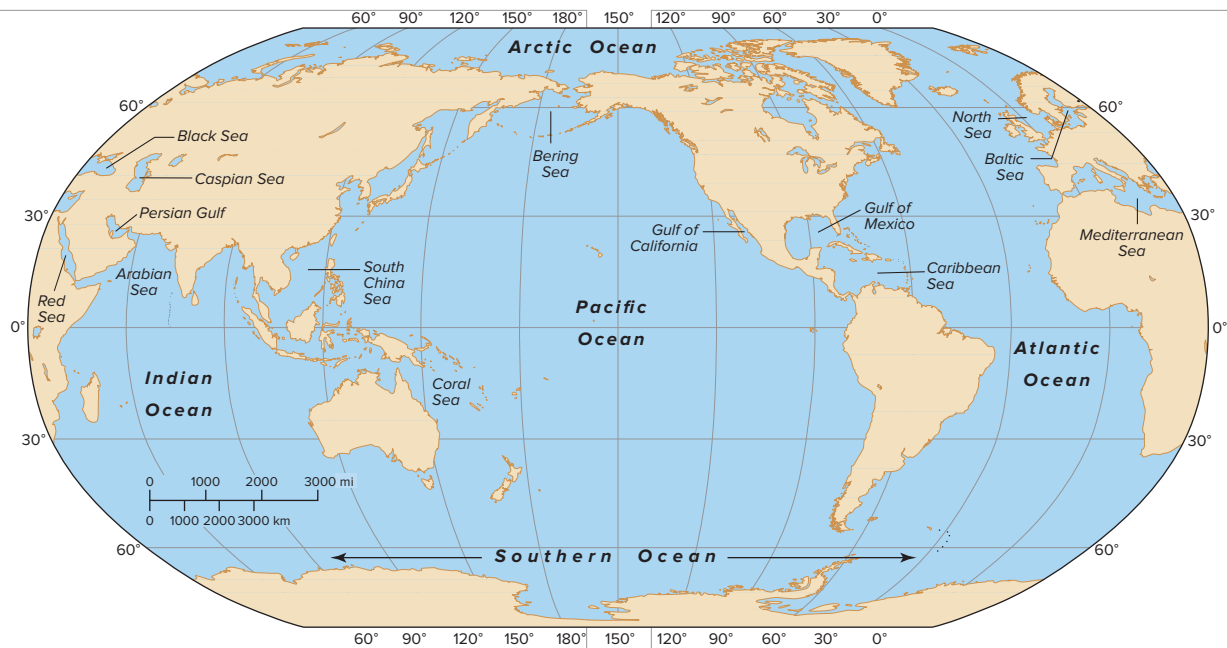


FIGURE 2.1 The major ocean basins and some of the marginal seas.

The Geography of the Ocean Basins

The oceans are not distributed equally with respect to the Equator. About two-thirds of Earth’s land area is found in the Northern Hemisphere, which is only 61% ocean. About 80% of the Southern Hemisphere is ocean.

The oceans are traditionally classified into four large basins (Fig. 2.1). The **Pacific** is the deepest and largest, almost as large as all the others combined (Table 2.1). The **Atlantic** Ocean is a little larger than the **Indian** Ocean, but the two are similar in average depth. The **Arctic** is the smallest and shallowest ocean. A number of shallow seas, such as the Mediterranean Sea, Gulf of Mexico, and South China Sea, are marginal or connected to the main ocean basins.

Though we usually treat the oceans as four separate entities, they are actually interconnected. This connection is most obvious when the world is viewed from the South Pole (Fig. 2.2). From this view it is clear that the Pacific, Atlantic, and Indian oceans are large branches of one vast system. The connections among the major basins allow seawater, materials, and some organisms to move from one ocean to another. Because the oceans are actually one great interconnected system, oceanographers often speak of a single **world ocean**. They also refer to the continuous body of water that surrounds Antarctica as the **Southern Ocean**.

The world ocean, which covers 71% of the planet, is divided into four major basins: the Pacific, Atlantic, Indian, and Arctic oceans.

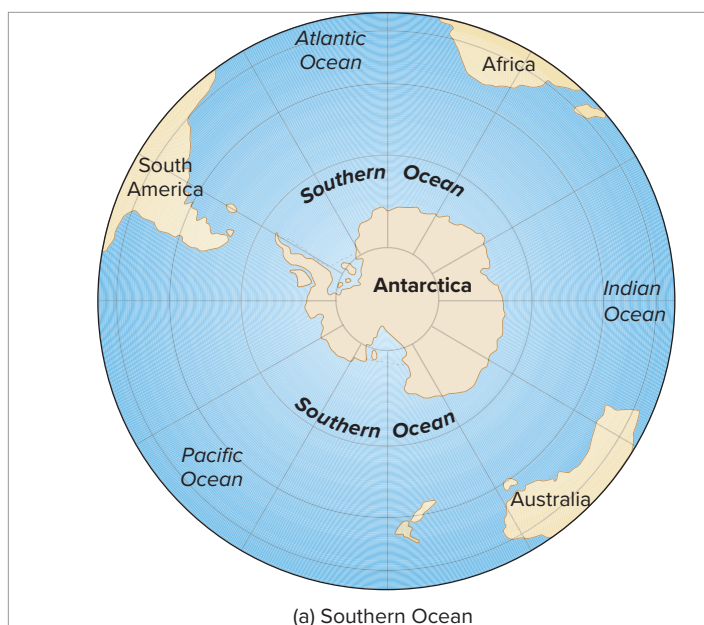
The Structure of Planet Earth

Earth and the rest of the solar system are thought to have originated about 4.5 billion years ago from a cloud or clouds of dust formed by the explosion of a star. The dust particles collided with each other, clumping into larger particles. These larger particles collided in turn, joining into pebble-sized rocks that collided to form larger rocks, and so on. The process eventually built up Earth and the other planets.

Earth’s formation generated so much heat that the entire early planet was molten. This allowed materials to settle within the planet according to their **density**. Density is the mass of a given volume of a substance. Obviously, a pound of styrofoam weighs more than an ounce of lead, but most people think of lead as “heavier” than styrofoam even though a kilogram of lead weighs the same as a kilogram of styrofoam. This is because lead weighs more than styrofoam if *equal volumes* of the two are compared. In other words, lead is denser than styrofoam. The density of a substance is calculated by dividing its mass by its volume. If two substances are mixed, the denser material tends to sink and the less dense to float.

Table 2.1
Average Depths and Total Areas of the Four Major Ocean Basins

Ocean	AREA		AVERAGE DEPTH		Deepest Place
	Millions of km ²	Millions of mi ²	Meters	Feet	
Pacific	166.2	64.2	4,188	13,741	Marianas Trench, 10,994 m (36,070 ft)
Atlantic	86.5	33.4	3,736	12,258	Puerto Rico Trench, 8,605 m (28,233 ft)
Indian	73.4	28.3	3,872	12,704	Java Trench, 7,725 m (25,344 ft)
Arctic	9.5	3.7	1,330	4,364	Molloy Deep, 5,608 m (18,400 ft)



Source: Bill Ober

FIGURE 2.2 (a) South polar view of the world. The major ocean basins can be seen as extensions of one interconnected world ocean. The ocean that surrounds Antarctica is often called the Southern Ocean. (b) North polar view of the world showing the partially enclosed Arctic Ocean.

Density is the mass of a substance per unit volume. Substances of low density will float on substances of higher density.

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

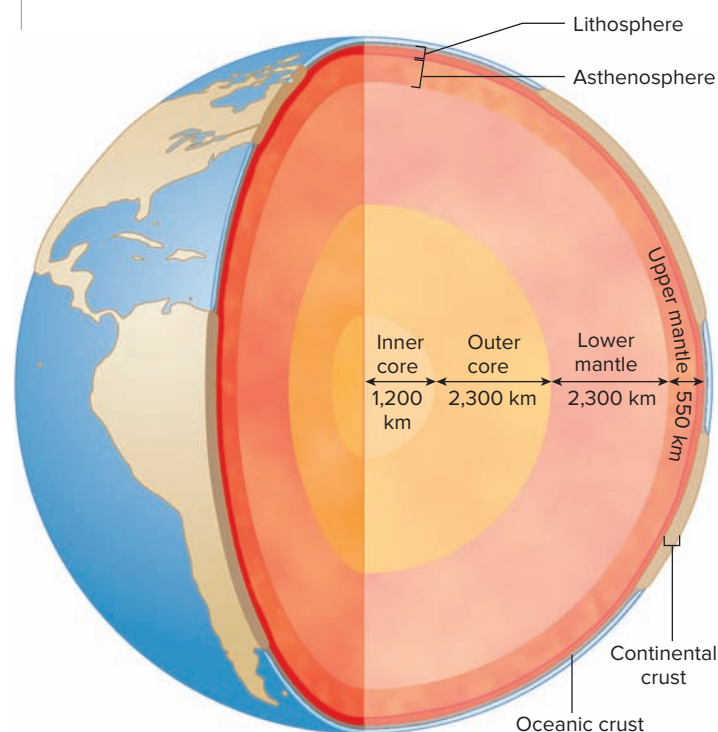
While the young Earth was molten, the densest material sank toward the center of the planet, while lighter materials floated toward the surface. The light surface material cooled into a thin crust. Eventually, the atmosphere and oceans began to form. If Earth had settled into orbit too far away from or too close to the sun, or our atmosphere had formed differently, the planet would be either so hot that all the water would have evaporated away or so cold that all Earth's water would be perpetually frozen. Fortunately for us, both our planet's orbit and its atmosphere allow liquid water, and therefore life as we know it, to exist.

Internal Structure The internal structure of Earth reflects the planet's early beginnings. As materials sank or floated according to their density, they formed layers (Fig. 2.3). The innermost layer, the **core**, is mostly iron. The pressure in the core is more than a million times that at Earth's surface, and the temperature is over 4,000 °C (7,200 °F). The core consists of a solid inner core and a liquid outer core. It is thought that swirling motions of the liquid material in the iron-rich outer core produce Earth's magnetic field.

The layer outside Earth's core is the **mantle**. Though most of the mantle is thought to be solid, it is very hot—near the melting point of the rocks. Because of this, much of the mantle slowly flows like a liquid, swirling and mixing over hundreds of millions of years.

The **crust** is the outermost, and therefore best-known, of Earth's layers. Compared with the deeper layers, it is extremely thin, like a rigid skin floating on top of the mantle. The composition and characteristics of the crust differ greatly between the oceans and the continents.

Earth is composed of three main layers: the iron-rich core, the semiplastic mantle, and the thin outer crust.



Source: Bill Ober

FIGURE 2.3 Earth's interior is divided into the core, mantle, and crust. The core is subdivided into the solid inner core and the liquid outer core. The mantle is also subdivided into upper and lower layers. The crust and uppermost layer of the mantle together form the lithosphere. Most of the upper mantle in the lithosphere is relatively solid, except for a fluid layer at the base of the lithosphere. The upper mantle below the lithosphere is relatively fluid, though not nearly as much as the lower layer of the lithosphere, and is called the asthenosphere. The thickness of the crust and lithosphere is exaggerated here, and the thickness of all layers varies from place to place.

Continental and Oceanic Crusts The geological distinction between ocean and continents results from physical and chemical differences in the rock that makes up the crust (Table 2.2). Oceanic crust, which makes up the sea floor, consists of a dark-colored mineral called **basalt** (see the photo at the beginning of the chapter).

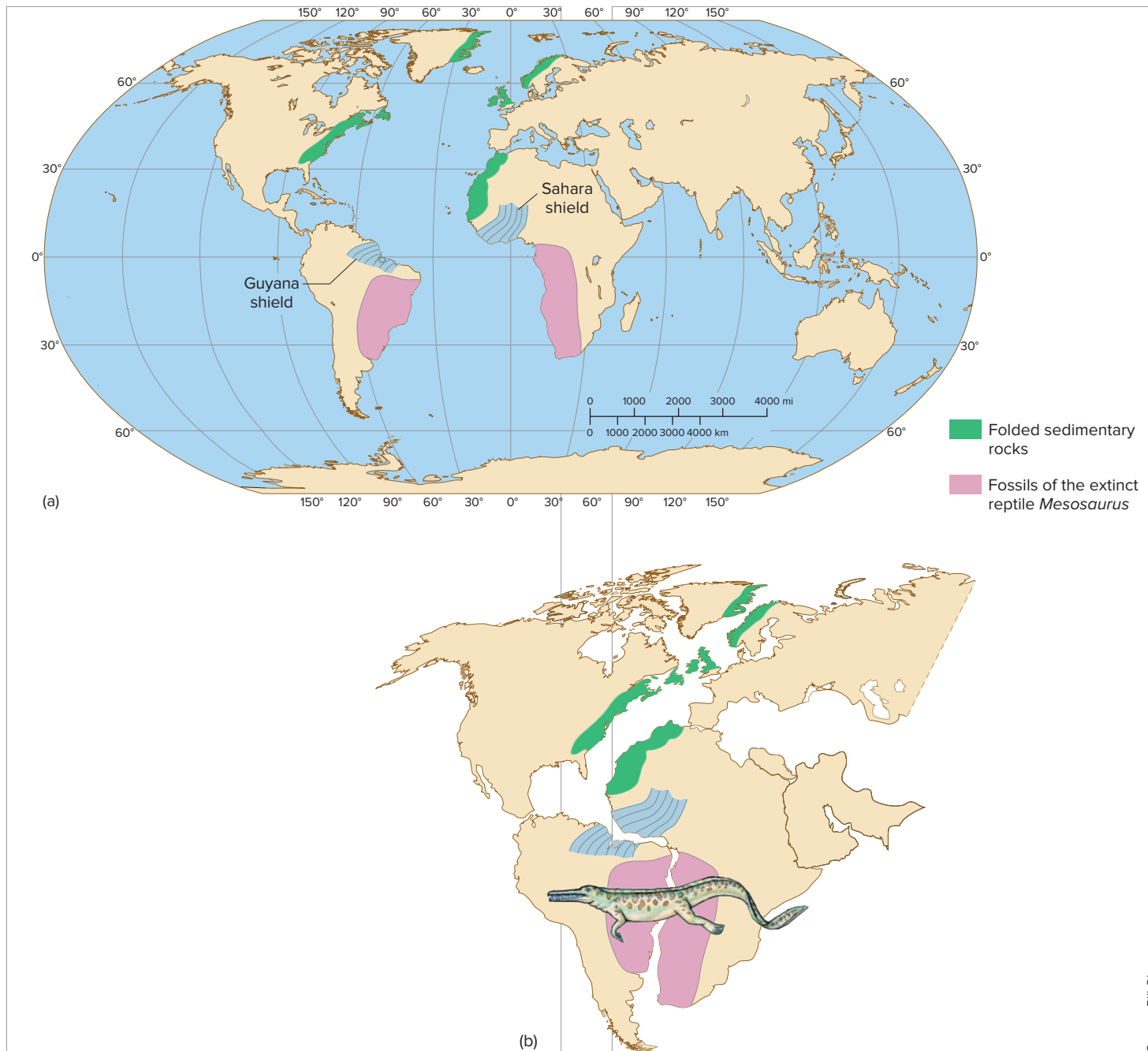


FIGURE 2.4 (a) The landmasses on opposite sides of the Atlantic have coastlines and geological features that (b) fit together like pieces of a puzzle.

Most continental rocks are of a general type called **granite**, which has a different chemical composition than basalt and is lighter in color. Oceanic crust is denser than continental crust. Ocean crust is also much thinner than continental crust, so it doesn't retain as much of the heat coming up from the mantle. The continents can be thought of as thick blocks of relatively warm, light crust floating on the mantle, much as icebergs float in water. Oceanic crust floats on the mantle, too, but because it is denser it doesn't float as high. That is why the continents lie high and dry above sea level and oceanic crust lies below sea level, covered with water.

Oceanic and continental crusts also differ in age. The oldest oceanic rocks are less than 200 million years old, quite young by geological standards. Continental rocks, on the other hand, can be as old as 3.8 billion years.

2.2 THE ORIGIN AND STRUCTURE OF THE OCEAN BASINS

We are surrounded by evidence of geological change—catastrophic earthquakes, volcanic eruptions, the erosion of river valleys, for example—but for centuries people somehow viewed the world as static and unchanging. People eventually understood that the face of the planet does indeed change. Today scientists recognize Earth as a planet of constant transformation where even the continents move.

Early Evidence of Continental Drift

As early as 1620 the English philosopher, writer, and politician Sir Francis Bacon noted that the coastlines on opposite sides of the Atlantic fit together like pieces of a puzzle (Fig. 2.4). It was

Table 2.2**Comparison of Continental and Oceanic Crusts**

Oceanic Crust (Basalt)	Continental Crust (Granite)
Density about 3.0 g/cm ³	Density about 2.7 g/cm ³
Only about 5 km (3 mi) thick	20 to 50 km (12 to 30 mi) thick
Geologically young	Can be very old
Dark in color	Light in color
Rich in iron and magnesium	Rich in sodium, potassium, calcium, and aluminum

later suggested that the Western Hemisphere might once have been joined to Europe and Africa. Coal deposits and other geological formations, for example, match up on opposite sides of the Atlantic. Fossils collected on opposing coasts are also similar.

On the basis of such evidence, the German scientist Alfred Wegener proposed the first detailed hypothesis of **continental drift** in 1912. Wegener hypothesized that all the continents had once been joined in a single “supercontinent,” which he named **Pangaea**. He thought Pangaea began breaking up into the continents we know today about 180 million years ago.

Plate Tectonics

Wegener’s hypothesis was not widely accepted because he could not explain *how* the continents moved. Later proposals of continental drift also failed to provide a workable mechanism, but evidence continued to accumulate. In the late 1950s and the 1960s, scientists finally put the evidence together. They showed that the continents *do* drift, as part of larger plates in the process of **plate tectonics**, a phenomenon that involves the entire surface of our planet.

Discovery of the Mid-Ocean Ridge In the years after World War II, sonar allowed the first detailed surveys of large areas of the sea floor. These surveys resulted in the discovery of the **mid-ocean ridge** system, a continuous chain of submarine volcanic mountains that encircles the globe like seams on a baseball (Figs. 2.5 and 2.6). The mid-ocean ridge system is the largest geological feature on Earth. At regular intervals the mid-ocean ridge is displaced to one side or the other by cracks, or **faults**, in Earth’s crust known as **transform faults**. Occasionally the submarine mountains of the ridge rise so high that they break the surface to form islands, such as Iceland and the Azores (Fig. 2.7).

The mid-ocean ridge in the Atlantic, called the **Mid-Atlantic Ridge**, runs right down the center of the Atlantic Ocean, parallel to the opposing coastlines. The ridge forms an inverted Y in the Indian Ocean and runs up the eastern side of the Pacific (Fig. 2.5). The main section of ridge in the Eastern Pacific is called the **East Pacific Rise**.

The mid-ocean ridge system is a continuous, submarine range of volcanic mountains that runs through all the ocean basins.

Surveys of the sea floor also revealed the existence of a system of deep depressions in the sea floor called **trenches** (Fig. 2.5). Trenches are especially common in the Pacific. How they are formed is discussed in “Sea-Floor Spreading and Plate Tectonics,” below.

Significance of the Mid-Ocean Ridge When the mid-ocean ridge system and trenches were discovered, geologists realized that geological activity is concentrated around them. Earthquakes are clustered at the ridge and volcanoes are associated with trenches (Fig. 2.8). Sea-floor rock at the ridge is very young and gets progressively older moving away from the ridge. Right at the ridge crest there is little, if any, **sediment**, loose material like sand and mud, that settles to the bottom, but sediment gets thicker and thicker at

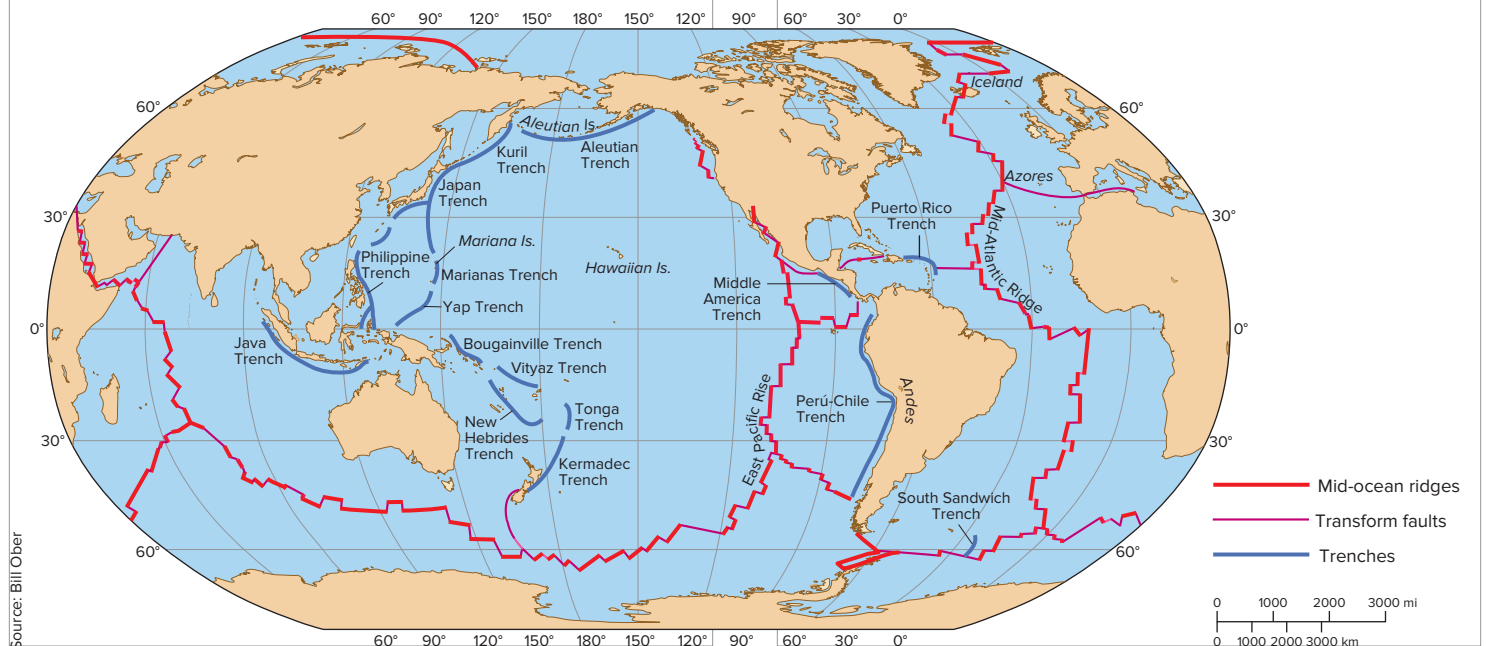


FIGURE 2.5 The major features of the sea floor. Compare this map with Figure 2.6.

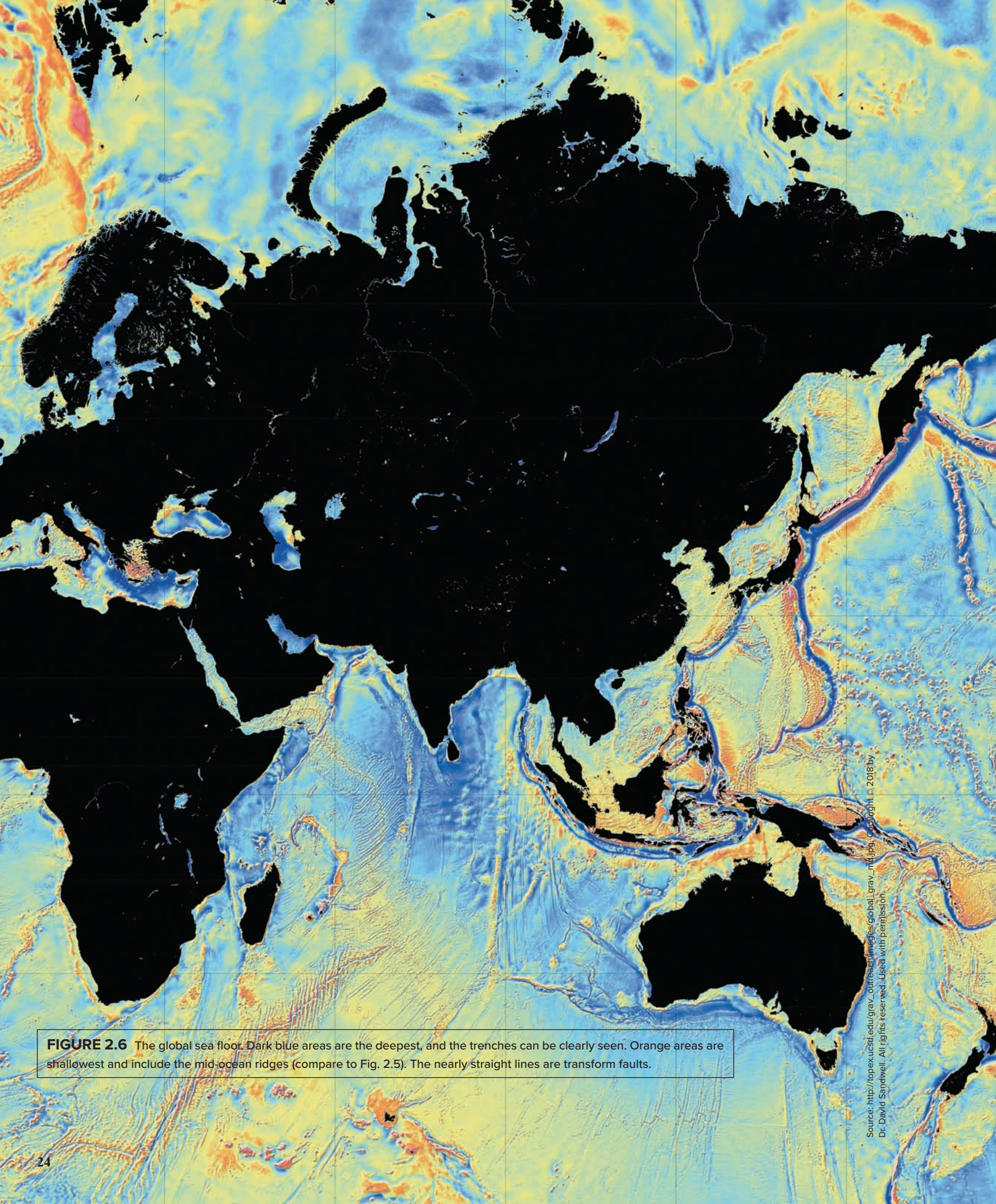
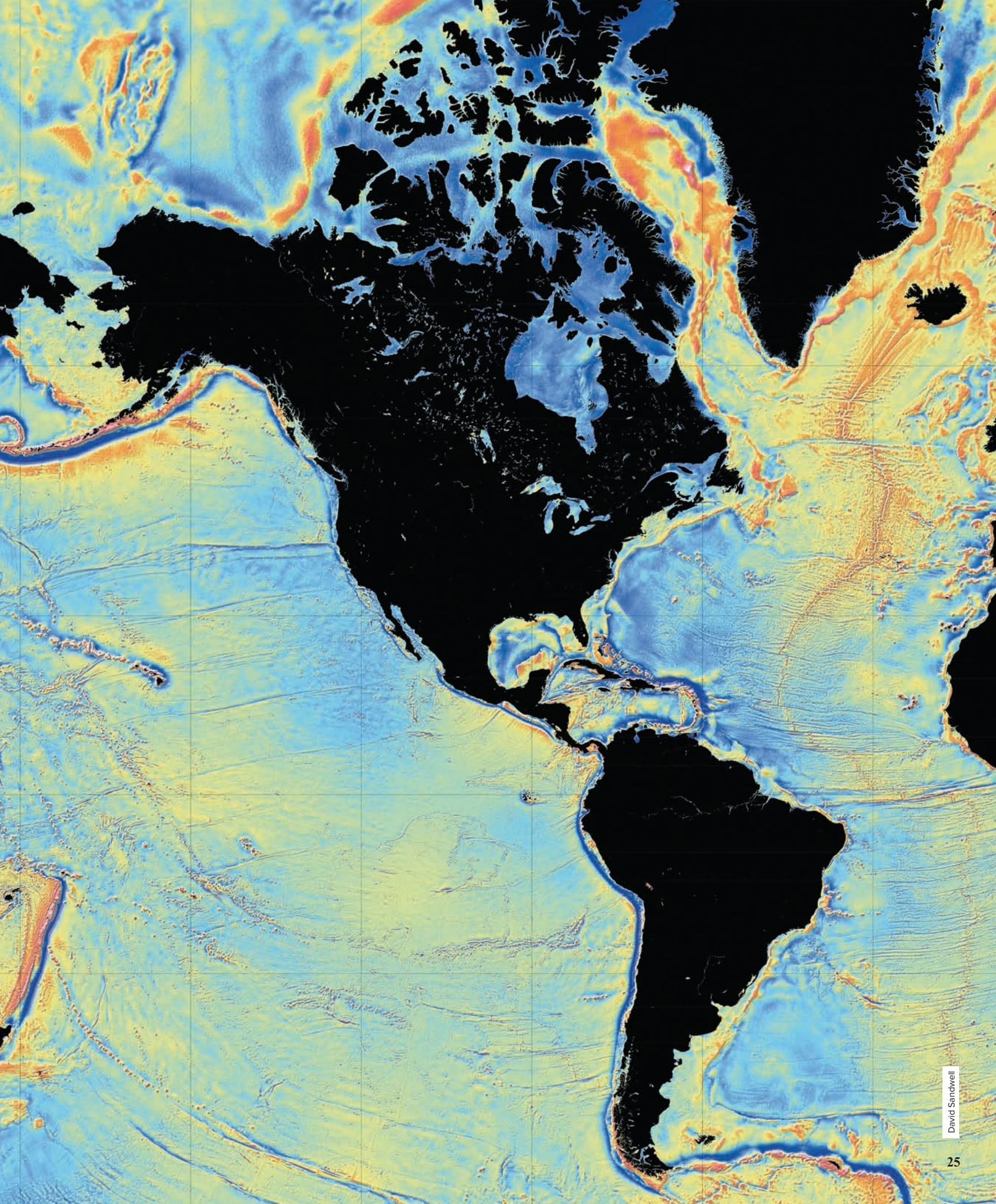


FIGURE 2.6 The global sea floor. Dark blue areas are the deepest, and the trenches can be clearly seen. Orange areas are shallowest and include the mid-ocean ridges (compare to Fig. 2.5). The nearly straight lines are transform faults.

Source: http://topex.ucsd.edu/grav_outreach/images/global_grav_md.jpg. Copyright © 2018 by Dr. David Sandwell. All rights reserved. Used with permission.





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FIGURE 2.7 A portion of the Mid-Atlantic Ridge above the sea surface in Iceland.

greater distance from the ridge. The deepest sediment, that resting directly on the sea-floor rock, gets older away from the ridge.

One of the most important findings came from studying the magnetism of rocks on the sea floor. Earth's magnetic field constantly "wobbles," moving around slightly so that the magnetic North Pole constantly moves around a little. In fact, in recent years this movement seems to be increasing. Every so often, however, the pole completely flips, so that instead of pointing north as it does today, a compass would point south. Our present magnetic field is arbitrarily called "normal," when the compass points north it is called a "reversal." In the recent past, geologically speaking, reversals have occurred about every 300,000 years, though the interval has varied, and there have been times in Earth's history when no reversals occurred over tens of millions of years. Reversals are thought to be caused by changes in the motion of material in the iron-rich outer core.

Many rocks contain tiny magnetic particles. When the rock is molten these particles can move, and they act like tiny compasses, pointing north or south depending on whether Earth's field is normal or reversed. When the rocks cool, the particles are frozen in place and keep their orientation even when the magnetic field changes. It is therefore possible to tell the orientation of Earth's magnetic field at the time the rocks cooled.

Sea-floor rocks have patterns of magnetic bands, or "stripes," that run parallel to the mid-ocean ridge (Fig. 2.9). The bands represent zones in which the rocks alternate between normal and reversed magnetization. The bands are symmetric around the ridge, so that the pattern on one side of the ridge is a mirror image of the pattern on the other side. These bands, or **magnetic anomalies** (Fig. 2.10), could only have formed if the normally magnetized rock cooled from molten material at different times than the reverse-magnetized bands. The sea floor, then, was not formed all at once but in strips that parallel the mid-ocean ridge.

Earthquakes and volcanoes are associated with the mid-ocean ridge. The sediments are thicker and the rock of the actual sea floor is older the farther they are from the ridge. Bands of rock alternating between normal and reversed magnetism parallel the ridge.

Creation of the Sea Floor The discovery of magnetic anomalies tied together the other evidence into an understanding of plate tectonics. The jump from observations of the sea floor and mid-ocean ridges to the theory of plate tectonics is a good example of the use of **induction** in science.

Huge slabs of oceanic crust separate at mid-ocean ridges, creating cracks in the crust called **rifts**. When a rift occurs it releases some of the pressure on the underlying mantle, like removing the cap from a bottle of soft drink. The reduced pressure allows hot mantle material to melt and rise up through the rift. The ascending

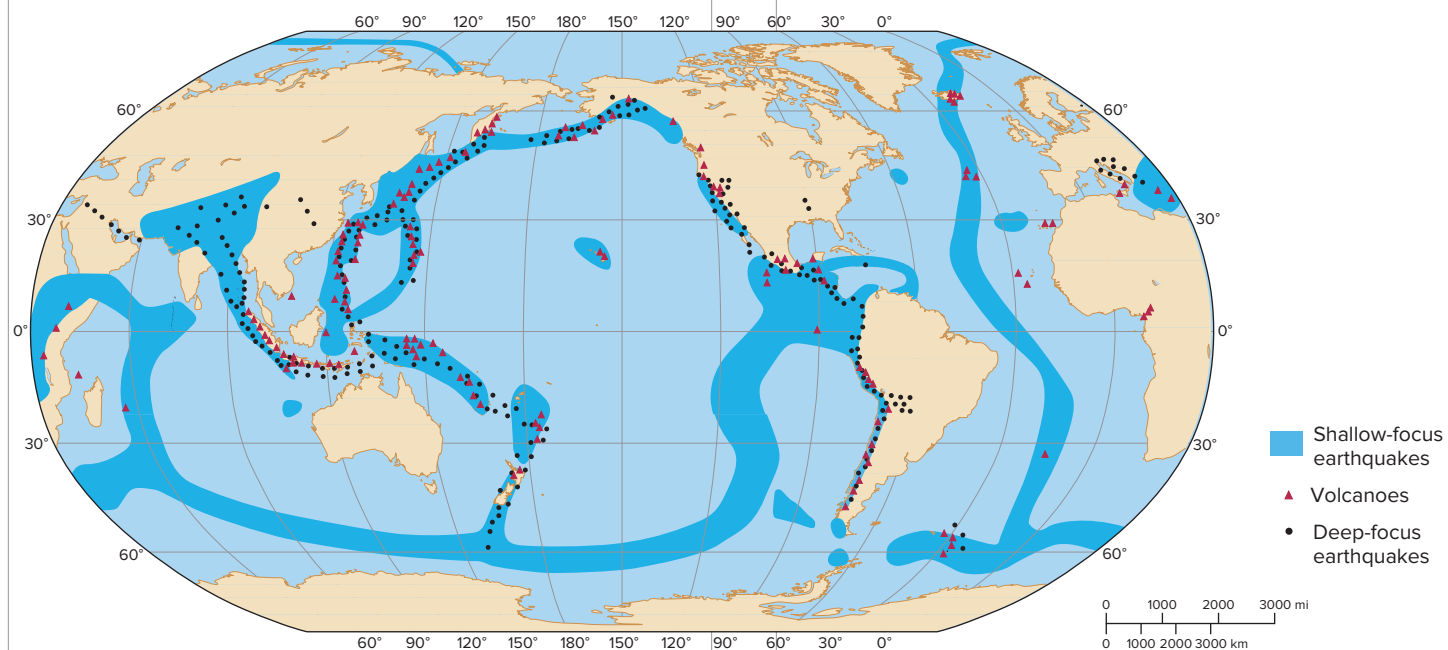


FIGURE 2.8 The world distribution of earthquakes and volcanoes. Compare these with the locations of mid-ocean ridges and trenches shown in Figure 2.5.

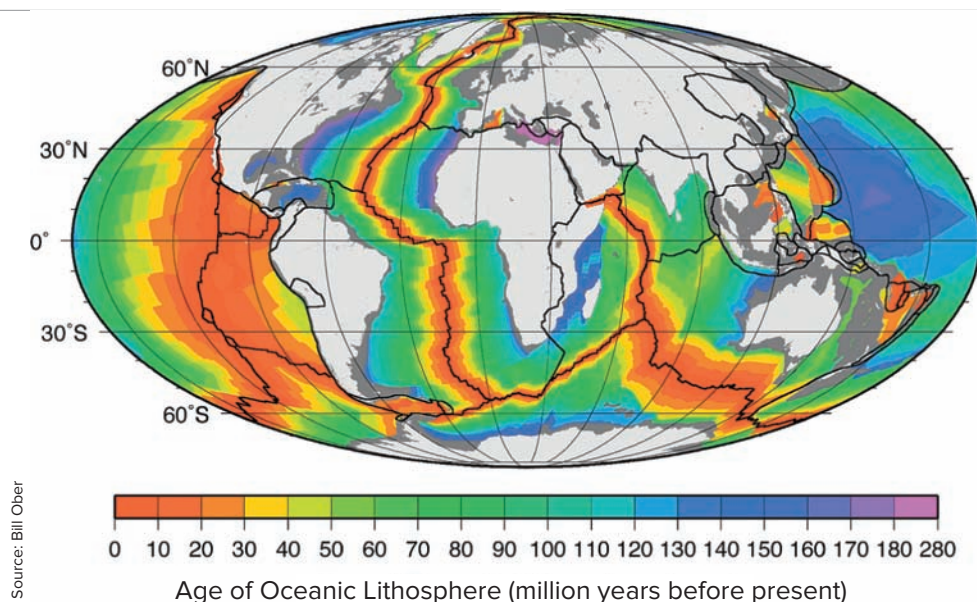


FIGURE 2.9 Examination of the age of sea-floor rocks reveals stripes that parallel the mid-ocean ridges (shown as black lines). The youngest crust (red) is found nearest the ridge, and the oldest (blue) the farthest away. The alternating bands can be correlated to rocks with normal and reversed magnetization; the rocks right at the ridge crest have normal magnetization.

mantle material, or magma, pushes up the oceanic crust around the rift to form the mid-ocean ridge (Fig. 2.10). When this molten material reaches Earth's surface, it cools and solidifies to form new oceanic crust (see the photo at the beginning of the chapter). The process repeats itself as the sea floor continues to move away from the mid-ocean ridge. The entire process of the sea floor moving away from the mid-ocean ridges to create new sea floor is called **sea-floor spreading** (see Fig. 2.10), and the ridges are also called spreading centers.

Sea-floor spreading explains many features of the mid-ocean ridge. Right at the ridge crest the crust is new and has not had time to accumulate sediment. As the crust moves away from the ridge it ages and sediment builds up. This explains why the sediment gets thicker and the rocks get older moving away from the ridge. Sea-floor spreading also explains the pattern of magnetic stripes. As new sea floor is created, it “freezes” the magnetic field prevailing at the time and preserves that magnetization as it moves away from the ridge. Eventually Earth's magnetic field reverses, starting a new stripe.

Sea-Floor Spreading and Plate Tectonics Sea-floor spreading is only part of the story of plate tectonics. Earth's surface is covered by a fairly rigid layer composed of the crust and the uppermost part of the mantle. This layer, averaging about 100 km (60 mi) thick, is called the **lithosphere**, meaning “rock sphere” (see Fig. 2.3). The lithosphere is broken into a number of plates called **lithospheric plates** or **tectonic plates** (Fig. 2.11). Different plates contain continental crust, oceanic crust, or both. The lithosphere floats on a denser, more plastic layer of the upper mantle called the **asthenosphere** with a thin (in geological terms) layer of unusually fluid mantle material in between. While the crust, mantle, and core are distinguished by their chemical composition, the distinction between the lithosphere and the asthenosphere is based on how easily the rock flows.

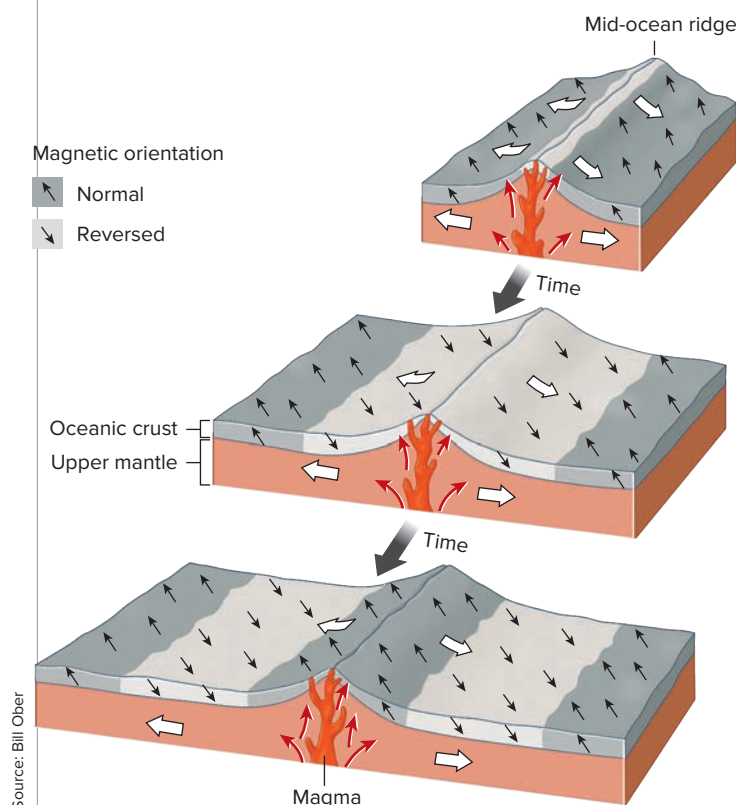


FIGURE 2.10 Cross section of the sea floor at a mid-ocean ridge showing the mechanism of sea-floor spreading. As the sea floor moves away from the rift, molten material rises from the mantle and cools to form new sea floor. When the rocks cool, they “freeze” whatever magnetic orientation, normal or reversed, is present at the time. The entire floor of the ocean was created at the mid-ocean ridge in this manner.

Induction The development of a generalized conclusion from a series of individual observations.

• 1.2, The Scientific Method

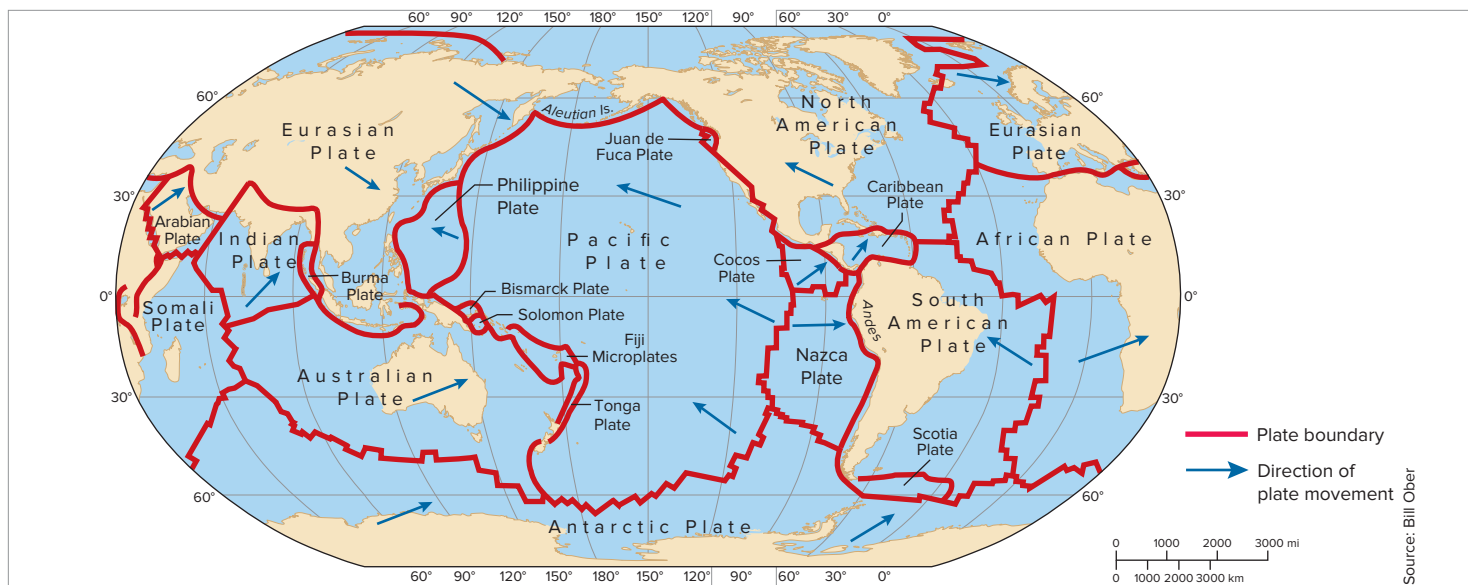


FIGURE 2.11 The division of Earth's surface into lithospheric plates. Some areas are not fully understood, and there are some small plates not shown here. Compare this map with those in Figures 2.5 and 2.8.

Earth's surface is broken up into a number of plates. These plates, composed of the crust and the top part of the mantle, make up the lithosphere. The plates are about 100 km (60 mi) thick.

Mid-ocean ridges form the edges of many plates. Here, the lithospheric plates move apart and new sea floor—that is, new oceanic lithosphere—is created. If the plate includes a block of continental crust, the continent is carried along with the plate as it moves away from the ridge. This is the mechanism of continental drift. The plates spread at around 2 to 18 cm (0.8 to 7 in) per year. For comparison, human fingernails grow at about 6 cm (2.4 in) per year. The spreading rate varies from place to place and over time.

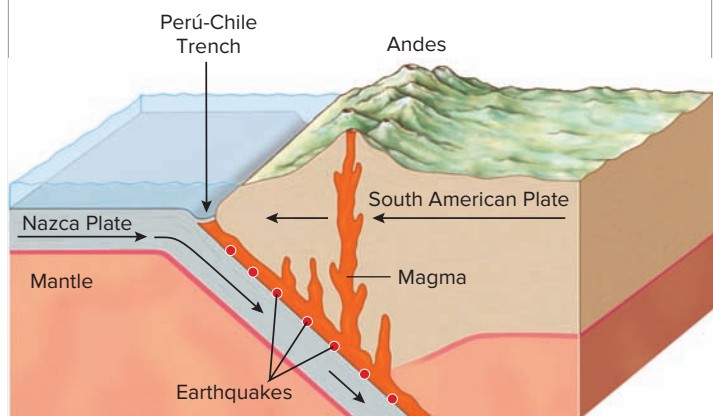


FIGURE 2.12 Some trenches are formed by the collision of continental and oceanic plates. Here, the Nazca Plate dips under the South American Plate. Earthquakes are produced as the plate descends into the mantle. Less dense material from the sinking plate rises to the surface as it melts, creating the volcanic Andes (see Figs. 2.5, 2.6, and 2.8).

As new lithosphere is created, old lithosphere is destroyed somewhere else. Otherwise, Earth would have to constantly expand to make room for new lithosphere. Lithosphere is destroyed at trenches, another main type of plate boundary. A trench is formed when two plates collide and one of the plates dips below the other and sinks back down into the mantle (Figs. 2.12 and 2.13). This downward movement of the plate into the mantle is called **subduction**, and trenches are also called **subduction zones**.

As the plate sinks, it weakens under the heat and pressure of the mantle and begins to break up, causing earthquakes. Eventually the plate gets so hot it melts. Some of the molten material rises back to the surface to form volcanoes. The rest continues to sink into the mantle. Some of this material is probably recycled eventually, rising again to the lithosphere millions of years later.

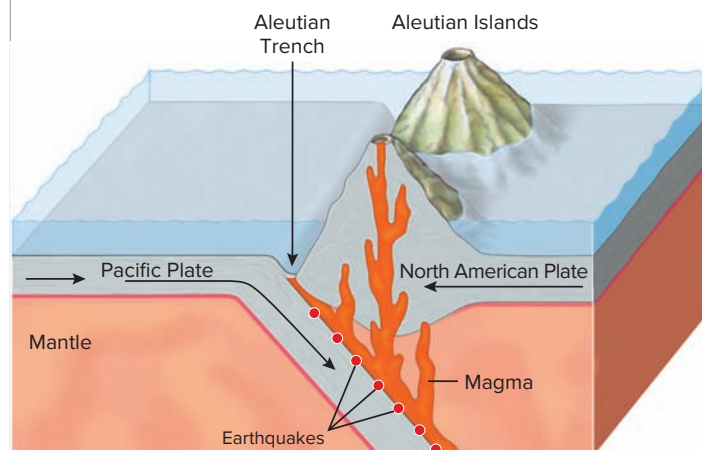


FIGURE 2.13 Trenches can also be caused when two oceanic plates collide. The oceanic portion of the North American Plate has collided with the Pacific Plate. The Pacific Plate dipped below the North American Plate, but either of the two plates might have done so. Earthquakes are produced by the descending plate. The volcanoes associated with the trench produced the Aleutian Island arc (see Figs. 2.5, 2.6, and 2.8).



EYE ON SCIENCE

Box 2.1 Life Below the Sea Floor

You might expect that the deepest-living organisms inhabit the deepest ocean trenches. In fact, life extends deeper—much deeper—than that. Single-celled organisms like bacteria live not only on, but *in* the sea floor, inhabiting deep layers of sediment and even the rocks of the crust. Rich communities of microbes live more than 3 km (1.9 mi) below the sea floor and probably extend to at least 10 km (6.2 mi). They live by **chemosynthesis**, using chemical energy in the rocks. Similar organisms abound on newly formed crust that has just cooled from magma erupting at mid-ocean ridges.

To study this “deep biosphere,” scientists drill deep into Earth’s crust. The drilling, of course, disturbs the microbial communities, but, using ROVs, scientists can install sea-floor observatories over the drill holes that can last a decade. These observatories allow the microbial communities to return to normal and can then make measurements, collect samples, and perform experiments.

This is a relatively new field of research because the tools required, such as ROVs, sea-floor observatories, and genetic biotechnologies, have only recently become available.

In a classic example of how scientific discoveries raise more questions, it appears that some 20 types of microbe occur in the deep crust all over the globe. How they came to be so widely distributed is a mystery.

Until recently microbes were the only life known from deep below the sea floor, but all those microbes are a food source so it is not surprising that worms that appear to feed on deep-Earth microbes were recently discovered up to 3.6 km (2.2 mi) deep in the crust.

Microbes on and below the sea floor not only support food chains but also alter the crust itself, breaking down some minerals and forming new ones. Geologists think that about two-thirds of the 4,300 minerals in Earth’s crust would never have formed if

not for marine microbes. **Photosynthesis** by microbes has had an even greater impact than chemosynthesis. Photosynthesis produces the oxygen in Earth’s atmosphere, and for billions of years microbes dominated oxygen production on Earth. Oxygen has been critical to the formation of minerals in Earth’s crust, since most contain oxygen and are believed not to exist elsewhere in the solar system, where oxygen is not available. In particular, oxygen and energy produced by marine microbes are probably responsible for the formation of granite, the dominant mineral type in continental crust. There is no sign of granite in the rest of the solar system. The production of granite led to the formation and stabilization of the continents. Thus, we may be indebted to primordial marine microbes for the very rocks under our feet.

For more information, explore the links provided in the Marine Biology Online Learning Center.

At trenches, a lithospheric plate descends into the mantle, where it breaks up and melts. This process, called subduction, produces earthquakes and volcanoes.

The collision that produces a trench can be either between an oceanic plate and a continent or between two oceanic plates. When an oceanic plate collides with a continent, it is always the oceanic plate that descends into the mantle. The continental block is less dense than the oceanic plate and floats on top. That is why very old rocks are only found on continents: oceanic crust is continually destroyed at trenches and never gets old by geological standards. Continental crust, on the other hand, is not destroyed in trenches and can last for billions of years.

When oceanic and continental plates collide, continental volcanoes develop behind the trench. These volcanoes may form coastal mountain ranges. The Andes on the Pacific coast of South America are a good example (Fig. 2.12).

The oceanic plate lifts the edge of the continent slightly when it slides down under the continent. As the slab of cold lithosphere sinks deeper in the mantle, however, it tends to drag the interior of the continent down with it. The central part of the continent subsides, sometimes so much that seawater floods in to form shallow seas. After tens of millions of years the continent breaks free of the sinking plate and floats back up to its normal elevation, and the shallow sea disappears. This probably happened in North America when a huge slab of oceanic lithosphere called the Farallon Plate slid under

the west coast. That explains why Denver, Colorado, the “mile-high city,” is surrounded by rocks formed from marine sediments.

When two oceanic plates collide, one of the plates dips beneath the other to form the trench. Again the trench is associated with earthquakes and volcanoes (Figs. 2.13 and 2.14). The volcanoes may rise from the sea floor to create chains of volcanic islands. As viewed on a map, trenches are curved because of Earth’s spherical shape. The volcanic island chains associated with the trenches follow the trenches’ curvature and are called **island arcs**. Examples include the Aleutian and Mariana islands (see Figs. 2.5 and 2.6).

Occasionally two continental plates collide. Because of the relatively low density of continental crust, both plates float and neither is subducted. Therefore, no trench is formed. Instead, the two continental blocks push against each other with such tremendous force that the continents become “welded” together. The force is eventually too much for the rocks, which buckle and fold. The huge folds form mountain ranges. The Himalayas, for example, were formed when India collided with the rest of Asia (see “The Geological History of the Earth,” above).

Chemosynthesis The use by microbes of energy contained in inorganic chemicals rather than sunlight to make organic matter.

• 5.2, Prokaryotes; Table 5.1

Photosynthesis

$\text{CO}_2 + \text{H}_2\text{O} + \text{Sun energy} \rightarrow \text{organic matter} + \text{O}_2$
(glucose)

• 4.1, The Ingredients of Life



FIGURE 2.14 Mount Veniaminof, an active volcano on the Alaska Peninsula. Geologically, the Alaska Peninsula is part of the Aleutian Island chain that has formed behind the Aleutian Trench (see Figs. 2.5 and 2.13).

There is a third type of plate boundary in addition to trenches and mid-ocean ridges. Sometimes two plates slide past each other, neither creating nor destroying lithosphere. This type of plate boundary is called a **shear boundary**. In the crack, or fault, where the two plates move past each other there is immense friction between the plates. This friction prevents the plates from sliding smoothly. Instead they lock, and stress builds up until the plates suddenly break free and slip, causing an earthquake. The San Andreas Fault in California is the largest and most famous example of a shear boundary (Fig. 2.15).

Geologists once thought the most likely explanation for what makes the plates move was **convection**, in which heat from Earth's core causes the mantle to swirl like thick soup heating in a saucepan. They thought the convection currents carried the overlying plates along like icebergs in a current (Fig. 2.16). Mantle convection, however, probably plays only a small part in plate motion. The main cause of plate motion is that as oceanic lithosphere ages and cools, it becomes denser. Eventually it sinks into the mantle, forming a trench and pulling the rest of the plate along behind it. This "slab pull" causes the plates to separate at the mid-ocean ridge, allowing fresh magma to well up from the mantle. The fluid layer at the base of the lithosphere may help "lubricate" this motion. Though not the main driver of plate movement as once thought, the upwelling of mantle at the ridge may help push the plates apart.

Earth's Geological History

Earth's surface has undergone dramatic alterations. The continents have been carried long distances by the moving sea floor, the ocean basins have changed in size and shape, and new oceans have been born.

Continental Drift and the Changing Oceans About 200 million years ago all the continents were joined in the supercontinent Pangaea, just as Wegener proposed. Antarctica was in approximately the same place it is today, but all the other continents were

in different positions (Fig. 2.17a). India was attached to Antarctica and Africa rather than to Eurasia as it is now.

Pangaea was surrounded by a single, vast ocean called **Panthalassa**. Panthalassa, which covered all the rest of the planet, was the ancestor of the modern Pacific Ocean. A relatively shallow sea, the **Tethys Sea**, separated Eurasia from Africa. The Tethys Sea, the precursor of the present-day Mediterranean, was home to many of the world's shallow-water organisms. Another indentation in the coast of Pangaea, the Sinus Borealis, was to become the Arctic Ocean. Before Pangaea began to break up, there was no sign of the modern Atlantic or Indian oceans.

About 180 million years ago, a rift appeared between North America and the combined continents of South America and Africa (Fig. 2.17b). This was the beginning of the Mid-Atlantic Ridge, and its formation marked the birth of the North Atlantic Ocean. Pangaea

was now separated into two large continents. One was **Laurasia**, composed of what is now North America and Eurasia. South America, Africa, Antarctica, India, and Australia made up the southern continent of **Gondwana**.

At around the same time another rift began to split up Gondwana, marking the beginning of the Indian Ocean. South America and Africa began to move to the northeast, and India, separated from the other continents, began to move north.

Some 135 million years ago the South Atlantic was born when a new rift occurred between South America and Africa (Fig. 2.17c). This rift eventually joined the mid-ocean ridge in the North Atlantic to form a single mid-ocean ridge. As the Atlantic Ocean grew, the Americas were carried away from Eurasia and Africa. To make room for the new sea floor produced in the Atlantic, the Pacific Ocean—the descendant of Panthalassa—steadily shrank. The Atlantic is still growing, and the Pacific shrinking.

The Y-shaped ridge that produced the Indian Ocean gradually extended to separate Australia from Antarctica (Fig. 2.17d). The base of the inverted Y extended into the African continent, forming the Red Sea, which is actually a young ocean. India continued to move north faster and faster, reaching speeds of up to 20 cm/yr (8 in/yr) before colliding with Asia (Fig. 2.17e) to create the Himalayas. The Tethys Sea closed up and disappeared as Africa, and then India moved up into Asia. Most of the organisms that once lived in the Tethys Sea are now known only as fossils, although the descendants of a few species still live in the Caspian, Black, and Mediterranean seas.

The continents were once united in a single supercontinent called Pangaea that began to break up about 180 million years ago. The continents have since moved to their present positions.

The breakup of Pangaea to form today's continents is only the most recent turn of a continuing cycle. For hundreds of millions of years the continents have been adrift. They alternately collide and re-form into larger landmasses, only to break up and drift apart again.

Kip Evans/Alamy Stock Photo



FIGURE 2.15 Aerial view of a section of the San Andreas fault on the Carrizo Plain in central California.

The Record in the Sediments We have seen how the increase in sediment thickness away from mid-ocean ridges gave a clue to how plate tectonics works. Marine sediments provide a wealth of other information about Earth's past. The type of sediment on the sea floor often reflects conditions in the ocean above. By studying sediments that were deposited in the past, oceanographers have learned a great deal about the history of our planet.

Most marine sediments are of two basic types. The first is **lithogenous sediment**, which is derived from the physical and chemical breakdown, or **weathering**, of rocks, mostly on the continents. Coarse sediments, which consist of relatively large particles, tend to sink to the bottom rapidly rather than being carried out to sea by currents (see “The Shifting Sediments,” in 11.2). Coarse lithogenous sediments, therefore, are usually deposited near the edges of the continents. Finer material sinks much more slowly and is carried far out to sea by currents. Some is even transported as dust

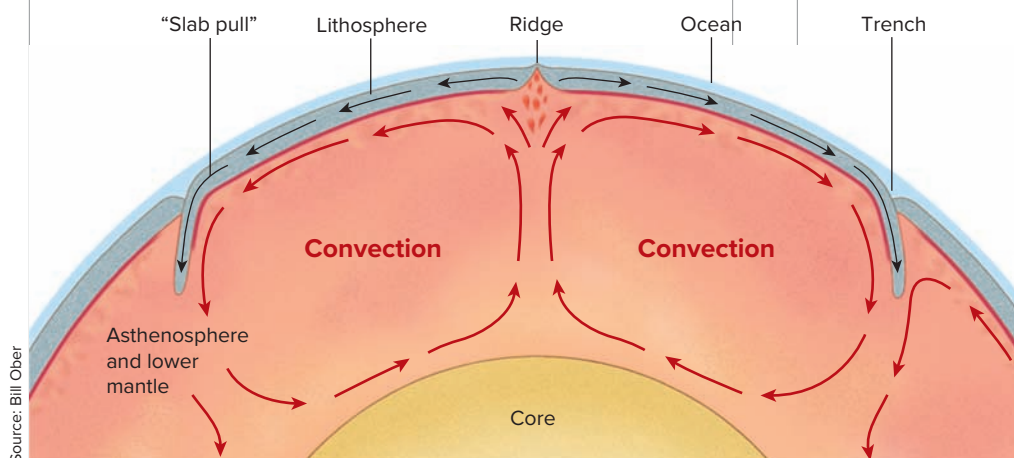
by the wind. The most common lithogenous sediment on the open ocean floor is a fine sediment called **red clay**.

The second major type of marine sediment, **biogenous sediment**, consists of the skeletons and shells of marine organisms, including **diatoms**, **radiolarians**, **foraminiferans**, and **coccolithophorids**. Some biogenous sediments are composed of the mineral **calcium carbonate** (CaCO_3). This type of sediment is called **calcareous ooze**. The other type of biogenous sediment is made of **silica** (SiO_2), which is similar to glass. It is called **siliceous ooze**.

The two most abundant types of marine sediment are lithogenous sediment, which comes from the weathering of rocks on land, and biogenous sediment, which is composed of the remains of marine organisms. Biogenous sediment is primarily either of calcium carbonate or silica.

Though large fossils like whale bones and shark teeth can be found, most of the organisms that produce biogenous sediments are microscopic or nearly so. Such sediment particles are sometimes called **microfossils**, since each particle represents the preserved remains of a dead organism (Fig. 2.18). Microfossils reveal the organisms that lived in the ocean in the past. Some of these organisms are known to prefer cold or warm water, so microfossils also give clues to ancient ocean temperatures. Ocean temperatures are determined by Earth's climate and ocean currents.

Earth's past climate can also be determined by the chemical composition of the microfossils. Various methods including **carbon dating**, a procedure in which the ratios of different atomic forms, or **isotopes**, of carbon are measured, can be used to determine the age of microfossils. It is also possible to tell the temperature of the water in which the organisms lived by measuring the ratios of magnesium (Mg) to calcium (Ca) or of different isotopes of oxygen in the microfossils. Thus, microfossils preserve a detailed record of Earth's climate history. This record isn't always easy to read, but it is supplemented by other information. The ratio of the elements



Source: Bill Ober

FIGURE 2.16 The movement of lithospheric plates was long thought to be driven by large-scale convection currents in the asthenosphere and lower mantle, caused by heat from Earth's core. Today, the prevailing hypothesis is that the plates move mainly because of slab pull, in which old, cold, and dense lithosphere sinks into the mantle and pulls the rest of the plate behind it. It may be this sinking cold rock rather than heat from the core that stirs the mantle. A layer of relatively fluid material at the base of the lithosphere may help the plates slide more easily.

Diatoms Single-celled algae with a shell, or test, made of silica.

• 5.3, Unicellular Algae; Figure 5.6

Coccolithophorids Single-celled algae covered with plates made of calcium carbonate.

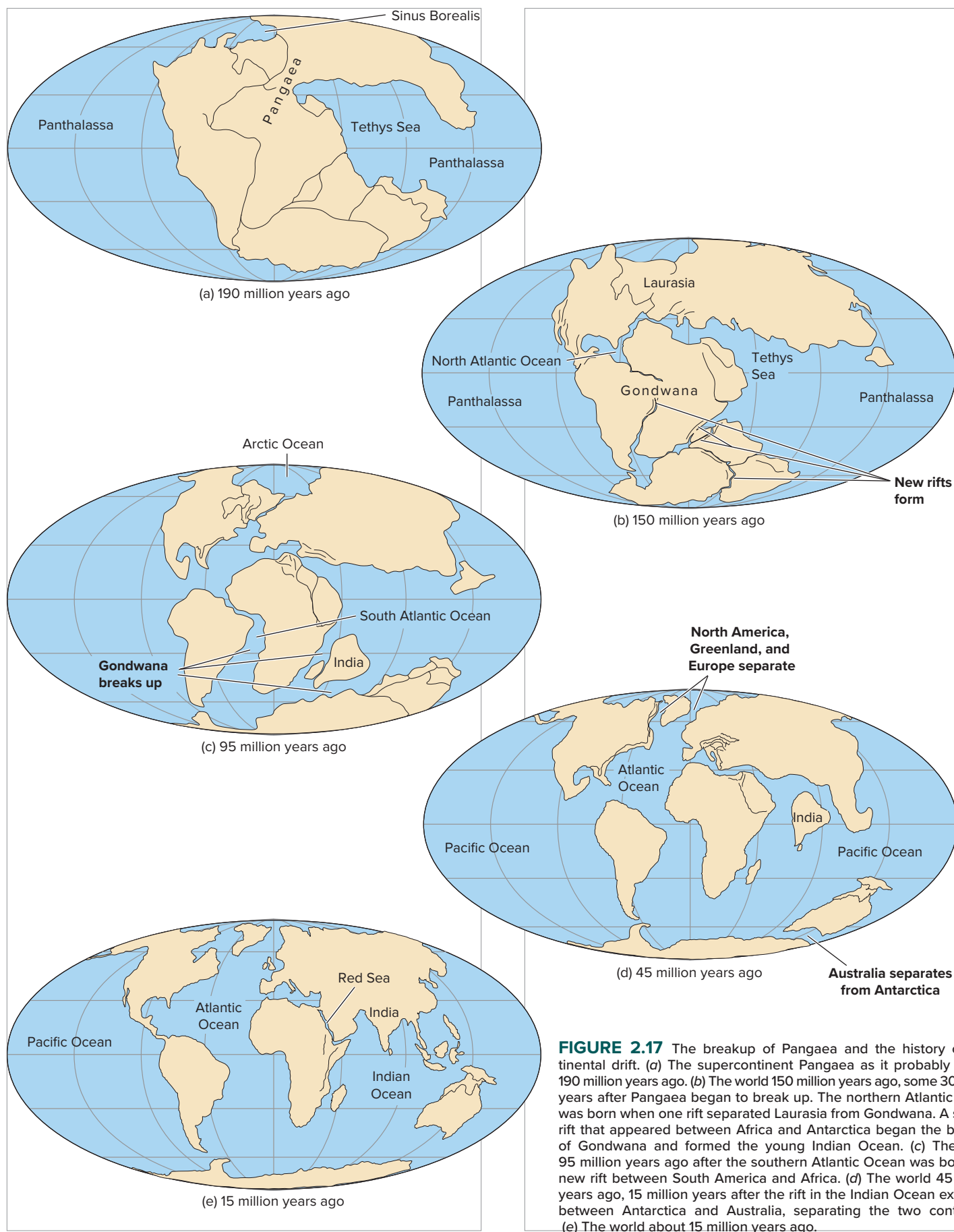
• 5.3, Unicellular Algae; Figure 5.10

Foraminiferans (Forams) Protozoans, often microscopic, with a calcium carbonate test.

• 5.3, Unicellular Algae; Figure 5.11

Radiolarians Single-celled protozoans with a test made of silica.

• 5.3, Unicellular Algae; Figure 5.12



Source: Bill Ober

FIGURE 2.17 The breakup of Pangaea and the history of continental drift. (a) The supercontinent Pangaea as it probably looked 190 million years ago. (b) The world 150 million years ago, some 30 million years after Pangaea began to break up. The northern Atlantic Ocean was born when one rift separated Laurasia from Gondwana. A second rift that appeared between Africa and Antarctica began the breakup of Gondwana and formed the young Indian Ocean. (c) The world 95 million years ago after the southern Atlantic Ocean was born as a new rift between South America and Africa. (d) The world 45 million years ago, 15 million years after the rift in the Indian Ocean extended between Antarctica and Australia, separating the two continents. (e) The world about 15 million years ago.

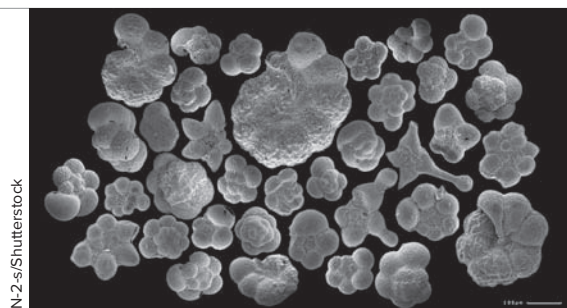


FIGURE 2.18 The fossilized tests of several species of foraminiferans.

strontium (Sr) and calcium in ancient coral skeletons, for example, also records past ocean temperatures. Ice cores from polar areas like Greenland and Antarctica also preserve a record of past temperatures, as well as samples of the ancient atmosphere in the form of tiny bubbles trapped in the ice. These and other studies are providing an increasingly detailed picture of Earth's past climate (see Special Report, Climate Change).

Climate and Changes in Sea Level Earth's climate has fluctuated rhythmically through much of its history, alternating between warm, or **interglacial**, periods and cold periods, or **ice ages** (Fig. 2.19). We are currently in an interglacial period. During ice ages, great glaciers build up on the continents. Because large amounts of water are trapped as ice instead of flowing to the sea in rivers, there is less water in the ocean. Thus, sea level falls during ice ages.

The **Pleistocene Epoch**, which began 2.6 million years ago, was the last major period of glaciation. During the Pleistocene a series of ice ages was interspersed by brief warm periods of melting. The peak of the last ice age occurred about 18,000 years ago, when vast ice sheets as thick as 3 km (2 mi) covered much of North America and Europe. Sea level was about 130 m (425 ft) lower than it is today.

Sea level falls during ice ages because water is trapped in ice on the continents. The last major ice age was about 18,000 years ago.

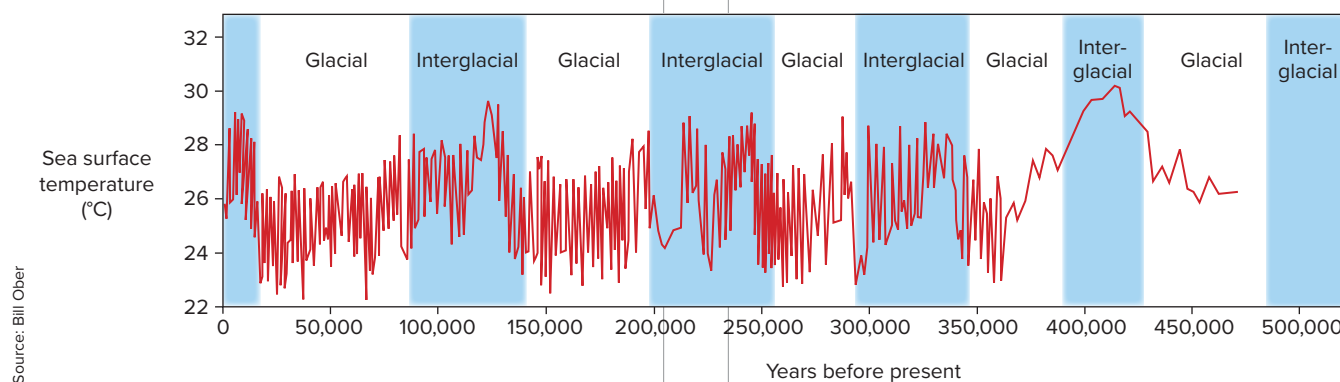


FIGURE 2.19 A history of Earth's climate over the past half-million years as determined from foraminiferan microfossils. The red line shows the average sea surface temperature in the equatorial Pacific Ocean as determined from the magnesium-to-calcium ratio in the microfossils. The white and blue bands indicate major glacial and interglacial periods, respectively, recorded in oxygen isotope ratios. Shifts between ice ages and interglacial periods involve relatively small changes in average temperature.

Sea level continues to rise, though the rate of melting slowed during the past 3,000 years until about 150 years ago. Without human influence, Earth would be entering another ice age. Our impact on the atmosphere, however, has intensified the **greenhouse effect**, the retention of heat in the lower atmosphere as a result of an increase in carbon dioxide and other gases (see Special Report, Climate Change). Global temperatures and glacial melting are now increasing rapidly, and sea level is projected to continue rising for at least the next century. The loss of ice is also causing Earth's crust to warp slightly.

2.3 THE GEOLOGICAL PROVINCES OF THE OCEAN

The structure of the ocean floor is dominated by plate tectonics. Because this is a global process, the major features of the sea floor are quite similar from place to place around the world. The sea floor is divided into two main regions: the **continental margins**, which represent the submerged edges of the continents, and the deep-sea floor itself.

Continental Margins

The continental margins are the boundaries between continental and oceanic crust. Most sediments from the continents settle to the bottom soon after entering the sea and accumulate on the continental margins, where sediment deposits may be up to 10 km (6 mi) thick. Continental margins generally consist of a shallow, gently sloping **continental shelf**, a steeper **continental slope**, and another gently sloping region, the **continental rise**, at the base of the continental slope (Fig. 2.20).

The Continental Shelf The shallowest part of the continental margin is the continental shelf. Though they make up only about 8% of the ocean's sea floor, continental shelves are the biologically richest part of the ocean, with the most life and the best fishing. The shelf is composed of continental crust and is really just the edge of the continent that presently happens to be under water.

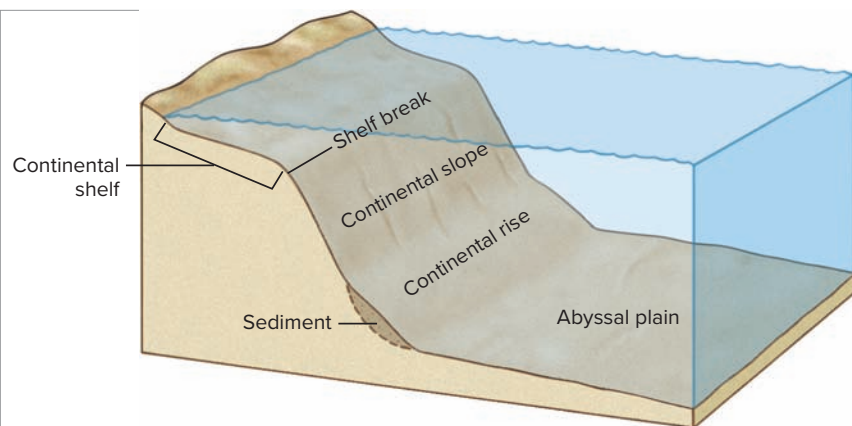


FIGURE 2.20 An idealized continental margin consists of a continental shelf, continental slope, and a continental rise. Seaward of the continental rise lies the deep-sea floor or abyssal plain. These basic features vary from place to place.

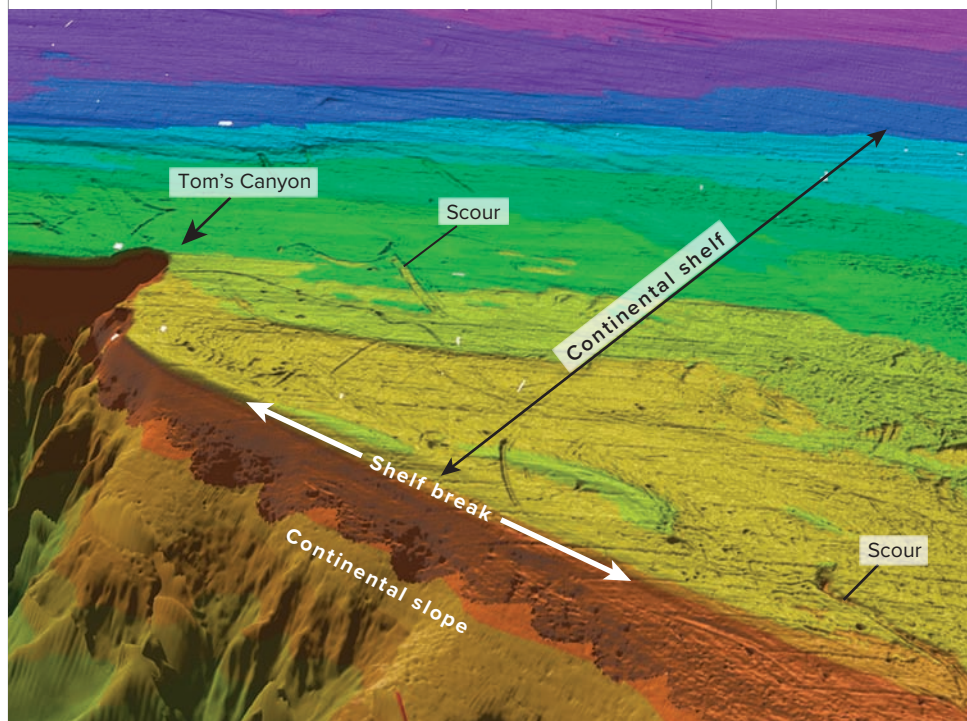


FIGURE 2.21 A section of the continental shelf (upper right) off Atlantic City, New Jersey, approximately 30 km (19 mi) wide. The white arrows indicate the shelf break. The red arrow shows the head of a submarine canyon called Tom's Canyon. The linear marks on the shelf are iceberg scours made during the last ice age. This image was created with a sophisticated form of sonar known as multibeam sonar. The steepness of the continental slope is exaggerated.

During past times of low sea level, in fact, most of the continental shelves were exposed. At these times, rivers and glaciers flowed across the continental shelves and eroded deep canyons. When sea level rose, these canyons were submerged and gave rise to much larger **submarine canyons**.

The continental shelf extends outward at a gentle slope that in most places would be too gradual to see with the naked eye. The shelf varies in width from less than 1 km (0.6 mi) on the Pacific coast of South America and other places to more than 750 km (470 mi) on the Arctic coast of Siberia. The continental shelf ends at the **shelf break**, where the slope abruptly gets steeper (Fig. 2.21). The shelf break

usually occurs at depths of 120 to 200 m (400 to 600 ft) but can be as deep as 400 m (1,300 ft). The precise edge is difficult to define but is of more than academic interest because, under international law, countries have the right to control the resources on their adjacent continental shelves. Recently there has been intense interest in detailed mapping of the continental shelves in the Arctic Ocean, because shrinking Arctic sea ice due to global warming is set to give countries, including Russia, the United States, and Canada, unprecedented access to oil and other Arctic seabed resources—if they can claim them.

The Continental Slope The continental slope is the closest thing to the exact edge of the continent. It begins at the shelf break and descends to the deep-sea floor. Submarine canyons beginning on the continental shelf cut across the continental slope to its base at a depth of 3,000 to 5,000 m (10,000 to 16,500 ft; Fig. 2.22). These canyons channel sediments from the continental shelf to the deep sea.

The Continental Rise Sediment moving down a submarine canyon accumulates at the canyon's base in a deposit called a **deep-sea fan**, similar to a river delta. Adjacent deep-sea fans may merge to form the continental rise. The rise consists of a thick layer of sediment piled up on the sea floor. Sediment may also be carried along the base of the slope by currents, extending the continental rise away from the deep-sea fans.

Continental margins have three main parts. The continental shelf is the submerged part of the continent and is almost flat. The relatively steep continental slope is the actual edge of the continent. The continental rise is formed by sediments building up on the sea floor at the base of the continental slope.

Active and Passive Margins The nature of the continental margin, and therefore of coastal biological habitats, depends to a large extent on the plate tectonic processes occurring in the region. The continent of South America provides a good example of the relationship between the continental margin and plate tectonics (Fig. 2.23). The South American Plate (see Fig. 2.11) consists of both the continent itself and Atlantic sea floor created by the Mid-Atlantic Ridge. South America is carried westward with the plate as new sea floor is created at the ridge. The west coast of South America is colliding with the Nazca Plate, leading to the creation of a trench (see Figs. 2.5 and 2.12). Trenches are zones of intense geological activity, including earthquakes and volcanoes, so this type of continental margin is called an **active margin**. The west coast of North America also has a type of active margin, but it is more complex than that of South America.

Source: Bill Ober

Center for Coastal and Ocean Mapping, University of New Hampshire, courtesy of Larry Mayer

Reprinted by permission of Dr. William Haxby, Columbia University, The Earth Institute

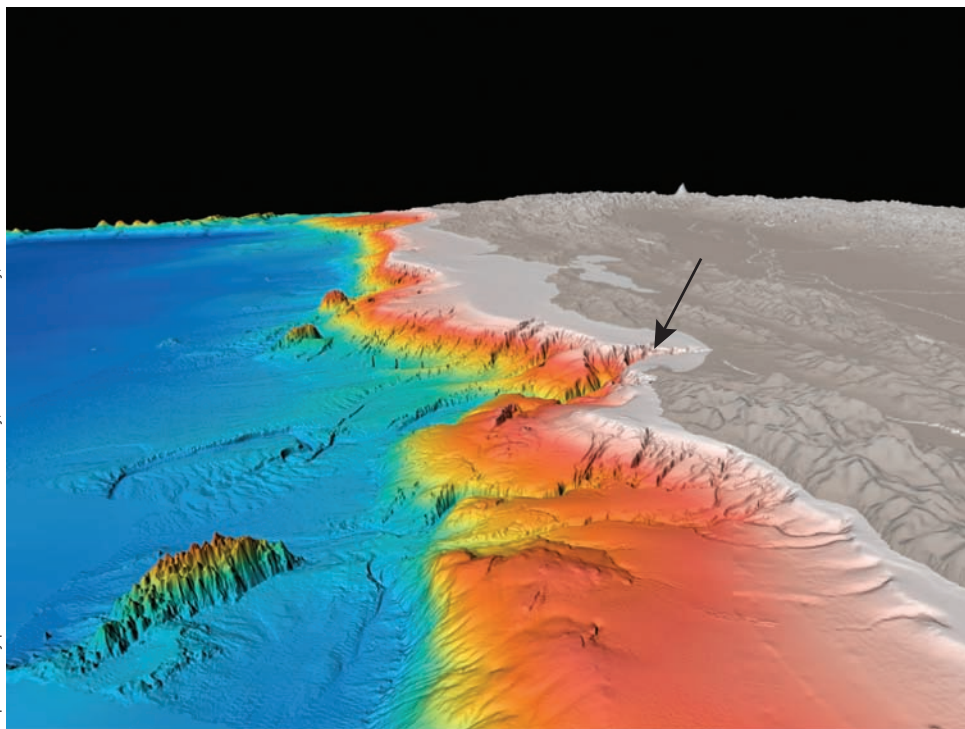


FIGURE 2.22 Multibeam sonar image of the continental margin off California. Numerous submarine canyons cut across the continental shelf and down the continental slope to the deep-sea floor. The largest is Monterey Canyon, which extends nearly to the shore at Monterey Bay (arrow).

As the colliding plate descends into the trench, some of the sediment gets scraped off, folded, and “plastered” onto the continental margin. The edge of the continent is lifted by the oceanic plate passing below (see “Sea-Floor Spreading and Plate Tectonics,” above), and the coast is built up by volcanoes. These processes give active margins steep, rocky shorelines, narrow continental shelves, and steep continental slopes. Because the sediments at the base of the continental slope are either carried down into the trench or scraped onto the continent, active margins usually lack a well-developed continental rise.

South America’s east coast, on the other hand, is not a boundary between plates and is therefore relatively inactive geologically. The continental margin here can be thought of as the trailing edge left when South America separated from Africa. This type of margin is called a **passive margin**. Passive margins typically have flat coastal plains (Fig. 2.24), wide shelves, and relatively gradual continental slopes. Because there are no tectonic processes to remove it, sediment accumulates at the base of the continental slope. Passive margins therefore usually have a thick continental rise.

Active continental margins have narrow shelves, steep slopes, and little or no continental rise. Passive margins have wide shelves, relatively gentle slopes, and a well-developed rise.

Deep-Ocean Basins

Most of the deep-sea floor lies at a depth of 3,000 to 5,000 m (10,000 to 16,500 ft), averaging about 4,000 m (13,000 ft). The deep-sea floor, or **abyssal plain**, rises at a very gentle slope of less than 1° toward the mid-ocean ridge. Though relatively flat, it often

has submarine channels, low **abyssal hills**, plateaus, rises, and other features. The abyssal plain is also dotted with volcanic islands and submarine volcanoes called **seamounts**. Distinctive flat-topped seamounts called **guyots** are common in parts of the Pacific. Guyots and many other seamounts were once islands, but are now several hundred meters beneath the sea surface because the lithosphere has sunk into the mantle under the weight of the island, and also because sea level has risen. The abyssal plain and seamounts support a tremendous variety of marine life (see Box 16.2, “Biodiversity in the Deep Sea”).

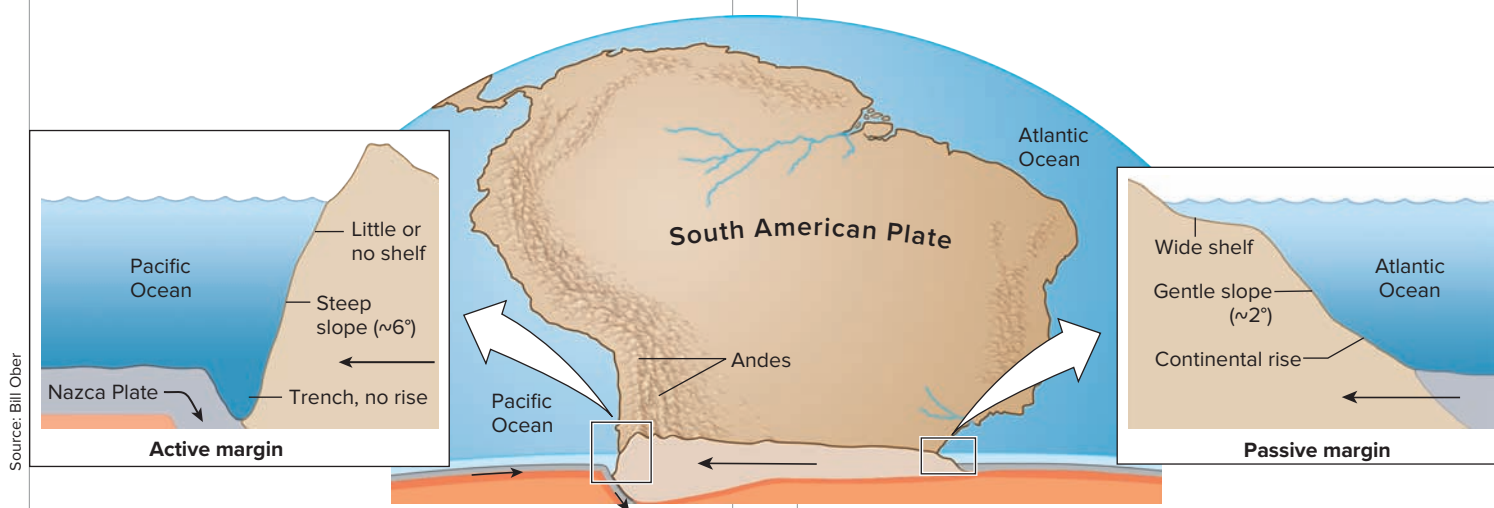


FIGURE 2.23 The opposite sides of South America have very different continental margins. The leading edge, or west coast, is colliding with the Nazca Plate. It has a narrow shelf and steep slope, and a trench rather than a continental rise. The trailing edge—that is, the Atlantic coast—has a wide shelf, a relatively gentle continental slope, and a well-developed continental rise. The steepness of all the slopes is exaggerated for illustrative purposes. Compare this with the map in Figure 2.5.