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Tom **Garrison** | Robert **Ellis**

ESSENTIALS OF Oceanography

EIGHTH EDITION

Essentials of Oceanography

8e


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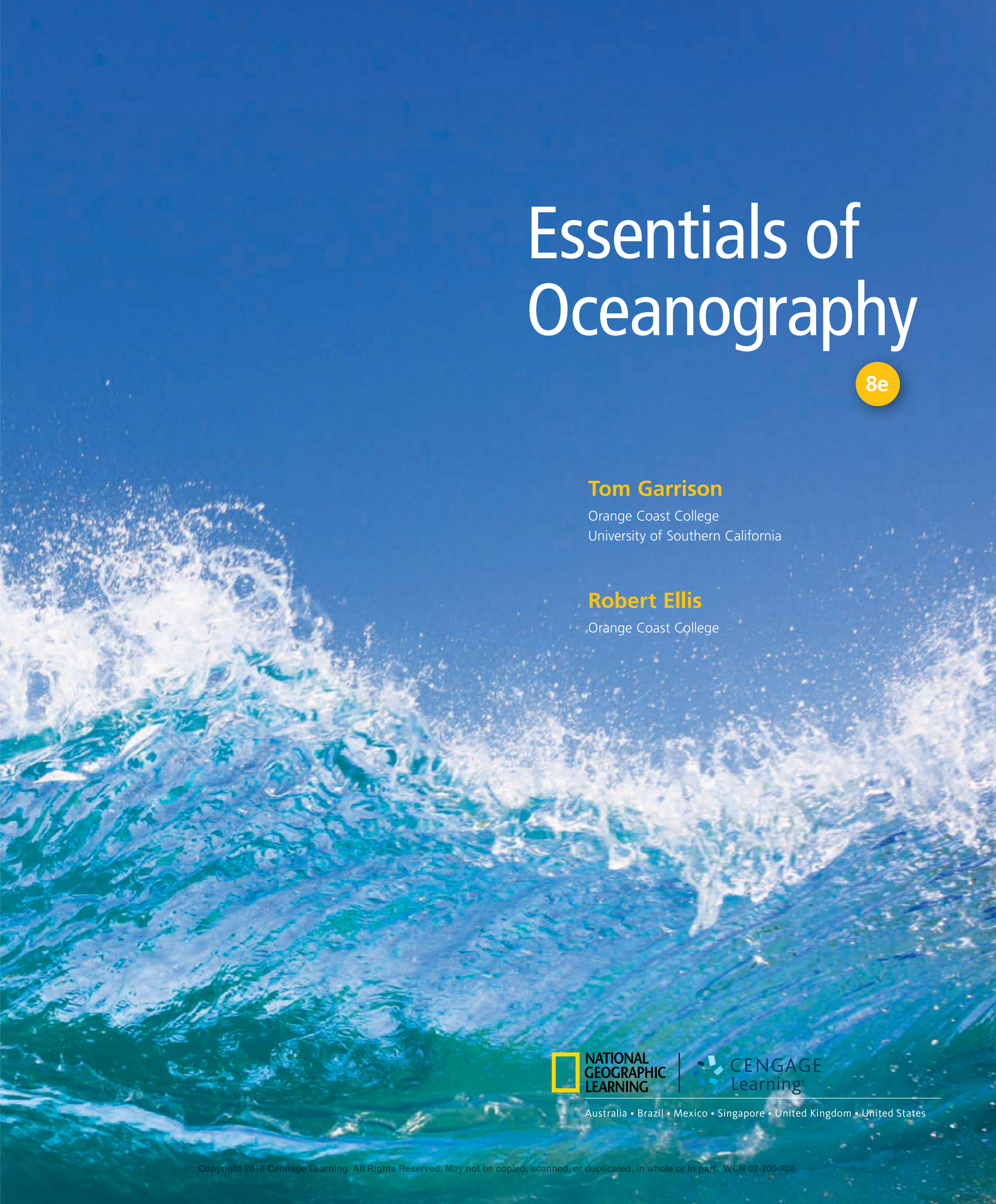

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Tom Garrison
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To our families and our students,
our hope for the future

About the Authors

Hank Schellengerhaut, Orange Coast College PR department

Tom Garrison (PhD, University of Southern California) was an inspiring professor of Marine Science for over 47 years at Orange Coast College (OCC) in Costa Mesa, California, one of the largest undergraduate marine science departments in the United States. Dr. Garrison also held an adjunct professorship at the University of Southern California. He was named the country's Outstanding Marine Educator by the National Marine Technology Society, was a founding member of COSEE, wrote a regular column for the journal *Oceanography*, and enjoyed writing for *National Geographic* magazine. He was a winner of the prestigious Salgo-Noren Foundation Award for Excellence in College Teaching, and in 1992, 1993, and 1997 was a recipient of the University of Texas NISOD award in recognition of his outstanding contributions in teaching and learning. In 1997, students and faculty at Orange Coast College elected him Faculty Member of the Year. He served as a grants judge for the National Science Foundation in Washington, DC. Dr. Garrison was an Emmy Award team participant as writer and science advisor for the PBS syndicated *Oceanus* television series, and was writer and science advisor for *The Endless Voyage*, a set of television programs in oceanography completed in 2003. His widely used textbooks in oceanography and marine science are the college market's best sellers. In 2009, the faculty of OCC selected Dr. Garrison as the institution's first Distinguished Professor, and in 2010, he was honored by the Association of Community College Trustees as the outstanding community college professor in western North America.

His interest in the ocean dates from his earliest memories. As he grew up with a U.S. Navy admiral as a dad, the subject was hard to avoid! He had the good fortune to meet great teachers who supported and encouraged this interest. Years as a midshipman and commissioned naval officer continued the marine emphasis; graduate school and 42 years of teaching allowed him to pass his oceanic enthusiasm to more than 65,000 students in his career. He retired from full-time professoring in 2011; however, he bothered OCC staff and students on a regular basis right up until his final days.

Dr. Garrison traveled extensively and served as a guest lecturer at the University of Hong Kong, the University of Tasmania (Australia), and the National University of Singapore. He was married to an astonishingly patient lady for nearly 50 years, and had a daughter who teaches in a local public school, a diligent son-in-law, three astonishingly cute granddaughters and a grandson, and a son who, along with his fashionista wife, works in international trade. He and his family lived in and around Newport Beach, California. To most, he was known as Dr. Garrison, the inspiring and enthusiastic professor of marine science, but to a select few he was known as Papa and will forever be remembered as a loving friend, grandpa, dad, and husband.

©Robert Ellis

Robert Ellis (M.E.S.M., University of California, Santa Barbara) has been teaching marine, earth, and environmental science courses in both the classroom and the field since 2000. He currently serves as Assistant Professor in the Marine Science Department at Orange Coast College in southern California. When not on campus, Robert often helps to develop and teach international field courses in marine science and management in various parts of the Caribbean, Central America, and South Pacific. His graduate work focused on Marine Resource Management at UC Santa Barbara, and he has participated in and managed research projects and educational programs in many parts of the world. He hopes to have the good fortune to continue to travel and explore the world with his wife, Katie, son, Kalen, and daughter, Abigail.

Brief Contents

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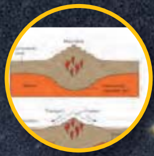


Preface

The Eighth Edition

Our aim in writing this book was to produce a text that would enhance students' interest in the ocean. Students bring a natural enthusiasm to their study of this subject, an enthusiasm that is greatly enhanced by our partnership with the National Geographic Society. Access to 125 years of archival resources make this National Geographic Learning text uniquely appealing. The most indifferent lecture hall occupant will perk up when presented with stories of encounters with huge waves, photos of giant squid, tales of exploration under the best and worst of circumstances, evidence that vast chunks of Earth's surface slowly move, news of Earth's past battering by asteroids, micrographs of glistening diatoms, and data showing the growing economic importance of seafood and marine materials. If pure spectacle is required to generate an initial interest in the study of science, oceanography wins hands down!

In the end, however, it is subtlety that triumphs. Studying the ocean reinstills in us the sense of wonder we all felt as children when we first encountered the natural world. There is much to tell. The story of the ocean is a story of change and chance—its history is written in the rocks, the water, and the genes of the millions of organisms that have evolved here.

Our students have been involved in this book from the very beginning—indeed, it was their request for a readable, engaging, and thorough text that initiated the project a long time ago. Through the years we have been writing textbooks, our enthusiasm for oceanic knowledge has increased (if that is possible), forcing our patient reviewers and editors to weed out an excessive number of exclamation points. But that enthusiasm does shine through. One student reading the final manuscript of an earlier edition commented, "At last, a textbook that does not read like stereo instructions." Good!

As were its predecessors, this new edition is designed for students who are curious about Earth's largest feature, but who may have little formal background in science. Our goal is to use unintimidating, yet accurate language to create a narrative that showcases many of the wonders of the ocean and use these examples to explain how they relate to important scientific concepts.

The Plan of This Book

This new edition builds on the established successes of past editions. National Geographic resources have been instrumental in the book's focus on the *processes* of science and exploration. Decades of original art, charts and maps, explorers' diaries, data compilations, artifact collections, and historic photographs have been winnowed and included when appropriate.

Oceanography (also called *marine science*) is broadly interdisciplinary. As always in our books, connections between disciplines are emphasized throughout. Marine science draws on several fields of study, integrating the work of specialists into a unified whole. For example, a geologist studying the composition of marine sediments on the deep seabed must be aware of the biology and life histories of the organisms in the water above, the chemistry that affects the shells and skeletons of the creatures as they fall to the ocean floor, the physics of particle settling and water density and ocean currents, and the age and underlying geology of the study area. This book is organized to make those connections from the first. Readers are invited to see the connections between astronomy, economics, physics, chemistry, history, meteorology, geology, and ecology—areas of study they may once have considered separate.

Notable Changes to This Edition

This eighth edition of *Essentials of Oceanography* contains a number of substantial changes from the seventh edition. We have significantly streamlined this edition to remove excessive details that can distract students from key concepts. To accomplish this, we have tried to distill complex marine features and processes into a truly "essentials only" textbook that is appropriate for a wide range of students. An underlying goal of this edition was to focus on concise writing. Many of the interesting, but nonessential technical details, past student questions, explorer insights, and the detailed information boxes have been removed so that students can focus on the content without interruptions to the narrative flow.

This edition has a total of 11 chapters compared with the 15 chapters that were in the seventh edition. This allows instructors to cover one chapter a week and still leave time for introductions, exam days, and class activities during the term. We believe these changes result in a student-centered book that illustrates the complexity and beauty of the ocean while making it more economical and therefore accessible to a wider range of students.

Each chapter has been extensively revised to update the content and enhance its presentation with new figures. *Chapter 1: An Ocean World* is a combination of the key components of the seventh edition's first two chapters (Earth and Ocean and A History of Marine Science). The material has been streamlined and unified into a single chapter that describes the Earth's origin and the process by which marine scientists are able to study the ocean. Additional information that reflects our changing understanding of the source of the oceans has also been added. *Chapter 2: Plate Tectonics* has been streamlined and reorganized to put the focus of the chapter on how plate tectonics has shaped ocean features while limiting the historical account of our evolving understanding of Earth's geology. *Chapter 3: The Ocean Floor* is a new chapter that combines material from the previous edition's chapters Ocean Basins and Ocean Sediments. This chapter emphasizes the key features of the seafloor and couples it with the role marine sediments play in our understanding of marine processes.

The next few chapters focus on physical oceanography. *Chapter 4: Water and Ocean Structure* has been revised to improve the flow. It presents a survey of ocean physics and chemistry in preparation for future discussions of atmospheric circulation, classical physical oceanography, and coastal processes. Additional examples have been added and sections that we have found to confuse past students have been rewritten to clarify and emphasize the main points. *Chapter 5: Atmospheric Circulation* has significant changes to the discussion of the Coriolis effect and focuses on more recent storms that students can better relate to. *Chapter 6: Ocean Circulation* incorporates a new example to help understand Ekman spirals and adds a discussion on the 2015–2016 El Niño. *Chapter 7: Waves and Tides* combines two chapters that previously described these topics separately. The previous edition's chapters have been streamlined to focus attention on the similarities and differences among all types of waves and clarify some of the concepts to improve student understanding. *Chapter 8: Coasts* contains new information on sea level rise and a number of new and updated figures to better illustrate the diversity of coasts in different areas of the world.

Our look at marine biology begins with an overview of the problems and benefits of living in seawater, continues with a discussion of the production and consumption of food, and ends with taxonomic and ecological surveys of marine communities. *Chapter 9: Life in the Ocean* begins with a section discussing how life is tied to the ocean. This is a revised section from the previous edition's first chapter that broadens the chapter's discussion and improves the book's overall flow. New figures help to illustrate key concepts. *Chapter 10: Marine Communities* is a new chapter that combines material from the previous edition's chapters Pelagic Communities and Benthic Communities. This information has been significantly reorganized and revised to allow the reader to explore a few of the most interesting and important marine communities and to profile some of their most common organisms. There are a number of new figures and information in this chapter to help students appreciate the diversity and complexity of marine life in the ocean. The last chapter, *Chapter 11: Uses and Abuses of the Ocean*, surveys marine resources and environmental concerns, and illustrates how our present rates of economic growth and environmental degradation are unsustainable. Many of the statistics and figures have been updated to better reflect how humans are impacting the marine environment.

As before, a great many students have participated alongside professional marine scientists in the writing and reviewing process. We have responded to their recommendations, as well as those of instructors who have adopted previous editions of this book. It is our sincere hope that the resulting work accurately reflects the present state of our fast-moving field of science.

Organization and Pedagogy

A broad view of marine science is presented in 11 chapters, each free-standing (or nearly so) to allow an instructor to assign chapters in any order he or she finds appropriate. Each chapter begins with a list of the **four or five most important concepts** highlighted by a small illustration. An engaging chapter opener photo and caption whets the appetite for the material to come.

The chapters are written in an **engaging style**. Terms are defined and principles are developed in a straightforward manner. Some of the more complex ideas are initially outlined in broad brushstrokes; then the same concepts are discussed again in greater depth after the reader has a clear view of the overall situation. When appropriate to their meanings, the derivations of words are shown. **Measurements** are given in both metric (SI) and American systems. At the request of a great many students, the units are written out (that is, we write *kilometer* rather than *km*) to avoid ambiguity and for ease of reading.

We have modified the **illustration program** to incorporate National Geographic Society assets. The maps, charts,

©Robert Ellis

A group of students learn navigational techniques before setting sail.

Learning about the ocean involves close contact, and often great fun.

paintings, and photographs drawn from Society archives have greatly enhanced the visual program for increased clarity and accuracy. **Heads and subheads** are written as complete sentences for clarity, with the main heads sequentially numbered.

Each chapter ends with an array of study materials for students, beginning with **Chapter in Perspective**, a narrative review of the chapter just concluded. Important **Terms and Concepts to Remember** are listed next; these are also defined in an extensive **Glossary** in the back of the book. **Study Questions** are also included in each chapter; writing the answers to these questions will cement your understanding of the concepts presented.

Appendixes will help you master measurements and conversions, geological time, absolute and relative dating, latitude and longitude, and chart projections. In case you'd like to join us in our life's work, Appendix 6 discusses **jobs in marine science**.

This book has been thoroughly **student tested**. You need not feel intimidated by the concepts—this material has been mastered by students just like you. Read slowly and go step-by-step through any parts that give you trouble. Your predecessors have found the ideas presented in this book to be useful, inspiring, and applicable to their lives. Best of all, they have found the subject to be *interesting*!

Instructor Resources

Cognero Test Bank

Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to:

- Author, edit, and manage test bank content from multiple Cengage Learning solutions

Father, son, ocean—learning marine science is a joy at any age.

- Create multiple test versions in an instant
- Deliver tests from your learning management system (LMS), your classroom, or wherever you want

Instructor's Companion Site

Everything you need for your course in one place! This collection of book-specific lecture and class tools is available online via www.cengage.com/login. Access and download PowerPoint presentations, images, instructor's manual, videos, and more.

Student Resources

Earth Science MindTap for *Essentials of Oceanography*

MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center Web site, a course delivery platform, or an LMS. More than 70% of students surveyed said that it was unlike anything they have ever seen before. MindTap is a new personal learning experience that combines

©Robert Ellis

A marine science student finds a peaceful place to study on a crisp morning in British Columbia.

all of your digital assets—readings, multimedia, activities, and assessments—into a singular learning path to improve student outcomes.

Global Geoscience Watch

Updated several times a day, the Global Geoscience Watch is an ideal one-stop site for current events and research projects for all things geoscience! Broken into the four key areas (geography, geology, meteorology, and oceanography), you can easily find the most relevant information for the course you are taking.

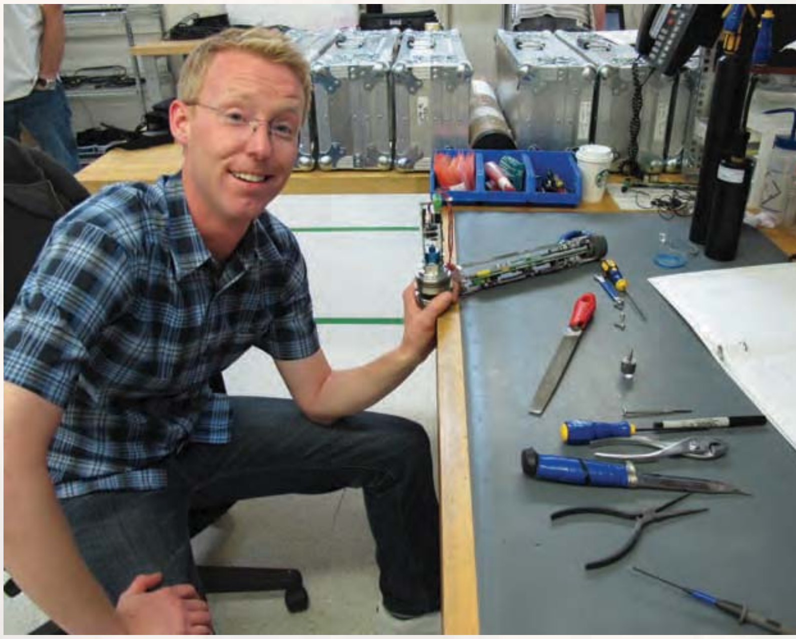
You will have access to the latest information from trusted academic journals, news outlets, and magazines. You will also receive access to statistics, primary sources, case studies, podcasts, and much more!

Acknowledgments

Many, many years ago, Jack Carey, the grand master of college textbook publishing, willed the first edition of this book into being. His suggestions have been combined with those of more than 1,400 undergraduate students and 175 reviewers to contribute to my continuously growing understanding of marine science. Donald Lovejoy, Stanley Ulanski, Richard Yuretich, Ronald Johnson, John Mylroie, and Steve Lund at the University of Southern California deserve special recognition for many years of patient direction. For this edition, we have especially depended on the expert advice of Wayne Henderson, Kurt Bretsch, Todd Benedict, Anne Gasc, Deborah Friele, Sammy Castonguay, Elizabeth Keddy, Stephen MacAvoy, and Ursula Quillman.

Our long-suffering departmental colleagues Karen Baker, Mary Blasius, Rip Profeta, Dennis Kelly, Don Johnston, Jesus Reyes, Julie Oswald, Lisa Snyder, Joana Tavares-Reager, and our division coordinator, JP Nguyen, again should be awarded medals for putting up with us, answering hundreds of our questions, and being so forbearing through the book's lengthy gestation period. Thanks also to our dean, Tara Giblin, and our college president, Dennis Harkins, for supporting this project and encouraging our faculty to teach, conduct research, and be involved in community service. Our past and present department teaching assistants and student aquarium managers deserve a great deal of praise for helping us develop new educational materials and maintain a positive learning environment for our students, especially Brian Schneiderman, Hannah Rodnunsky, Zane Calendine, Brynne McNabb, Jazmin Eck, Meghan Thompson, Megan Vandewalle, Jillian Demeter, David Krueger, Brittany Rodriguez, Carolynn Rohwer, Tammy Schofield, Casey Moore, Samantha Garcia, Michal Biggerstaff, Leslie Portugal, Jessey Luis, and Jack Bassham.

Yet another round of gold medals should go to our families for being patient (well, *relatively* patient) during those years of days and nights when we were holed up in our respective dark reference-littered caves again working late on "The Book." Thank you, Marsha, Jeanne, Greg, Grace, Sarah, John, Dinara, Alem, Alia, Katie, Kalen, and Abigail for your love and understanding. The many friends and colleagues whom we have bounced ideas off deserve special recognition including Karen Baker, Mary Blasius, Erik Bender, Jim Schneider, Kelli Elliott, Jan Goerrissen, Nick Contopoulos, Jerome Fang, Jenell Schwab, Mary Arbogast, Joana Tavares-Reager, Chris Krajacic, Sarah Sikich, and Andy Balendy.



©Tom Garrison

A marine technician assembles a sensor. Most oceanographic data are collected by remote sensors like this one.

A tourist photographs the steerboard of a restored Viking longship. "Steerboard" became "starboard," the right side of a vessel.

Kayaking in the crystal-clear waters of the tropics can provide relaxation for the entire family.

Despite a severe California drought, these supratidal plants are sustained by heavy morning fogs.

The Cengage Learning team performed the customary miracles. The charge was led by Lauren Oliveira, who helped polish the chapters. Sheila Higgins, our copy editor, saved us from many errors. Christine Myaskovsky and Nick Barrows worked tirelessly to assist us in photo research and permissions, and Carol Samet was in charge of production. Kellie Petruzzelli and Lauren Oliveira kept the digital world in line for the book's Web site. The amazing Dawn Giovanniello and Morgan Carney kept us all running in the same direction. What skill!

My unending thanks to all.

A Goal and a Gift

The goal of all this effort: *To allow you to gain an oceanic perspective. Perspective* means being able to view things in terms of their relative importance or relationship to one another. An oceanic perspective lets you see this misnamed planet in a new light and helps you plan for its future. You will see that water, continents, seafloors, sunlight, storms, seaweeds, and society are connected in subtle and beautiful ways.

The ocean's greatest gift to humanity is intellectual—the constant challenge its restless mass presents. Let yourself be swept into this book and the class it accompanies. Give yourself time to ponder: "Meditation and water are wedded forever," wrote Herman Melville in *Moby Dick*. Ask questions of your instructors and TAs, read some of the references, try your hand at the questions at the end of the chapters.

Be optimistic. Take pleasure in the natural world. Please write to me when you find errors or if you have comments. Above all, *enjoy yourself!*

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©Zak Noyle/A-Frame

Trash in the surf in Java, southern Indonesia. Residents dump their waste in rivers that lead to the sea.

In Loving Memory of Dr. Tom S. Garrison

From a daughter to her dad—From a student to her teacher

On February 24, 2016, Dr. Garrison, my dad, passed away after a long battle with Lymphoma.

To quote my dad's idyllic professor, Earl Pullius, USC, "A teacher is many things...a guide, a model, a modernizer, a searcher, a student, a counselor, and a friend. A teacher is a creator, a doer of routine, a storyteller, and a builder of community. A teacher is a way of being." My dad was the embodiment of this quote. He realized the impact he had on his students, not just in teaching the subject of marine science, but in setting students on the right course by exemplifying the different roles of a teacher, just as Dr. Pullius emphasized.

My dad saw the potential in us all. He called us all "Masters of the Universe." He made all of us want to be better and he made us want to continue growing and pushing forward for the rest of our lives. He celebrated so many victories with *me* and always guided *me* forward when *I* needed it the most, as he did with all his students. As a teacher, my dad was a master at sucking you in to the material through the magic, the mystery, and the astonishing power of his stories and then guiding you on a path that would lead you to exactly where you needed to be. It was then that he would stop and watch you walk ahead, confidently, into your future.

My dad always told me that the most important goal of anyone's life is to be happy. He defined happiness as a state of peace, satisfaction, and friendship. He said it comes from having the education to see the connections between things,

the stability to have meaningful relationships, the ability to get and hold a job, and the desire to make a difference in the world. He always said that Thomas Jefferson was amazingly insightful in basing his vision for a new country on the pursuit of happiness. Not a guarantee, mind you, but the assurance of freedom to pursue whatever you wanted. He also reminded me that there would be hard times and I would need to weather the storms of my own doubts. He encouraged me, as he did with all his students, and was always confident in our abilities to succeed.

He explained to me that teaching is the immortal profession because you have the ability to inspire students long after you're gone. My dad still lives on in me, as I hope he will in all of you. His personality shines through in his textbooks. Growing up, I have fond memories of him sitting at his desk at all hours of the night, listening to classical music and writing. His hope was to pass on his joy, his love of learning, and his knowledge of the ocean to the world. He was a distinguished professor, a world-renowned author, an endearing husband, and a beloved father and friend. He made a difference! I hope he will continue to inspire you to achieve your fullest potential. He told me regularly, "There is much good in this world, go and add to it." This was his motto, along with *citius*, *altius*, *fortius*—faster, higher, stronger. He dedicated his life to his family, his friends, and his students. He wants all of us to know that *we* are his hope for the future. He wants us to find what makes us truly happy and then race, unwaveringly, toward it.

Do as Tennyson suggests in his Ulysses: *To strive*, *to seek*, *to find*, *and not to yield.*

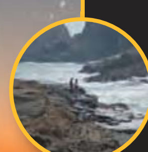
1 An Ocean World

KEY CONCEPTS

The world ocean is Earth's largest surface feature, covering 70.8% of its area. Due to its enormous size, the ocean influences many aspects of life on the planet.

Science is a systematic process of asking questions about the observable world by gathering and then analyzing information.

The materials that formed the Earth and ocean were constructed during the life cycle of stars.



Water vapor from volcanic outgassing and water delivered to Earth during impacts are the most likely sources of the water in Earth's ocean.

Past and current scientific investigations have helped us better understand the ocean's integral role of supporting and influencing life on Earth.

Nearby stars shine over the ocean as the sun begins to rise in Los Cabos, Mexico. Earth, its ocean, and all of its inhabitants were formed by unimaginable energies across enormous spans of time. Our story begins here, with the stars.
Kenneth_Wilson/Getty Images

1.1 Earth Is an Ocean World

This is a book about the dominant surface feature of a poorly named planet. "Earth" seems a strange name for our home world, 71% of which is covered by an ocean of water.

Traditionally, we have divided this ocean into artificial compartments called *oceans* and *seas*, using the boundaries of continents and relative position on the planet. In fact, the ocean has few dependable natural divisions—only one great mass of water. The Pacific and Atlantic oceans, the Mediterranean and Baltic seas, so named for our convenience, are in reality only temporary features of a single **world ocean**.[1] In this book we refer to the ocean *as a single entity*, with subtly different characteristics at different locations and very few natural partitions. Such a view emphasizes the interdependence of ocean and land, life and water, atmospheric and oceanic circulation, and natural and human-made environments (**Figure 1.1**).

The *ocean* may be defined as the vast body of saline water that occupies the depressions of Earth's surface. On a *human* scale, the ocean is impressively large—it covers 331 million square kilometers (128 million square miles).[2] Its average temperature is a cool 3.9°C (39°F). The average land elevation is only 840 meters (2,756 feet), but the average ocean depth is 4½ times greater! More than 97% of the water on or near Earth's surface is contained in the ocean; only about 2.5% is held in land ice, groundwater, and all the freshwater lakes and rivers. If all Earth's surface water were gathered into a sphere, its diameter would measure only 1,380 kilometers (860 miles) (**Figure 1.2**). The ocean borders most of Earth's largest cities—nearly half of the planet's 7+ billion human inhabitants live within 240 kilometers (150 miles) of a coastline.

[1] When an important new term is introduced and defined, it is printed in boldface type. These terms are listed at the end of the chapter and are defined in the Glossary.

[2] Throughout this book, SI (metric) measurements precede U.S. measurements. For a quick review of SI units and their abbreviations, please see Appendix 1.

On a *planetary* scale, however, the ocean is insignificant. Its average depth is a tiny fraction of Earth's radius—the blue ink representing the ocean on an 8-inch paper globe is proportionally thicker. The ocean accounts for only slightly more than 0.02% of Earth's mass, or 0.13% of its volume. Much more water is trapped within Earth's hot interior than exists in its ocean and atmosphere.

Regardless of the scale in which it is viewed, the ocean's influence on the planet is undeniable. Weather patterns and regional microclimates are significantly affected by the ocean, as is the longer-term global climate. The ocean provides a variety of resources ranging from food and water to energy, construction materials, and life-saving pharmaceuticals. It supports a significant proportion of the biodiversity on the planet and has played a large role in human history and culture through both limiting and promoting trade and providing a means for transportation. The ocean gives us a sense of awe, offers inspiration, and provides many types of recreational opportunities for people all over the world.

1.2 Marine Scientists Use the Logic of Science to Study the Ocean

Oceanography (or **marine science**) is the scientific study of the ocean, its associated life-forms, and its bordering lands. Marine science draws on many disciplines, integrating the fields of geology, physics, biology, chemistry, astronomy, atmospheric science, anthropology, ecology, computer science, and engineering as they apply to the ocean and its surroundings. Nearly all marine scientists specialize in one area of research, but they also must be familiar with related disciplines and appreciate the linkages between them. **Figure 1.3** shows marine scientists in action.

Marine scientists today are asking some critical questions about the origin of the ocean, the age of its basins, and the nature of the life-forms it has nurtured. We are fortunate to

Simon Dannhauer/Shutterstock.com

Figure 1.1 The ocean influences, and is influenced by, many of the other features on planet Earth. This Costa Rican beach is clearly shaped by a combination of elements including land, ocean, weather, wave energy, living organisms, and nonliving structures.

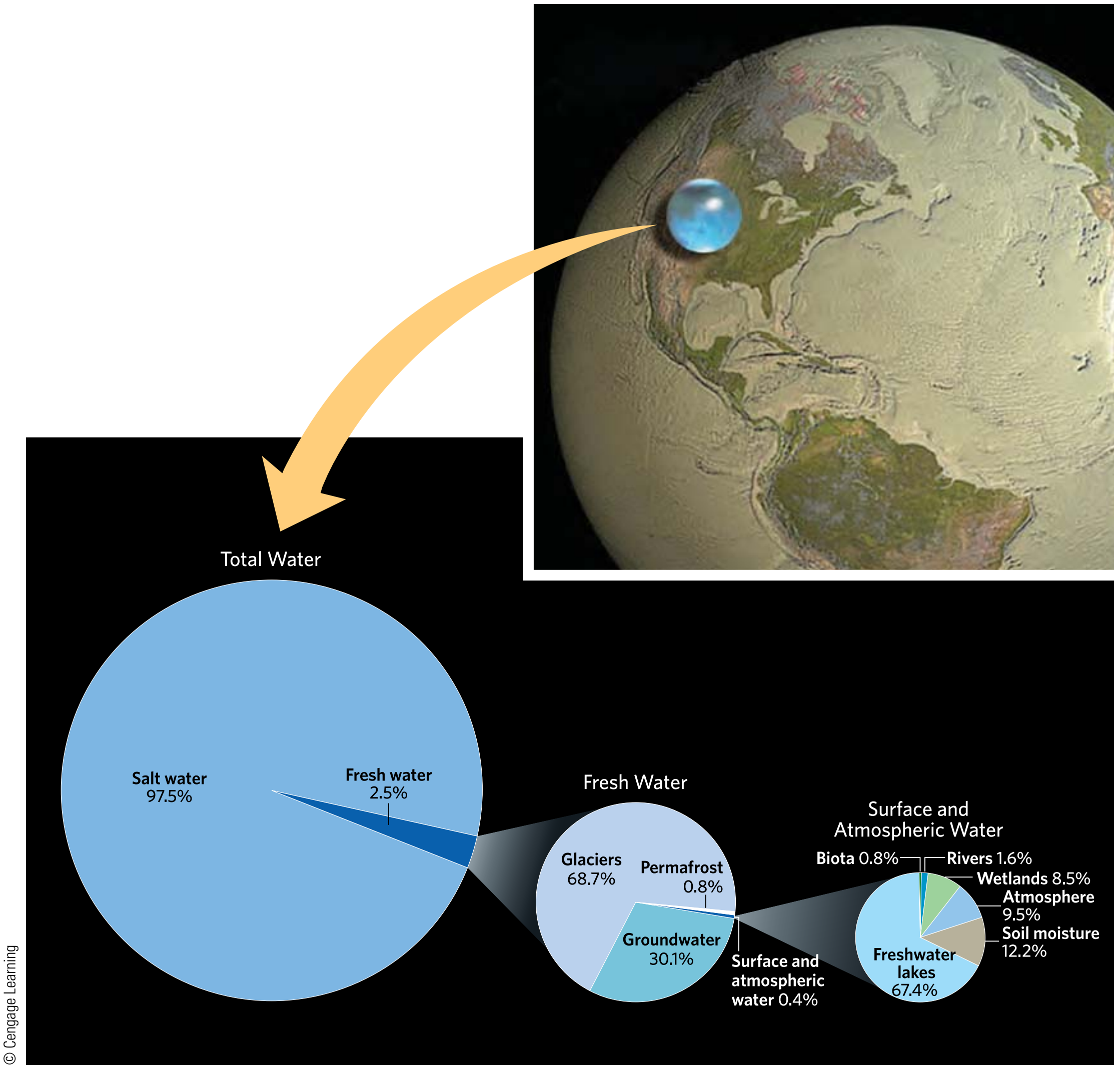


Figure 1.2 The relative amount of water in various locations on or near Earth's surface. More than 97% of the water lies in the ocean. If all the water at Earth's surface were gathered into a sphere, its diameter would measure only 1,380 kilometers (860 miles).

live at a time when scientific study may be able to answer some of those questions. **Science** is a systematic *process* of asking questions about the observable world by gathering and then studying information (data), but the information by itself is not science. Science *interprets* raw information by constructing a general explanation with which the information is compatible.

Scientists start with a question—a desire to understand something they have observed or measured. They then form a tentative explanation for the observation or measurement. This explanation is often called a working **hypothesis**, a speculation about the natural world that can be tested and verified or disproved by further observations and controlled experiments. (An **experiment** is a test that simplifies observation in nature or in the laboratory by manipulating or controlling the conditions under which the observations are made.) A hypothesis consistently supported by observation, experiment, or historical exploration is advanced to the status of **theory**, a statement that explains the observations. **Laws** are principles explaining events in nature that have been observed to occur with unvarying uniformity under the same conditions. A law *summarizes* observations, usually as a concise mathematical or verbal expression; a theory provides an *explanation* for the observations. *One is not "more true" than the other—both a law and a theory can be statements of facts.*

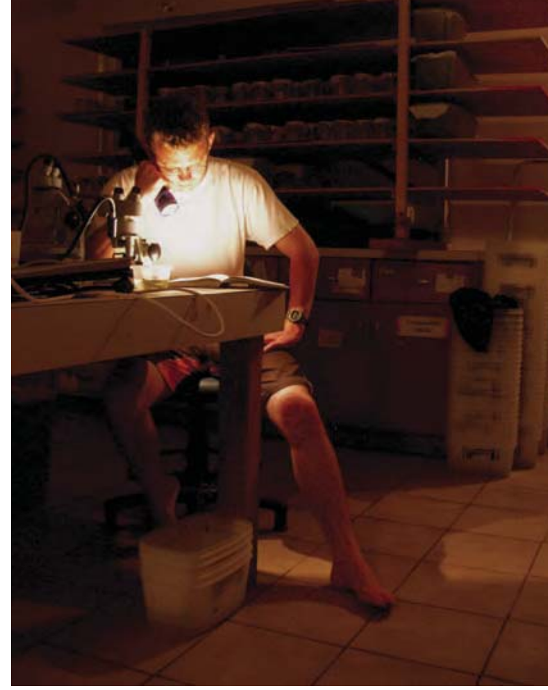
Theories and laws in science do not arise fully formed or all at once. Scientific thought progresses as a continuous chain of questioning, testing, and matching theories to observations. A theory is strengthened if new facts support it. If not, the theory is modified or a new explanation is sought (science is thus "self-correcting"). The power of science lies in its ability to operate *in reverse;* that is, in the use of a theory or law to predict and anticipate new facts to be observed later.

This procedure, often called the **scientific method**, is an orderly process by which theories are verified or rejected. The scientific method rests upon the assumption that nature "plays fair"—that the rules governing natural phenomena do not change capriciously as our powers of questioning and observing improve. We believe that the answers to our questions about nature are *ultimately knowable.*

There is no one way to conduct science. Some researchers design experiments to investigate their own hypotheses, whereas others observe, describe, and report on a subject and leave it to others to hypothesize. What is called the scientific method is also not a rigid way of looking at an issue. The general method scientists use is a critical attitude

Robert Ellis

a A student research team attempts to identify a humpback whale by comparing its unique fluke patterns to previously catalogued individuals.



Ingrid Burke and Stephen Hatosy

b Quiet, thoughtful study comes before an experiment is begun and after the data are obtained. A student works with a flashlight on a laboratory report during a power outage at the University of California's Moorea Research Station in the South Pacific.

Philippe Crassous/Science Source

c Sometimes marine scientists come up with an unanticipated surprise. Fortunately, this marine worm is very, very small.

Figure 1.3 Doing marine science is sometimes anxious, sometimes patterns, and always interesting.

about being *shown* rather than being *told*, and taking a logical approach to problem solving. The process is circular and collaborative—new theories and laws always suggest new questions (**Figure 1.4**).

Although clearly powerful in its implications and applications, nothing is ever proven *absolutely true* by the scientific method. Still, the mechanism of science has provided durable, valuable, long-lasting answers to questions about the natural world.

Science is neither a democratic process nor a popularity contest. As we can sense from the current acrimonious debates over global climate change or even evolution, conclusions about the natural world that we reach by scientific process may not always be comfortable, easily understood, or immediately embraced. But if those conclusions consistently match observations, they may be considered true.

This textbook shows some of the results of the scientific process as they have been applied to the world ocean. It presents facts, interpretations of facts, examples, stories, and some of the crucial discoveries that have led to our present understanding of the ocean and the world on which it formed. As the results of science change, so will the ideas and interpretations presented in books like this one.

1.3 Stars Form Seas

To understand the ocean, we need to understand how it formed and evolved through time. Because the world ocean is the largest feature of Earth's surface, it should not be surprising to find that the origin of the ocean is closely linked to the origin of Earth.

You may be startled to discover that most of the atoms that make up Earth, its ocean, and its inhabitants were formed within stars billions of years ago. The universe's observable mass consists mostly of hydrogen and helium atoms. Stars spend their lives changing this hydrogen and helium to heavier elements such as carbon, oxygen, silicon, and iron through **nuclear fusion**. This process is also responsible for generating the light and heat that influence everything from weather and currents to photosynthesis. As they die, some larger stars can produce even heavier elements and eject these materials into space during cataclysmic explosions known as *supernova* (**Figure 1.5**). The sun and the planets, including Earth, condensed from a cloud of dust and gas enriched by the recycled remnants of exploded stars that disappeared billions of years ago. We are also made of that stardust. Our bones and brains are composed of ancient atoms constructed by stellar fusion long before the solar system existed.

New planets formed in the cloud of dust and debris surrounding the young sun through a process known as **accretion**—the clumping of small particles into large masses. The period of accretion lasted perhaps 30 to 50 million years. Our sun became a star when its internal temperature rose high enough to fuse atoms of hydrogen into helium. The violence of these nuclear reactions sent a solar wind of radiation sweeping past the inner planets, clearing the area of excess particles and ending the period of rapid accretion. Gases like those we now see on the giant outer planets may once have surrounded the inner planets, but this rush of solar energy and particles stripped them away.

1.4 Earth, Ocean, and Atmosphere Accumulated in Layers Sorted by Density

The young Earth, formed by the accretion of cold particles within this cloud of dust and gas, was probably chemically homogeneous throughout. Then, in the midst of the accretion phase, Earth's surface was heated by the impact of asteroids, comets, and other falling debris. This heat, combined with gravitational compression and heat from decaying radioactive elements accumulating deep within the newly assembled planet, caused Earth to partially melt. Gravity pulled most of the iron and nickel inward to form the planet's core. The sinking iron released huge amounts of gravitational energy, which, through friction, heated Earth even more. At the same time, a slush of lighter minerals—silicon, magnesium, aluminum, and oxygen-bonded compounds—rose toward the surface, forming Earth's crust (**Figure 1.6**). The lightest of these became the atmosphere. This important process, called **density stratification**, lasted perhaps 100 million years.[3] We can consider the formation of a permanent crust as the "birthday" of Earth, some 4.6 billion years ago.[4]

Earth's surface was so hot that no water could collect there, and no sunlight could penetrate the thick clouds. (A visitor approaching from space 4.4 billion years ago would have seen a vapor-shrouded sphere blanketed by lightning-stroked clouds.) After millions of years the upper clouds cooled enough for some of the outgassed water to form droplets. Hot rains fell toward Earth, only to boil back into the clouds again. As the surface became cooler, water collected in basins and began to dissolve minerals from the rocks. Some of the water evaporated, cooled, and fell again, but the minerals remained behind. The familiar salty world ocean was gradually accumulating.

These heavy rains may have lasted about 20 million years. Large amounts of water vapor and other gases continued to escape through volcanic vents during that time and for millions of years thereafter. The impact of water-containing bodies from space (asteroids and comets) likely delivered additional water.[5] The ocean grew deeper.

The atmosphere was also evolving. Geochemists believe the early atmosphere may have been rich in carbon dioxide, nitrogen, and water vapor, with traces of ammonia and methane. Beginning about 3.5 billion years ago, this mixture began a gradual alteration to its present composition, mostly nitrogen and oxygen. At first this change was brought about by carbon dioxide dissolving in seawater to form carbonic acid, which then combined with crustal rocks. The chemical breakup of water vapor by sunlight high in the atmosphere also played a role. Then about 1.5 billion years later, the ancestors of today's green plants produced—by photosynthesis—enough oxygen to oxidize minerals dissolved in the ocean and surface sediments. Additional oxygen then began to diffuse into the air and accumulate in the atmosphere. (This monumental event in Earth's history is called the *oxygen revolution*.)

1.5 Understanding the Ocean: A Short History of Oceanography

Humans are a restless and inquisitive lot, and despite the ocean's great size, we have populated nearly every inhabitable place. This fact was aptly illustrated when European explorers set out to "discover" the world, only to be met by native peoples at nearly every landfall! Clearly the ocean did not prevent the spread of humanity.

Any coastal culture skilled at raft building or small-boat navigation would have economic and nutritional advantages over less skilled competitors (**Figure 1.7**). The first direct evidence we have of **voyaging**, traveling on the ocean for a specific purpose, comes from records of trade in the Mediterranean Sea. The Egyptians organized shipborne commerce on the Nile River, but the first regular ocean traders were probably the Cretans or the Phoenicians.

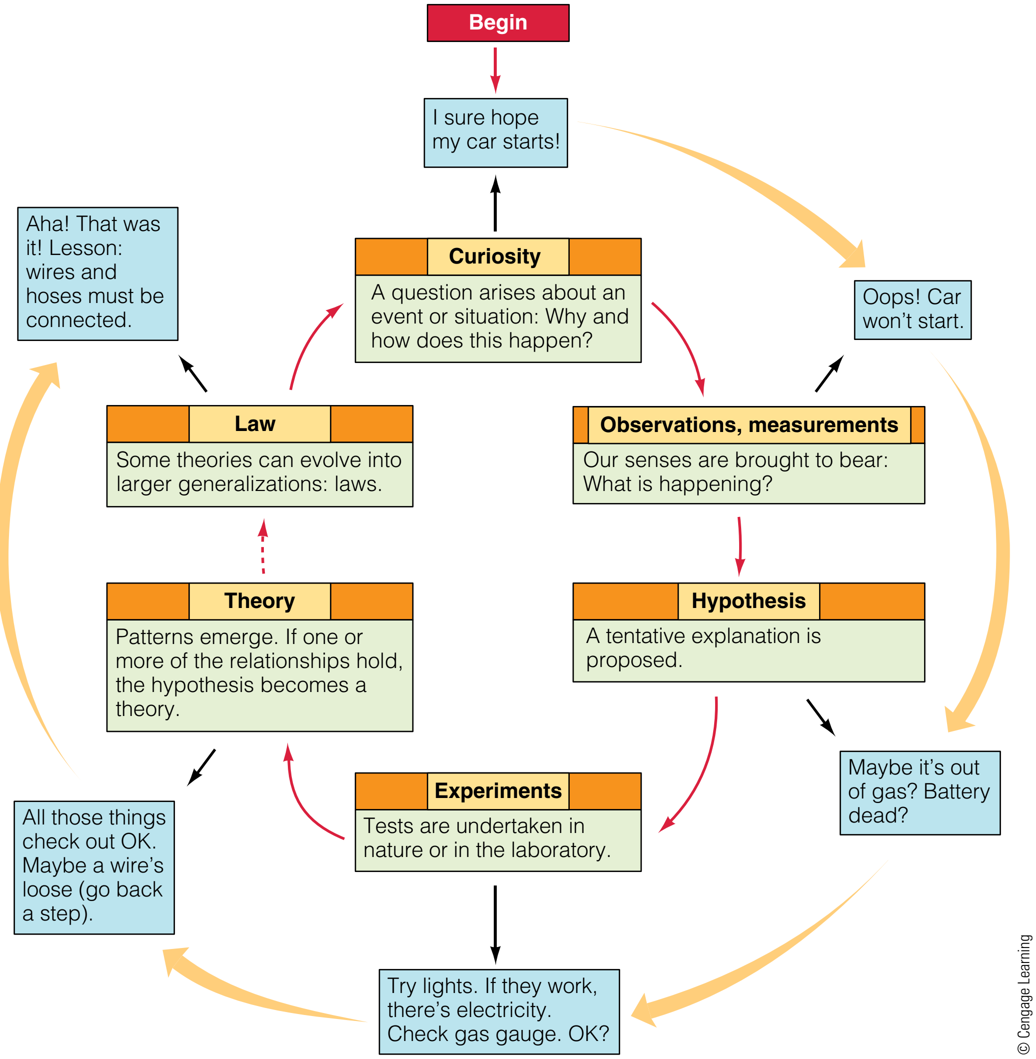
As they went about their business, early mariners began to record information to make their voyages easier and safer—the location of rocks in a harbor, landmarks and the sailing times between them, the direction of currents. The Polynesian peoples learned to interpret more subtle directional clues based off of wind and wave patterns, the sun, moon, and stars, and marine organisms to help them navigate between islands in the Pacific Ocean. Accumulating data for ocean *science*, however, is

[3] Density is an expression of the relative heaviness of a substance; it is defined as the mass per unit volume, usually expressed in grams per cubic centimeter (g/cm^3). The density of pure water is 1 g/cm^3. Granite rock is about 2.7 times denser, at 2.7 g/cm^3.

[4] By the way, regardless of surprisingly persistent opinion, essentially no evidence supports the contention that Earth is between 6,000 and 10,000 years old.

[5] Isotopic ratios suggest that the water found in asteroids is a better match to the water in our ocean than that of comets. Therefore, current evidence points to asteroids as a more likely source of the majority of water that was delivered from impacting bodies.

Figure 1.4 There is no single "scientific method."



a In this oversimplistic view, a logical series of steps represents the *procedure* of science. A progression of rational assumptions backed by data (information) leads to a solution to a specific problem. In fact, there is no single way of applying scientific logic applicable to all situations.

Figure 1.5 A dramatic portrait of a star in the early stages of explosive collapse. The bulk of its mass, including the heavy elements constructed during its long life, will be violently ejected into space, perhaps eventually to condense into new stars and solar systems.


Tom Garrison

b The underlying method of science describes an attitude. Scientists like to be shown why an idea is correct, rather than simply being told. All science is a work in progress, never completed. The external world, not internal conviction, must be the testing ground for scientific beliefs. Here, marine scientists are planning an experiment to better understand how small intertidal snails withstand the high temperature of their tropical environment. They have a hypothesis and will design experiments to resolve it.

an activity undertaken by relatively advanced societies with the time and means to satisfy their curiosity. If financial or cultural rewards followed these explorations, so much the better.

The Alexandrian Library

Progress in applied marine science began at the **Library of Alexandria**, in Egypt (**Figure 1.8**). Founded in the third century B.C.E. at the behest of Alexander the Great, the library constituted history's greatest accumulation of ancient writings at that time. The library and the adjacent museum could be considered the first university in the world. Written knowledge of all kinds—characteristics of nations, trade, natural wonders, artistic achievements, tourist sights, investment opportunities, and other items of interest to seafarers—was warehoused around its leafy courtyards. When any ship entered the harbor, the books (actually scrolls) it contained were by law removed and copied; the *copies* were returned to the owner and the originals kept for the library. Caravans arriving over land were also searched. Manuscripts describing the Mediterranean coast were of great interest. Traders quickly realized the competitive benefit of this information.

The second librarian at Alexandria was the Greek astronomer, philosopher, and poet **Eratosthenes of Cyrene**. This remarkable man was the first to calculate the circumference of Earth. The Greek Pythagoreans had realized Earth was spherical by the sixth century B.C.E., but Eratosthenes was the first to estimate its true size. Historians estimate that his calculation, made in about 230 B.C.E. and based on the geometric observations of travelers, was accurate to within about 8% of the true value. Within a few hundred years most people in the West who had contact with the library or its scholars knew Earth's approximate size.

Cartography (chart making) flourished during this time. The first workable charts that represented a spherical surface on a flat sheet were developed by Alexandrian scholars. Latitude and longitude, systems of imaginary lines dividing the surface of Earth, were invented by Eratosthenes. **Latitude** lines were drawn parallel to the equator, and **longitude** lines ran from pole to pole (see Appendix 5). Eratosthenes placed the lines through prominent landmarks and important places to create a convenient, though irregular grid (**Figure 1.9**). Our present regular grid of latitude and longitude was invented by Hipparchus (c.165–c.127 B.C.E.), a librarian who divided the surface of Earth into 360 degrees. A later Egyptian-Greek, Claudius Ptolemy (90–168 C.E.), *oriented* charts by placing east to the right and north at the top.

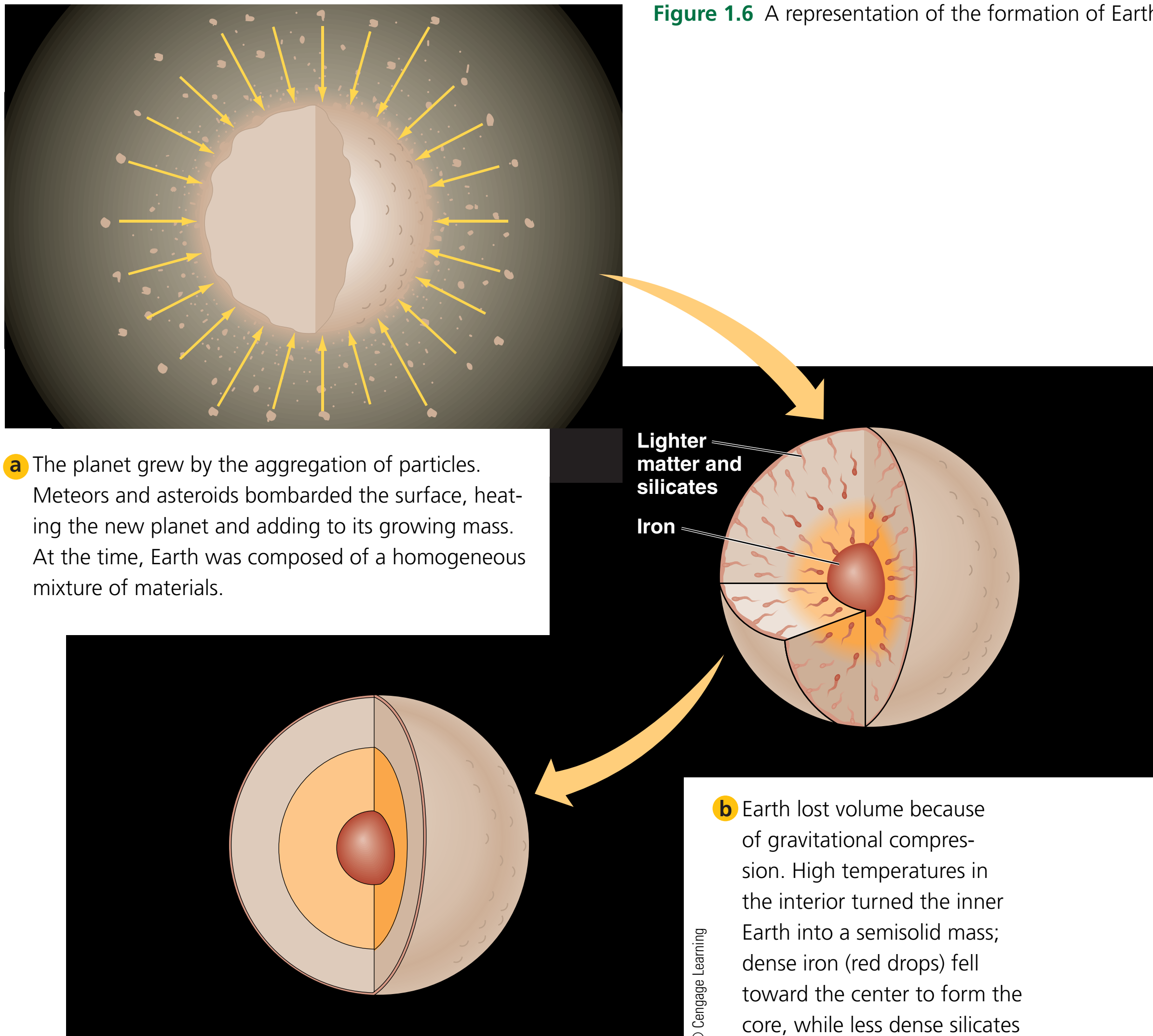


Figure 1.6 A representation of the formation of Earth.

a The planet grew by the aggregation of particles. Meteors and asteroids bombarded the surface, heating the new planet and adding to its growing mass. At the time, Earth was composed of a homogeneous mixture of materials.

b Earth lost volume because of gravitational compression. High temperatures in the interior turned the inner Earth into a semisolid mass; dense iron (red drops) fell toward the center to form the core, while less dense silicates moved outward. Friction generated by this movement heated Earth even more.

c The result of *density stratification* is evident in the formation of the inner and outer core, the mantle, and the crust.

Figure 1.7 An artist reconstructs the oldest known Greek cargo ship. Used in trade around 390 B.C.E., the lead-sheathed wooden vessel is shown at port on the island of Rhodes. Sailors are loading amphorae of oil for transport to the mainland. A Greek bireme—a warship—is seen in the distance.

Mohsen Allam/Egypt Today

a The exact site of the Library of Alexandria had been lost to posterity until the early 1980s. By 2004, a theater and 13 classrooms had been unearthed. One of the classrooms is shown here.

Taylor S.Kennedy/National Geographic Creative

b A modern Library of Alexandria opened in the spring of 2002. Sponsors of the new *Bibliotheca Alexandrina* hope it will become "a lighthouse of knowledge to the whole world." The goal of this conference center and storehouse is not to restore the past but to revive the ancient library's questing spirit.

Figure 1.8 The Alexandrian Library.

Ptolemy's division of degrees into minutes and seconds of arc is still used by navigators.

Although it weathered the dissolution of Alexander's empire, the Library of Alexandria did not survive the subsequent period of Roman rule. In 415 C.E., a mob burned the library with all of its contents. The academic loss was incalculable. Trade suffered because shipowners no longer had a clearinghouse for updating the nautical charts and information they had come to depend on. All that remains of the library today is a remnant of an underground storage room and the floors of a few lecture halls.

Captain James Cook Was the First Marine Scientist

Scientific oceanography as we know it begins with the departure from Plymouth Harbor in 1768 of HMS *Endeavour* under the command of **James Cook** of the British Royal Navy (**Figure 1.10**). An intelligent and patient leader, Cook was also a skillful navigator, cartographer, writer, artist, diplomat, sailor, scientist, and dietitian.

The primary reason for the voyage was to assert the British presence in the South Seas, but the expedition had numerous scientific goals as well. Cook conveyed several members of the Royal Society (a scientific research group) to Tahiti to observe the transit of Venus across the disk of the sun and verified calculations of planetary orbits. He and his men then found and charted New Zealand, mapped Australia's Great Barrier Reef, marked the positions of numerous small islands, made notes on the natural history and human habitation of these distant places, and initiated friendly relations with many chiefs. Cook completed the voyage around the world in 1771. During subsequent voyages in the 1770s Cook went on to discover many other islands and charted the west coast of North America. Because of his insistence on cleanliness and ventilation, and because his provisions included cress, sauerkraut, and citrus extracts, his sailors avoided scurvy—a vitamin C-deficiency disease that for centuries had decimated crews on long voyages.

Cook deserves to be considered a scientist as well as an explorer because of the accuracy, thoroughness, and completeness in his observations and descriptions. He and the scientists aboard took samples of marine life, land plants and animals, the ocean floor, and geological formations; they also reported the characteristics of these samples in their logbooks and journals. Cook's navigation was outstanding, and his charts of the Pacific were accurate enough to be used by the Allies in World War II invasions of the Pacific islands. He drew accurate conclusions, did not exaggerate his findings, and opened friendly diplomatic relations with many native populations. Cook recorded and successfully interpreted events in natural history, anthropology, and oceanography. This first marine scientist peacefully changed the map of the world more than any other explorer or scientist in history.

Matthew Maury Discovered Worldwide Patterns of Winds and Ocean Currents

Perhaps the first person engaged in full-time oceanographic work was a U.S. naval officer named **Matthew Maury**, who was interested in exploiting winds and currents for commercial and naval purposes. After being crippled in a stagecoach accident, in 1842 Maury was given charge of the navy's Depot of Charts and Instruments. There he studied a huge and neglected treasure trove of ships' logs, with their many regular readings of temperature and wind direction. By 1847 Maury had assembled much of this information into coherent wind and current charts. Maury began to issue these charts free to mariners in exchange for logs of their own new voyages.

Maury was a compiler, not a scientist, and he built on the work of Benjamin Franklin to promote maritime commerce. Nearly a hundred years earlier, Franklin had noticed the peculiar fact that the fastest ships were not always the fastest ships; that is, hull speed did not always correlate with out-and-return time on the European run. Franklin's cousin, a

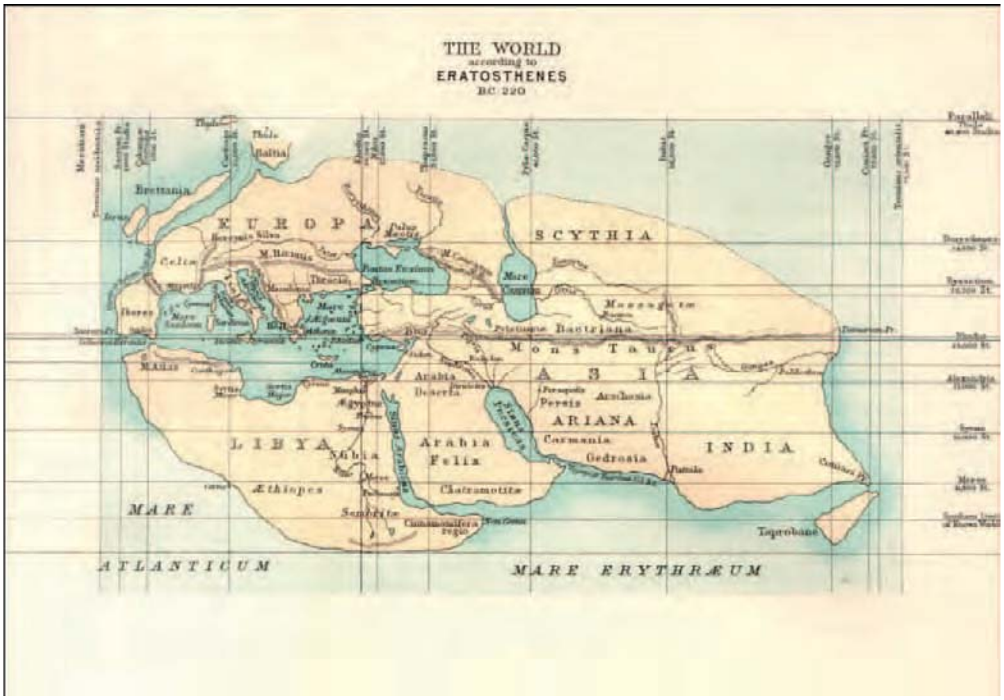


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Figure 1.9 The world, according to a chart from the third century B.C.E. Eratosthenes drew latitude and longitude lines through important places rather than spacing them at regular intervals as we do today. The Alexandrian perception of the world is reflected in the size of the continents and the central position of Alexandria at the mouth of the Nile. This representation was published in the first volume of the *Challenger Report.* (More on the *Challenger* expedition can be found later in this chapter.)

Superstock

Figure 1.10 In this 1776 painting by Nathaniel Dance, Cook is seen as a fully matured, self-confident captain who has twice circled the globe, penetrated into the Antarctic, and charted coastlines from Newfoundland to New Zealand.

Nantucket merchant named Tim Folger, noted Franklin's puzzlement and provided him with a rough chart of the "Gulph Stream" that he (Folger) had worked out. By staying within the stream on the outbound leg and adding its speed to their own, and by avoiding it on their return, captains could traverse the Atlantic much more quickly.

Maury was the first person to sense the worldwide pattern of surface winds and currents. Based on his analysis, he produced a set of directions for sailing great distances more efficiently. Maury's sailing directions quickly attracted worldwide notice: He had shortened the passage from the American east coast to Rio de Janeiro by 10 days, and to Australia by 20. His work became famous in 1849 during the California gold rush—his directions made it possible to save 30 days on the voyage around Cape Horn to California. His crowning achievement, *The Physical Geography of the Seas*, a book explaining his discoveries, was published in 1855.

The *Challenger* Expedition Was Organized from the First as a Scientific Expedition

The first expedition devoted completely to marine science was conceived by Charles Wyville Thomson, a professor of natural history at Scotland's University of Edinburgh, and his Canadian-born student, John Murray. Inspired by Charles Darwin's voyage in HMS *Beagle*, they convinced the Royal Society and British government to provide a Royal Navy ship and trained crew for a prolonged and arduous voyage of exploration across the world ocean. Thomson and Murray even coined a word for their enterprise: *oceanography.*[6] Prime Minister Gladstone's administration and the Royal Society agreed to the endeavor provided that a proportion of any financial gain from discoveries was handed over to the Crown.

HMS *Challenger*, a 2,306-ton steam corvette, set sail on 21 December 1872 on a 4-year voyage around the world, covering 127,600 kilometers (79,300 miles). Although the captain was a Royal Navy officer, the six-man scientific staff directed the course of the voyage shown in **Figure 1.11**.

One important mission of the ***Challenger* expedition** was to investigate Edinburgh professor Edward Forbes's contention that life below 549 meters (1,800 feet) was impossible

[6] Although the term literally implies only marking or charting, it has come to mean the science of the ocean.

Bridgeman Art Library

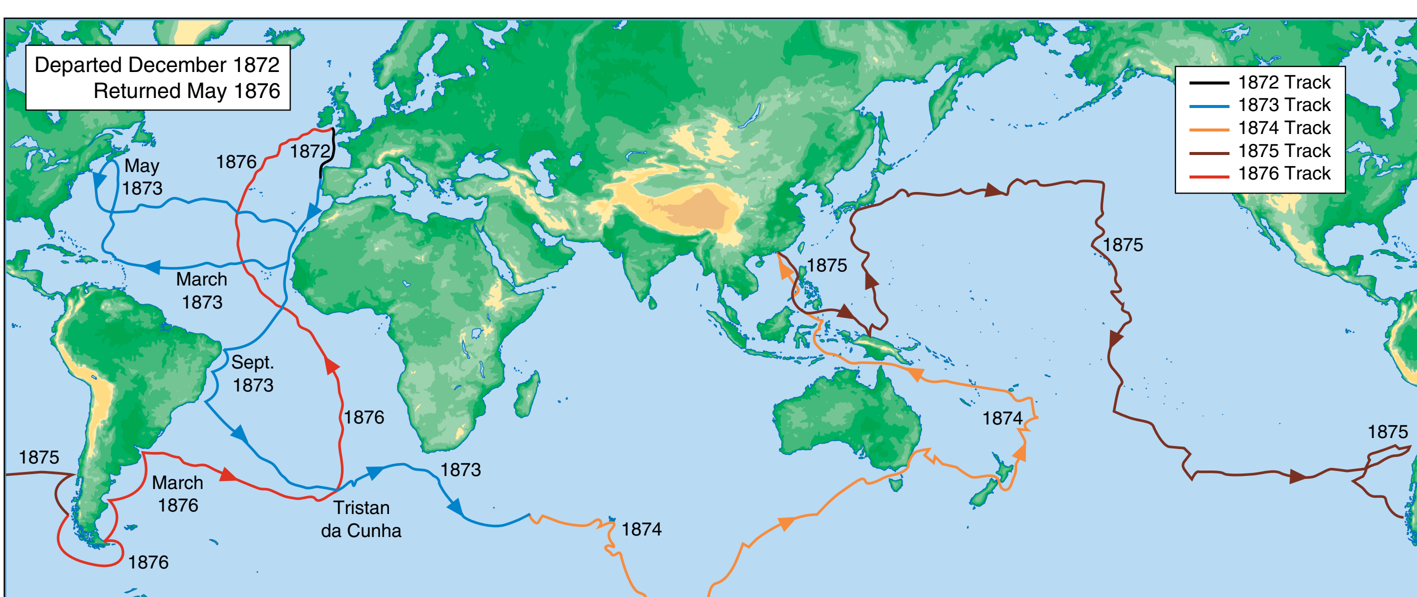
a Lt. Pelham Aldrich, first lieutenant of HMS *Challenger*, kept a detailed journal of the *Challenger* expedition. With accuracy and humor, he kept this record in good weather and bad, and had the patience and skill to include watercolors of the most exciting events. This is part of the first page of his journal.

because of high pressure and lack of light. The steam winch onboard made deep sampling practical, and samples from depths as great as 8,185 meters (26,850 feet) were collected off the Philippines. Through the course of 492 deep samples with mechanical grabs and nets at 362 stations, Forbes was proven resoundingly wrong. With each hoist, animals new to science were strewn on the deck; in all, staff biologists discovered 4,717 new species!

The scientists also took salinity, temperature, and water density measurements during these soundings. Each reading contributed to a growing picture of the physical structure of the deep ocean. They completed at least 151 open-water trawls and stored 77 samples of seawater for detailed analysis ashore. The expedition collected new information on ocean currents, meteorology, and the distribution of sediments; the locations and profiles of coral reefs were charted. Thousands of pounds of specimens were brought to British museums for study. Manganese nodules, brown lumps of mineral-rich sediments, were discovered on the seabed, sparking interest in deep-sea mining. The work was agonizing and repetitive—a quarter of the 269 crew members eventually deserted!

In spite of the drudgery, this first pure oceanographic investigation was an unqualified success. The discovery of life in the depths of the oceans stimulated the new science of marine biology. The *Challenger Report*, the record of the expedition, was published between 1880 and 1895 by Sir John Murray in a well-written and magnificently illustrated 50-volume set.

Figure 1.11 The voyage of HMS *Challenger*.



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b HMS *Challenger*'s track from December 1872 to May 1876. The *Challenger* expedition remains the longest continuous oceanographic survey on record.

It is still used today. Indeed, the 50-volume *Report*, rather than the cruise, provided the foundation for the new science of oceanography.

The expedition's many financial spin-offs indicated that pure research was a good investment, and the British government realized quick profits from the exploitation of newly discovered mineral deposits on islands. The *Challenger* expedition remains history's longest continuous scientific oceanographic expedition.

1.6 Contemporary Oceanography Makes Use of Modern Technology

In the 20th century, oceanographic voyages became more technically ambitious and expensive. Scientist-explorers sought out and investigated places that once had been too difficult to attain. Although the deep ocean floor was coming into reach, it was the forbidding polar ocean that attracted their first attentions.

Modern oceanography began with the pioneering efforts of **Fridtjof Nansen**. Nansen courageously allowed his specially designed ship *Fram* (**Figure 1.12**) to be trapped in the Arctic ice, where he and his crew of 13 drifted with the pack for nearly 4 years (1893–1896). The 1,650-kilometer (1,025-mile) drift of *Fram* proved that no Arctic continent existed. Nansen's studies of the drift, of meteorological and oceanographic conditions, of life at high latitudes, and of deep sounding and sampling techniques form the underpinnings of modern polar science. In 1910 Roald Amundsen, a student of Nansen's, set out in the sturdy little vessel for the coast of Antarctica, the first leg of a successful journey to the South Pole.

Image from Amundsen, Roald. The South pole; an account of the Norwegian Antarctic expedition in the "FRAM", 1910-1912, Keedick, 1913.

Figure 1.12 Nansen's 123-foot schooner *Fram* ("forward"). With 13 men, *Fram* sailed on 22 June 1893 to the high Arctic with the specific purpose of being frozen into the ice. *Fram* was designed to slip up and out of the frozen ocean and drifted with the pack ice to within about 4° of the North Pole. The whole harrowing adventure took nearly 4 years. The ship's 1,650-kilometer (1,025-mile) drift proved no Arctic continent existed beneath the ice. Living conditions aboard can be sensed from this recently rediscovered photograph.

New Ships for New Tasks

In 1925 the German ***Meteor* expedition**, which crisscrossed the South Atlantic for 2 years, introduced modern optical and electronic equipment to oceanographic investigation. Its most important innovation was the use of an **echo sounder**, a device that bounces sound waves off the ocean bottom, to study the depth and contour of the seafloor (Figure 3.1). The echo sounder revealed to *Meteor* scientists a varied and often extremely rugged bottom profile rather than the flat floor they had anticipated.

In October 1951 a new HMS *Challenger* began a 2-year voyage that would make precise depth measurements in the Atlantic, Pacific, and Indian oceans and in the Mediterranean Sea. With echo sounders, measurements that would have taken the crew of the first *Challenger* nearly 4 hours to complete could be made in seconds. *Challenger II*'s scientists discovered the deepest part of the ocean's deepest trench, naming it Challenger Deep in honor of their famous predecessor. In 1960 U.S. Navy lieutenant Don Walsh and Jacques Piccard were the first to descend into the Challenger Deep in *Trieste*, a Swiss-designed, blimplike bathyscaphe.[7]

In 1968 the drilling ship *Glomar Challenger* set out to test a controversial hypothesis about the history of the ocean floor. It was capable of drilling into the ocean bottom beneath more than 6 kilometers (~20,000 feet) of water and recovering samples of seafloor sediments. These long and revealing plugs of seabed provided confirming evidence for seafloor spreading and plate tectonics. (The wonderful details can be found in Chapter 2.) Beginning in October 2003, deep-drilling responsibilities were passed to the Integrated Ocean Drilling Program (IODP), an international research consortium that operates an even larger drillship, **R/V *Chikyu*** (Japanese for "Earth") (**Figure 1.13**). The ship, fully operational in 2007, contains equipment capable of drilling cores as much as 11 kilometers (36,000 feet, or nearly 7 miles) long! This ship cost US$500 million and houses one of the most completely equipped geological laboratories ever put to sea.

Satellites Have Become Important Tools in Ocean Exploration

The National Aeronautics and Space Administration (NASA), organized in 1958, has become an important institutional contributor to marine science.

AQUA, one of three of NASA's new generation of Earth-observing satellites, was launched into polar orbit on 4 May 2002. It is the centerpiece of a project named for the large amount of information that will be collected about Earth's water cycle, including evaporation from the oceans; water vapor in the atmosphere; phytoplankton and dissolved organic matter in the oceans; and air, land, and water temperatures. *AQUA* flies in formation with sisters *TERRA*, *AURA*, *Calypso*, *Shizuku*, and *CloudSat* to monitor Earth and air (**Figure 1.14**).

[7] The magnitude of this achievement is illustrated by the fact that it was more than 50 years until another person visited the very bottom of the ocean (James Cameron in 2012).

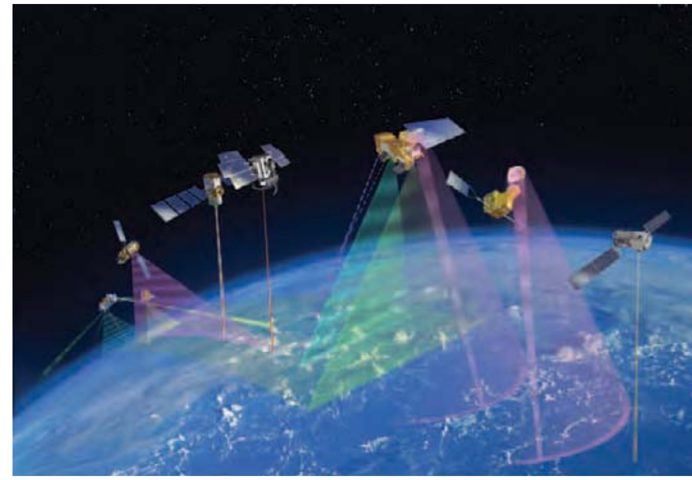
Tom Garrison

Figure 1.13 A model of R/V *Chikyu* ("Earth"), lead vessel in the 18-nation Integrated Ocean Drilling Program. *Chikyu* is 45% longer and 2.4 times the mass of *JOIDES Resolution,* the ship it replaces. Damaged in the 2011 tsunami, the ship has been repaired and is once again in operation.

Satellite oceanography is an important frontier, and discoveries made by satellites are discussed in later chapters.

Oceanographic Institutions Arose to Oversee Complex Research Projects

The demands of scientific oceanography have become greater than the capability of any single voyage. In the United States,



NASA

Figure 1.14 NASA's "A-Train," a string of satellites that orbit Earth one behind the other on the same track. They are spaced a few minutes apart so their collective observations may be used to build three-dimensional images of Earth's atmosphere, ocean surface, and land topography.

the three preeminent oceanographic research institutions are the Woods Hole Oceanographic Institution on Cape Cod, founded in 1930 (and associated with the Massachusetts Institute of Technology and the neighboring Marine Biological Laboratory, founded in 1888); the Scripps Institution of Oceanography, founded in La Jolla, California, and affiliated with the University of California in 1912 (**Figure 1.15a and 1.15b**); and the Lamont–Doherty Earth Observatory of Columbia University, founded in 1949.

The U.S. government has been active in oceanographic research. Within the Department of the Navy are the Office

Tom Garrison

a The Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. Marine science has been an important part of this small Cape Cod fishing community since Spencer Fullerton Baird, then assistant secretary of the Smithsonian Institution, established the U.S. Commission of Fish and Fisheries there in 1871. The Marine Biological Laboratory was founded in 1888 and the Oceanographic Institution in 1930.

Tom Garrison

b The Scripps Institution of Oceanography, La Jolla, California. Begun in 1892 as a portable laboratory-in-a-tent, Scripps was founded by William Ritter, a biologist at the University of California. Its first permanent buildings were erected in 1905 on a site purchased with funds donated by philanthropic newspaper owner E. W. Scripps and his sister, Ellen.

Figure 1.15 Oceanographic Institutions.

Tom Garrison

c The Ocean University in Qingdao, China. This is the world's largest institution dedicated exclusively to marine science education and research.

of Naval Research, the Office of the Oceanographer of the Navy, the Naval Oceanic and Atmospheric Research Laboratory, and the Naval Ocean Systems Command. These agencies are responsible for oceanographic research related to national defense. The **National Oceanic and Atmospheric Administration (NOAA)**, founded within the Department of Commerce in 1970, seeks to facilitate commercial uses of the ocean. NOAA includes the National Ocean Service, the National Weather Service, the National Marine Fisheries Service, and the Office of Sea Grant.

China is rapidly expanding its ocean research capabilities. Much of this effort is concentrated at the Ocean University of China in Qingdao, an institution of some 19,000 undergraduate and graduate students dedicated almost exclusively to marine science (**Figure 1.15c**).

Chapter in Perspective

In this chapter you learned Earth is a water planet. The world ocean covering nearly 71% of its surface has greatly influenced its rocky crust and atmosphere. This ocean dominates Earth, and the average depth of the ocean is about 4$^1/_2$ times the average height of the continents above sea level.

We study our planet using the scientific method, a systematic *process* of asking and answering questions about the natural world. Marine science applies the scientific method to the ocean, the planet of which it is a part, and the living organisms dependent on the ocean.

Most of the atoms that make up Earth and its inhabitants were formed within stars. Stars spend their lives changing hydrogen and helium to heavier elements. As they die, some stars eject these elements into space by cataclysmic explosions. The sun and the planets, including Earth, probably condensed from a cloud of dust and gas enriched by the recycled remnants of exploded stars. Earth formed by the accretion of cold particles about 4.6 billion years ago.

Heat from infalling debris and radioactive decay partially melted the planet, and density stratification occurred as heavy materials sank to its center and lighter materials migrated toward the surface.

The ocean formed later, as water vapor trapped in Earth's outer layers escaped to the surface through volcanic activity during the planet's youth. Water-containing asteroids may have brought additional water to Earth.

You also learned that science and exploration have gone hand in hand. Voyaging for necessity evolved into voyaging for scientific and geographical discovery. The transition to scientific oceanography was complete when the *Challenger Report* was completed in 1895. The rise of the great oceanographic institutions quickly followed, and those institutions and their funding agencies today mark our path into the future.

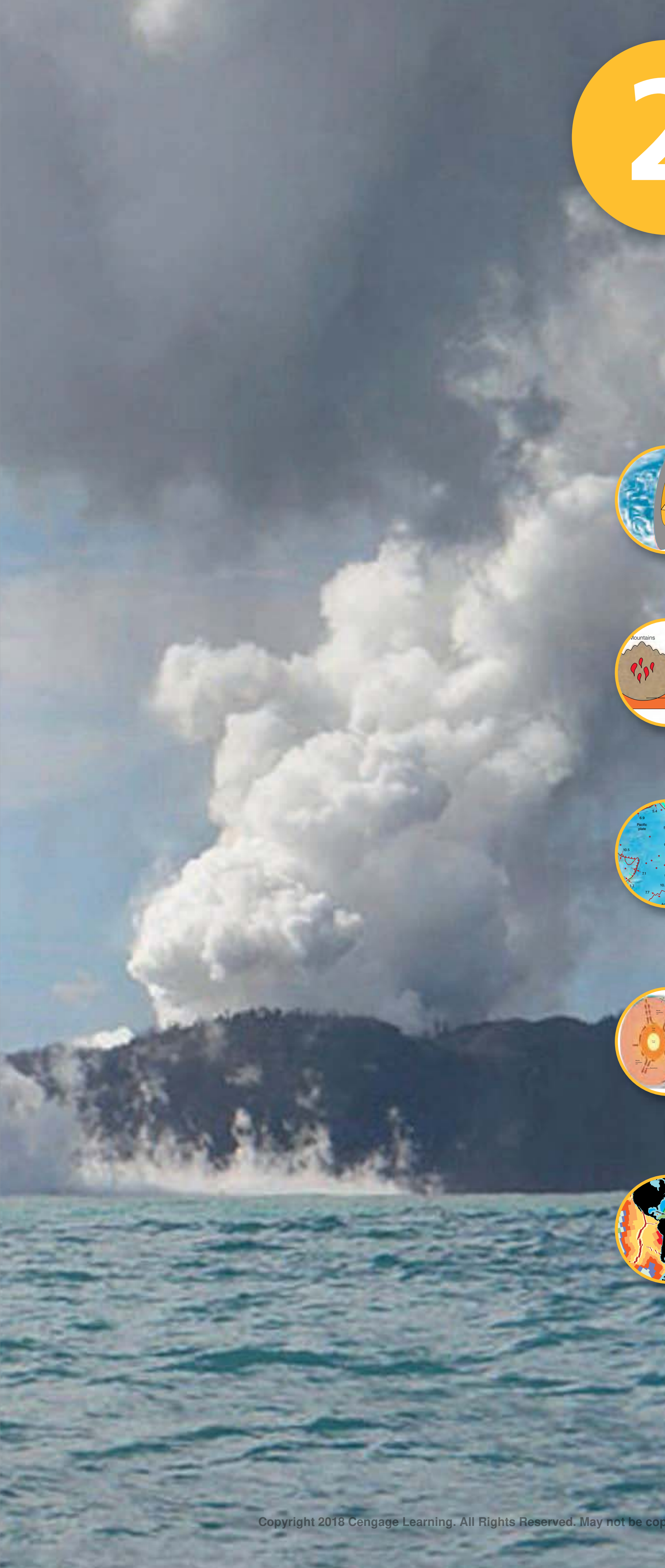
In the next chapter you will learn how scientific exploration has discovered Earth's inner layers—layers that are density stratified. You will find these layers to be heavier and hotter as depth increases, and you will learn how we know what's inside our planet even though we have never been beneath the outermost layer. As you'll see, today's earthquakes and volcanoes, and the slow movement of continents, are all remnants of our distant cosmological past.

TERMS AND CONCEPTS TO REMEMBER

accretion
AQUA
cartography
***Challenger* expedition**
Cook, James
density stratification
echo sounder
Eratosthenes of Cyrene
experiment
hypothesis
latitude
law
Library of Alexandria
longitude
marine science
Maury, Matthew
***Meteor* expedition**
Nansen, Fridtjof
National Oceanic and Atmospheric Administration (NOAA)
oceanography
R/V *Chikyu*
science
scientific method
theory
voyaging
world ocean

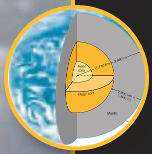
STUDY QUESTIONS

1. Why do we refer to only one world ocean? What about the Atlantic and Pacific oceans, or the Baltic and Mediterranean seas?
2. Which is greater: the average depth of the ocean or the average elevation of the continents?
3. Can the scientific method be applied to speculations about the natural world that are not subject to test or observation?
4. Where did Earth's heavy elements come from?
5. Where did Earth's surface water come from?
6. What happened to Earth during the accretion phase? What is density stratification?
7. How did the Library of Alexandria contribute to the development of marine science? What happened to most of the information accumulated there?
8. What were the contributions of Captain James Cook? Does he deserve to be remembered more as an explorer or as a marine scientist?
9. What was the first purely scientific oceanographic expedition, and what were some of its accomplishments?
10. Who was probably the first person to undertake the systematic study of the ocean as a full-time occupation? Are his contributions considered important today?
11. Where are advances in oceanography occurring today?

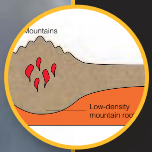


2 Plate Tectonics

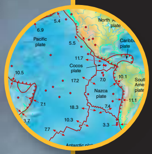
KEY CONCEPTS



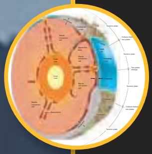
Earth's interior is layered, and the layers are arranged by density.



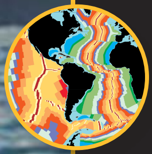
Continents rise above sea level because they float on a dense, deformable layer beneath them. Denser ocean crust does not float as high, resulting in the formation of ocean basins.



The brittle surface of Earth is fractured into about a dozen tilelike "plates."



Movement of the material on which these plates float moves them relative to one another.



Compelling evidence for plate movement is recorded in magnetic fields within the ocean floor.

Steam and ash explode through the sea surface as an undersea volcano erupts off the coast of Tonga in 2009.
Dana Stephenson/Getty Images

2.1 Earth's Interior Is Layered

Earth's interior is *layered*—it looks a bit like the inside of an onion (as in **Figure 2.1**). As discussed in Chapter 1, Earth was formed by accretion from a cloud of dust, gas, ice, and stellar debris. Gravity later sorted the components by density, separating Earth into the layers we observe today (see again Figure 1.6). Because each deeper layer is denser than the layer above, we say Earth is **density stratified**.

The escape of heat from Earth's interior generates powerful forces acting within and between these layers that ultimately form the major features of Earth's surface. The resulting slow movement of material determines the outlines and locations of the continents and ocean floors. It builds and destroys mountains and seabeds, raises islands, powers volcanoes, forms deep trenches, and influences the lives of millions of people when earthquakes or volcanoes occur. Few discoveries in marine science have been as exciting to geologists as the recent advances in our understanding of how these internal forces work.

The nature of the layers, their properties, and the forces that influence them have been learned largely by the study of shock waves associated with distant earthquakes.

Low-frequency pulses of energy generated by the forces that cause earthquakes—**seismic waves**—can spread rapidly into Earth in all directions and then return to the surface. Analysis of seismic waves reveals information about the nature of Earth's interior, much as a tap on a melon can tell the buyer if it is ripe.

Sensitive seismographs have allowed researchers to study the ways seismic waves refract and bounce off abrupt transitions between Earth's inner layers (**Figure 2.2c**). Waves that reach Earth's surface can be analyzed to better understand the composition, thickness, and structure of the layers inside of Earth.

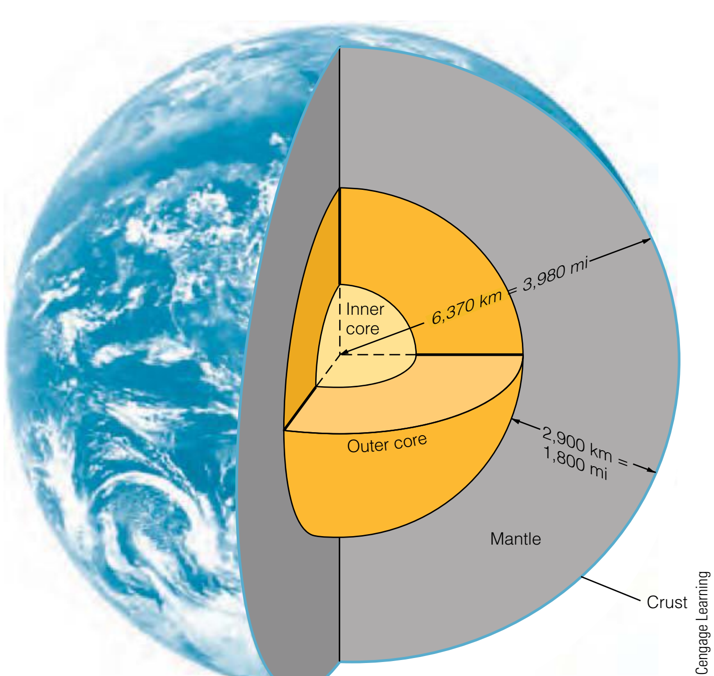


Figure 2.1 A cross section through Earth showing the internal layers. This representation is not to scale.

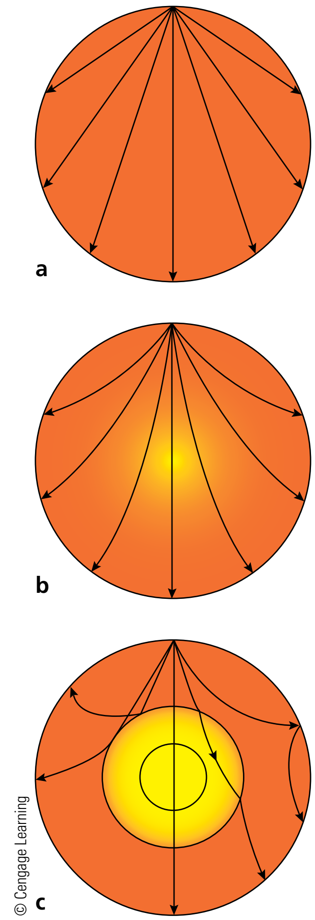


Figure 2.2 Possible paths of seismic waves through Earth.

a If Earth were uniform (homogeneous) throughout, seismic waves would radiate from the site of an earthquake in straight lines.

b If the density, or the rigidity, of Earth increased smoothly with depth, seismic wave velocity would increase evenly with depth, and the waves would gradually bend upward toward the surface.

c If Earth were layered inside, some seismic waves would be reflected at the boundaries between layers, whereas others would bend. Seismic evidence shows that Earth is layered.

Each of Earth's Inner Layers Has Unique Characteristics

Each layer inside Earth has different chemical and physical characteristics. One classification of Earth's interior emphasizes chemical composition. The uppermost layer is the lightweight, brittle, aptly named **crust**. The crust beneath the ocean differs in thickness, composition, and age from the crust of the continents. The relatively thin **oceanic crust** is primarily **basalt**, a heavy dark-colored rock composed mostly of oxygen, silicon, magnesium, and iron. By contrast, the most common material in the thicker **continental crust** is **granite**, a familiar speckled rock composed mainly of oxygen, silicon, and aluminum. The **mantle**, the layer beneath the crust, is thought to consist mainly of oxygen, iron, magnesium, and silicon. Most of Earth is mantle—it accounts for 68% of Earth's mass and 83% of its volume. The outer and inner **cores**, which consist mainly of iron and nickel, lie beneath the mantle at Earth's center.

Chemical makeup is not the only important distinction between layers. Different conditions of temperature and pressure occur at different depths, and these conditions influence the physical properties of the materials. The behavior of a rock is determined by three factors: temperature, pressure, and the rate at which a deforming force (stress) is applied. Geologists have therefore devised another classification of Earth's interior based on *physical* rather than *chemical* properties. These are shown in **Figure 2.3**.

- The **lithosphere** (*lithos*, "rock")—Earth's cool, rigid outer layer—is 70 to 200 kilometers (44–125 miles) in thickness.

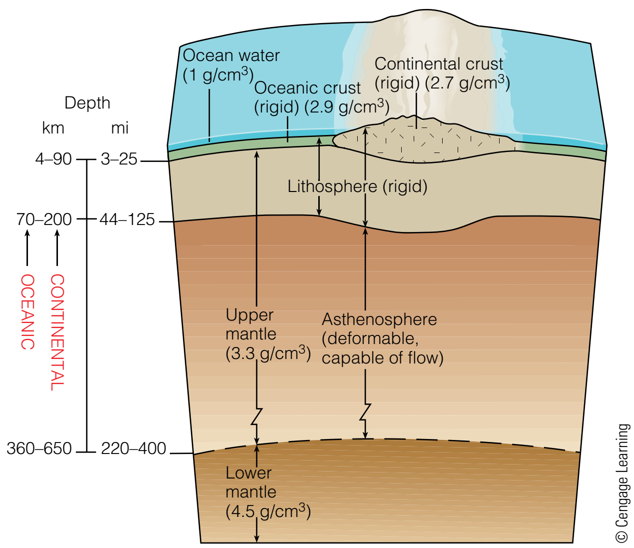


Figure 2.3 A cross section through Earth showing the internal layers near the surface. Note in this expanded section the relationship between lithosphere and asthenosphere, and between crust and mantle. This representation is not to scale.

It is composed of the continental and oceanic crusts *and* the uppermost cool and rigid portion of the mantle.

- The **asthenosphere** (*asthenes*, "weak") is the hot, partially melted, slowly flowing layer of upper mantle below the lithosphere extending to a depth of about 350 to 650 kilometers (220–400 miles).
- The **lower mantle** extends down to the core. The asthenosphere and the mantle below the asthenosphere (the lower mantle) have a similar chemical composition. Although it is hotter, the mantle below the asthenosphere does not melt because of rapidly increasing pressure. As a result, it is denser and flows much more slowly.
- The core has two parts. The outer core is a very dense, viscous liquid. The inner core is a solid and is even denser—about 16 g/cm^3, nearly six times the density of granite rock. Both parts are extremely hot, with an average temperature of about 5,500°C (9,900°F). Recent evidence indicates that the inner core may be as hot as 6,600°C (12,000°F) at its center, hotter than the surface of the sun! Curiously, the solid inner core also rotates eastward at a slightly faster rate than the mantle.

Figure 2.3 expands to show the lithosphere and asthenosphere in detail. *Note that the rigid sandwich of crust and upper mantle—the lithosphere—floats on (and is supported by) the denser, deformable asthenosphere.* The structure of oceanic lithosphere differs from that of continental lithosphere. Because the thick, granitic continental crust is not exceptionally dense, it can project above sea level. In contrast, the thin, dense basaltic oceanic crust is almost always submerged.

Radioactive Elements Generate Heat Inside Earth

The interior of Earth is hot. The main source of that heat is **radioactive decay**. Although most atoms are stable and do not change, some forms of elements are unstable and give off heat when their nuclei break apart (decay). Radioactive particles are ejected in the process. As explained in Chapter 1, radioactive decay within the newly formed Earth released heat that contributed to the melting of the original mass. Most of the melted iron sank toward the core, releasing huge amounts of energy. By now almost all of the heat generated by the formation of the core has dissipated, but radioactive elements within Earth's cores and mantle continue to decay and produce new heat. Today most of the radioactive heating takes place in the crust and upper mantle rather than in the deeper layers. Some of this heat journeys toward the surface by conduction, the same process by which heat migrates along a skillet's handle. Some heat also rises by **convection** in the asthenosphere. Convection occurs when a fluid is heated, expands and becomes less dense, and rises. (Convection also causes air to rise over a warm radiator; see Figure 5.7.)

Even after 4.6 billion years, heat continues to flow from within Earth. This heat powers the construction of mountains and volcanoes, causes earthquakes, moves continents, and shapes ocean basins.

Continents Rise above the Ocean Because of Isostatic Equilibrium

Why do large regions of continental crust stand high above sea level? If the asthenosphere is hot, nonrigid, and deformable, why don't mountains sink because of their mass and disappear? Another look at Figure 2.3 will help to explain the situation. The mountainous parts of continents have "roots" extending into the asthenosphere. Remember, the continental crust and the rest of the lithosphere "float" on the denser asthenosphere. The situation involves buoyancy, the principle that explains why ships float.

Buoyancy is the ability of an object to float in a fluid by displacing a volume of that fluid equal in weight to the floating object's own weight. *A steel ship floats because it displaces a volume of water equal in weight to its own weight plus the weight of its cargo.* An empty containership displaces a smaller volume of water than the same ship when fully loaded (**Figure 2.4**). The water supporting the ship is not *strong* in the mechanical sense—water does not support a ship the same way a steel bridge supports a car. Buoyancy, not mechanical strength, supports the ship and its cargo.

Any part of a continent that projects above sea level is supported in the same way. This concept of lighter rocks floating on denser material is known as **isostasy**. Consider the continent containing Mount Everest, the highest of Earth's mountains at 8.84 kilometers (29,007 feet) above sea level. Mount Everest and its neighboring peaks are not supported by the *mechanical* strength of the materials within Earth (nothing in our world is that strong). Over a long period, and under the tremendous weight of the overlying crust, the asthenosphere behaves like a dense, viscous, slowly moving fluid. *The continent's mountains float high above sea level because the lithosphere gradually sinks into the deformable asthenosphere until it has displaced a volume of asthenosphere equal in mass to their mass.* The mountains stand at great height, nearly in balance with their subterranean underpinnings, but susceptible to rising or falling as erosion or stresses in the crust dictate. Lower regions are supported by shallower roots. In a slow-motion version of a ship floating in water, the entire continent stands in **isostatic equilibrium**.

What happens when a mountain erodes? In much the same way a ship rises when cargo is removed, Earth's crust will rise in response to the reduced load. Ancient mountains that have undergone millions of years of erosion often expose rocks that were once embedded deep within their roots. This kind of isostatic readjustment results in the thinning of the continental crust beneath the mountains leading to uplift, and subsidence beneath areas of deposited sediments causing those specific areas to settle deeper into the semi-molten asthenosphere. This process is shown in **Figure 2.5**.

Unlike the asthenosphere on which the lithosphere floats, crustal rock does not slowly flow at normal surface temperatures. A ship reacts to any small change in weight with a correspondingly small change in vertical position in the water, but an area of continent or ocean floor cannot react to every small weight change because the underlying rock is *not* liquid, the deformation does not occur rapidly, and the edges of the continent or seabed are mechanically bound to adjacent sections of crust. When the force of uplift or downbending exceeds the mechanical strength of the adjacent rock, the rock will fracture along a plane of weakness—a **fault**. The adjacent crustal fragments will move vertically in relation to each other. This sudden adjustment of the crust to isostatic forces by fracturing, or faulting, is one cause of earthquakes.

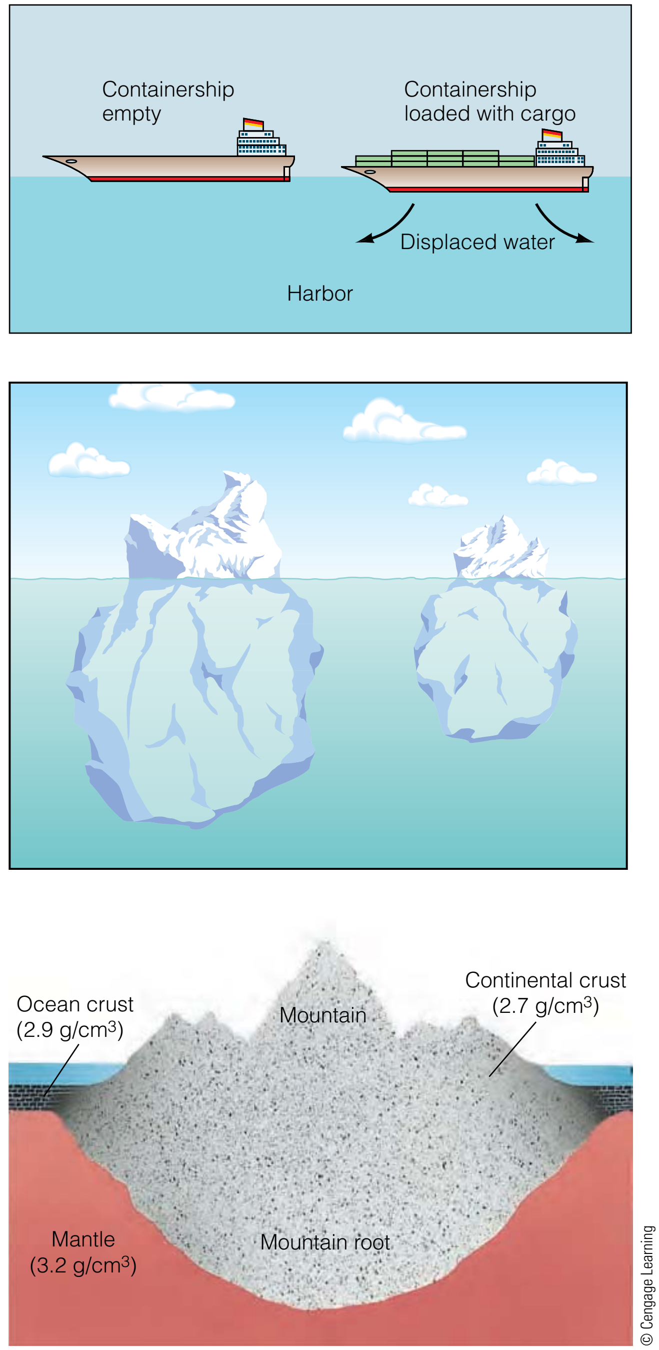


Figure 2.4 The principle of buoyancy.

a A ship sinks until it displaces a volume of water equal in weight to the weight of the ship and its cargo.

b Icebergs sink into water so that the same proportion of their volume (about 90%) is submerged. The more massive the iceberg, the greater this volume is. The large iceberg rides higher, but also extends to a greater depth than the small one.

c Continents are supported in a similar way.

2.2 Pieces of Earth's Surface Look Like They Once Fit Together

In some places the continents look as if they would fit together like jigsaw-puzzle pieces if the intervening ocean were removed. In 1620, Francis Bacon also wrote of a "certain correspondence" between shorelines on either side of the South Atlantic. **Figure 2.6a** shows this remarkable appearance. Could the continents have somehow been together in the distant past?

In a lecture in 1912, **Alfred Wegener**, a busy German meteorologist and polar explorer, proposed a startling and original theory, **continental drift**. Wegener suggested that all Earth's land had once been joined into a single supercontinent surrounded by an ocean. He called the landmass **Pangaea** (*pan*, "all"; *gaea*, "Earth, land") and the surrounding ocean **Panthalassa** (*pan*, "all"; *thalassa*, "ocean"). Wegener thought Pangaea had broken into pieces about 200 million years ago. Since then, he said, the pieces had moved to their present positions and were still moving.

Of course, Wegener's evidence included the apparent shoreline fit of continents across the North and South Atlantic, but he also commented on the alignment of mountain ranges of similar age, composition, and structure on both sides of the Atlantic. He pointed to the discovery of coal and the fossilized remains of tropical plants in frigid Antarctica, and even the similarities of fossils found across separated continents.

Wegener's ideas were originally dismissed because evidence at the time seemed to suggest that a deep, solid mantle supported the crust and mountains *mechanically* from below. Drift would be impossible with this kind of rigid subterranean construction. It took many years for the scientific consensus to

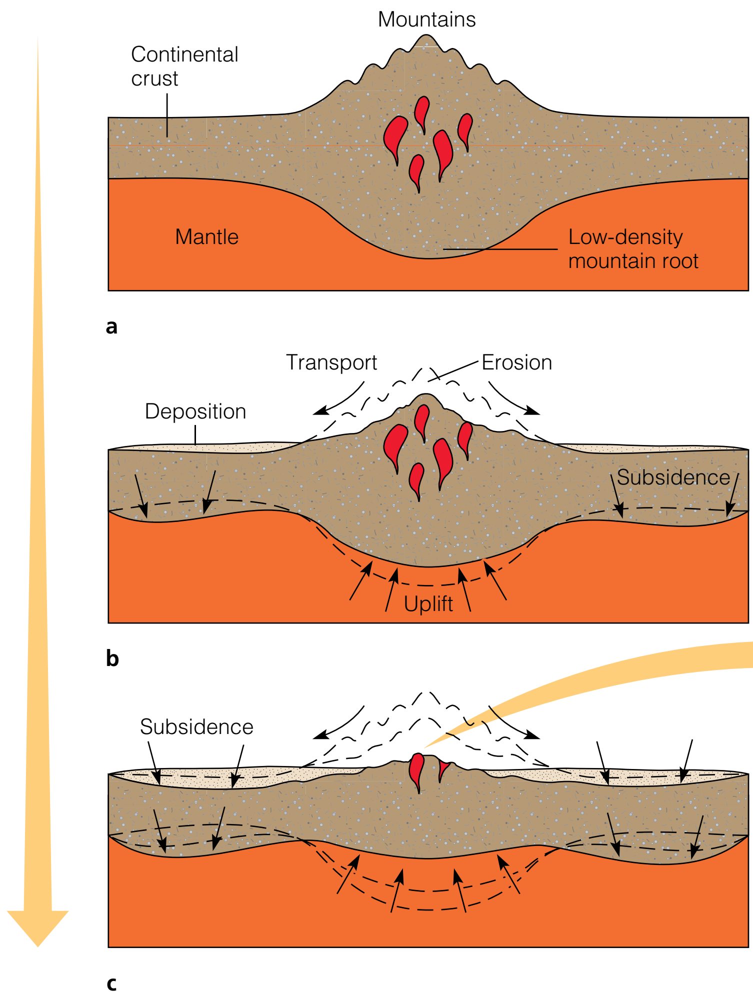
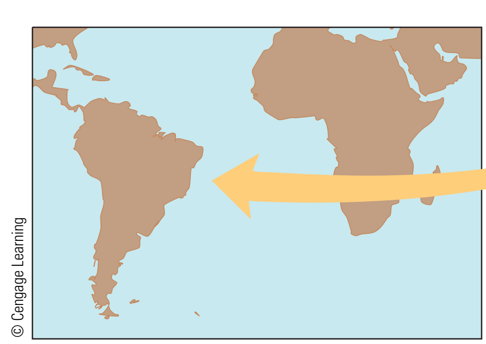


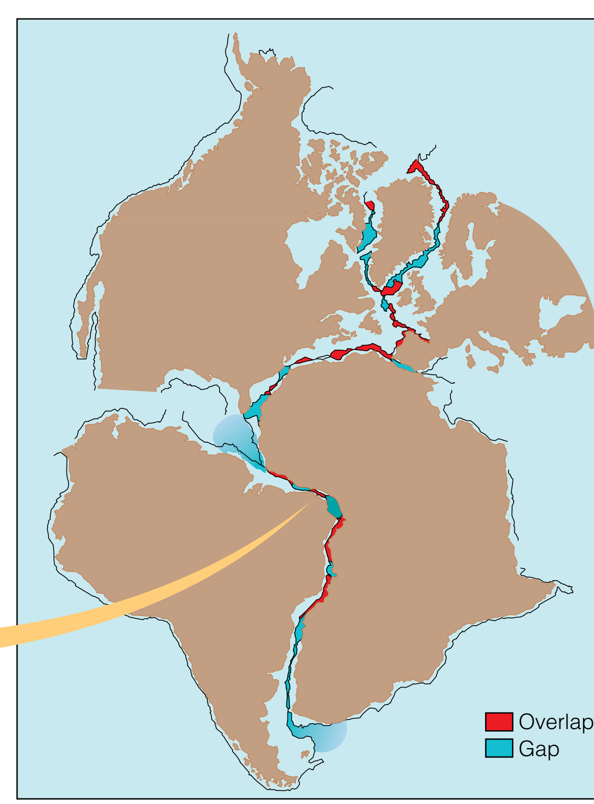
Figure 2.5 Erosion and isostatic readjustment can cause continental crust to become thinner in mountainous regions. As mountains are eroded over time **(a–c)**, isostatic uplift causes their roots to rise. (The same thing happens when a ship is unloaded or an iceberg melts.) Further erosion exposes rocks that were once embedded deep within the peaks, sometimes exposing once-buried structures like Half Dome in Yosemite Valley **(d)**.

Figure 2.6 Corresponding coastlines around the South Atlantic.

a From the time accurate charts became available in the late 1700s, observers noticed the remarkable coincidence of shape of the Atlantic coasts of Africa and South America.

b The fit of all the continents around the Atlantic at a water depth of about 137 meters (450 feet), as calculated by Sir Edward Bullard at the University of Cambridge in the 1960s. Note especially the relationship between Africa and South America. This early computer graphic was an effective stimulus to the tectonic revolution.





recognize that isostasy was responsible for a continent's vertical position and pave the way for a greater appreciation of Wegener's ideas.

In time, additional evidence began to support continental drift. Marine scientists probed the submerged edges of the continents and found that the ocean bottom nearly always sloped gradually out to sea for some distance and then dropped steeply to the deep-ocean floor. They realized that these shelflike continental edges were extensions of the continents themselves. Where they had measurements, researchers found that the fit between South America and Africa, impressive at the shoreline, was even better along the submerged edges of the continents. In an early use of computer graphics, researchers generated a best-fit view along these submerged edges (**Figure 2.6b**).

But if continents actually *move*, how could that occur?

2.3 The Breakthrough: Plate Tectonics

In 1960, Harry Hess of Princeton University and Robert Dietz of the Scripps Institution of Oceanography proposed a radical idea to explain the features of the ocean floor and the fit of the continents. They suggested that new seafloor develops at the Mid-Atlantic Ridge (and the other newly discovered ocean ridges) and then spreads outward from this line of origin. Continents would be pushed aside by the same forces that cause the ocean to grow. This motion could be powered by **convection currents**, slow-flowing circuits of material within the mantle (**Figure 2.7**).

Seafloor spreading, as the new theory was called, pulled many loose ends together. If the mid-ocean ridges were **spreading centers** and sources of new ocean floor rising from the asthenosphere, they should be hot. They were. If the new oceanic crust cooled as it moved from the spreading center, it should shrink in volume and become denser, and the ocean should be deeper farther from the spreading center. It was. Sediments at the edges of the ocean basin should be thicker

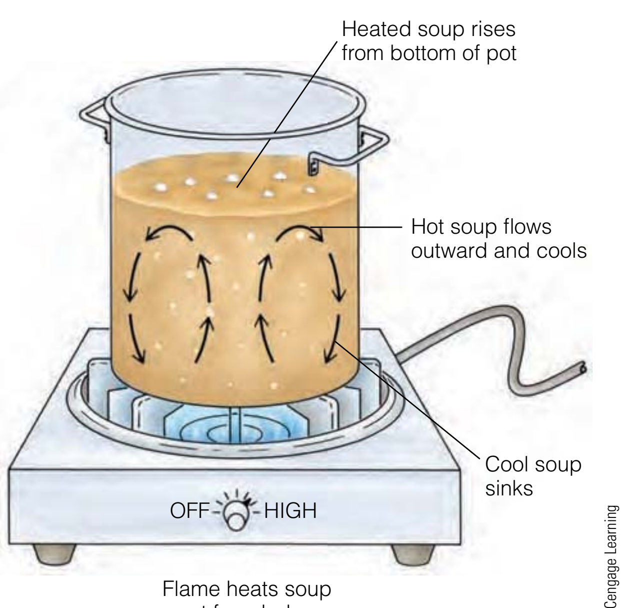


Figure 2.7 A convection current forms when soup is heated from the bottom of a pot.

than those near the spreading centers. They were, and they were also older.

Did this mean that Earth was continuously expanding? Since there was no evidence for an inflating Earth, the *creation* of new crust at spreading centers would have to be balanced by the *destruction* of crust somewhere else. Then researchers discovered that the crust plunges down into the mantle along the periphery of the Pacific. The process is known as **subduction**, and these areas are called **subduction zones**. The zones of concentrated earthquakes were found in regions of crustal formation (spreading centers) and crustal destruction (subduction zones).

In 1965, **John Tuzo Wilson**, a geophysicist at the University of Toronto, integrated the idea of seafloor spreading into the overriding concept of **plate tectonics**. In this theory Earth's outer layer consists of about a dozen separate major lithospheric **plates** floating on the asthenosphere. When heated from below, some parts of the deformable asthenosphere expand, become less dense, and rise (**Figure 2.8**). These rising plumes turn aside when they reach the lithosphere, lifting and cracking the crust to form the plate edges. The newly forming pair of plates (one on each side of the spreading center at the top of the plume) slides down the swelling ridges—they diverge from the spreading center. New seabed forms in the area of divergence. In subduction zones, the descending slab pulls the rest of the plate downward, influencing the rate of plate movement.

The large plates include both continental and oceanic crust. The major plates jostle about like huge slabs of ice on a warming lake. Plate movement is slow in human terms, averaging about 5 centimeters (2 inches) a year (about the rate at which your fingernails grow). The plates interact at converging, diverging, or sideways-moving boundaries, sometimes forcing one another below the surface or wrinkling into mountains. We now know *through the great expanse of geologic time, this slow movement remakes the surface of Earth, expands and splits continents, and forms and destroys ocean basins.* The less dense, ancient granitic continents ride high in the lithospheric plates, rafting on the slowly moving asthenosphere below. The more dense, younger basaltic oceanic crust rides lower on the asthenosphere in the same way that a fully loaded containership floats lower than when it is empty (see Figure 2.4a). The dense and thin crust forms the low-lying ocean basins. This process has progressed since Earth's crust first cooled and solidified.

Figure 2.8 presents an overview of the tectonic system. This modern understanding of the ever-changing nature of Earth has given fresh meaning to historian Will Durant's warning: "Civilization exists by geological consent, subject to change without notice."

Plates Interact at Plate Boundaries

Figure 2.9 is a plot of about 10,000 earthquakes. Notice the odd pattern they form that generally traces out the plate boundaries.

The lithospheric plates and their margins are shown in **Figure 2.10**. Plates interact with neighboring plates along their mutual boundaries. The three types of plate boundaries that result from these interactions are:

- Divergent plate boundaries (two plates move apart from each other)

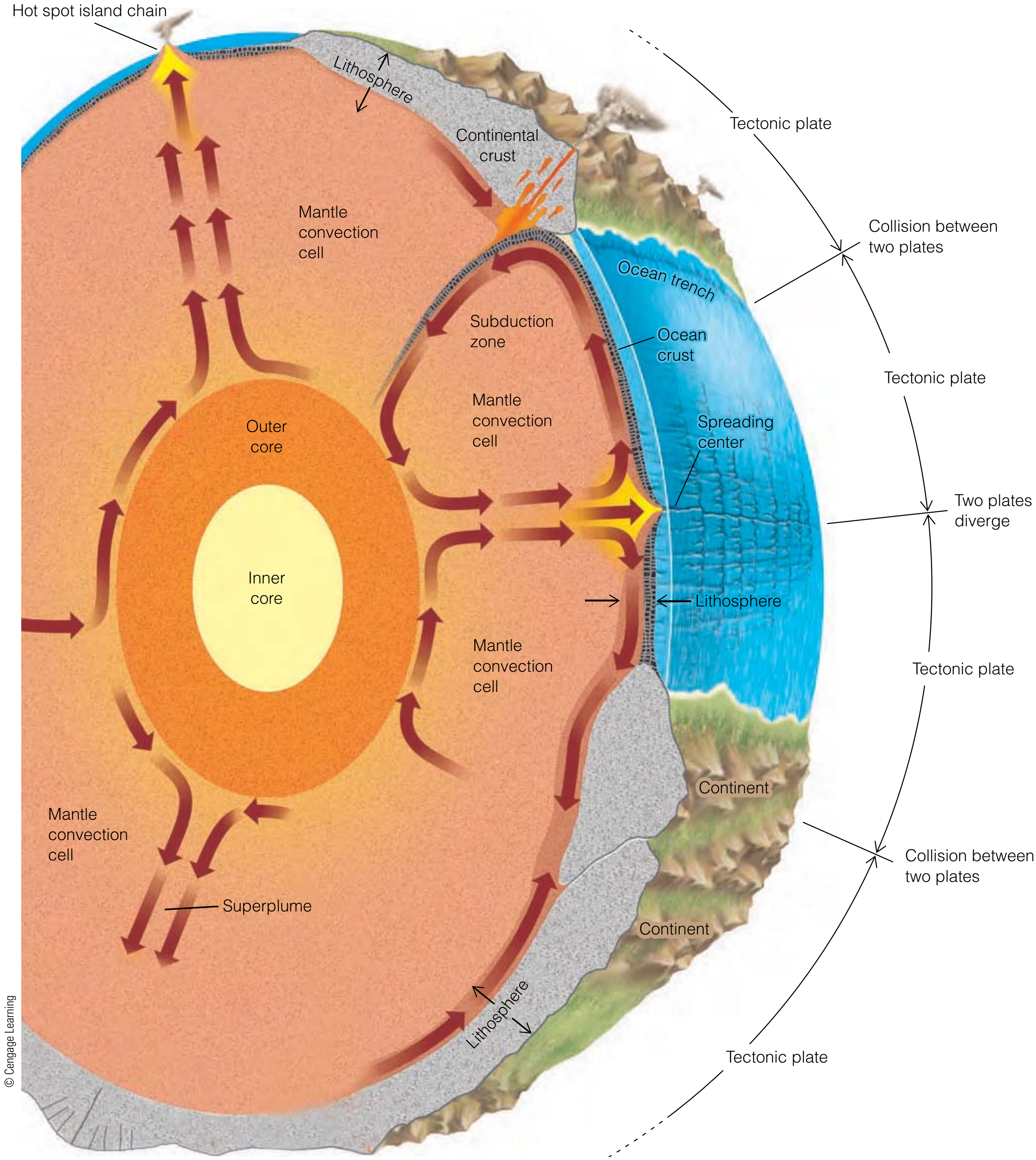


Figure 2.8 The tectonic system is powered by heat. Some parts of the mantle are warmer than others, and convection currents form when warm mantle material rises and cool material falls. Above the mantle floats the cool, rigid lithosphere, which is fragmented into plates. Plate movement is powered by gravity: The plates slide down the ridges at the places of their formation; their dense, cool leading edges are pulled back into the mantle. Plates may move away from one another (along the ocean ridges), toward one another (at subduction zones or areas of mountain building), or past one another (as at California's San Andreas Fault). Smaller localized convection currents form cylindrical plumes that rise to the surface to form hot spots (like the Hawai'ian Islands). Note that the whole mantle appears to be involved in thermal convection currents.

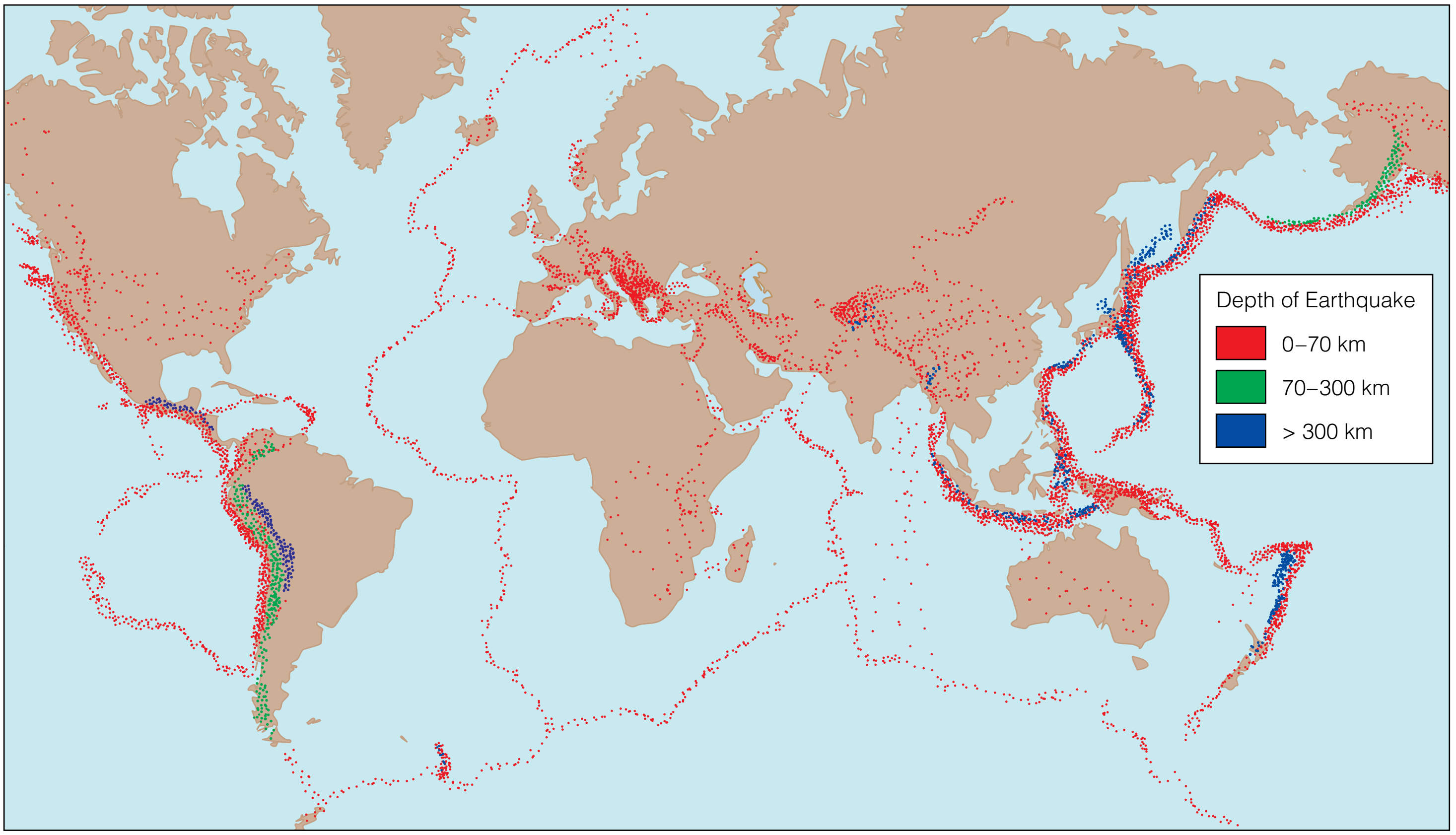


Figure 2.9 Seismic events worldwide, January 1977 through December 1986. The locations of about 10,000 earthquakes are colored red, green, and blue to represent event depths of 0 to 70 kilometers (0–43 miles), 70 to 300 kilometers (43–186 miles), and below 300 kilometers (186 miles), respectively.

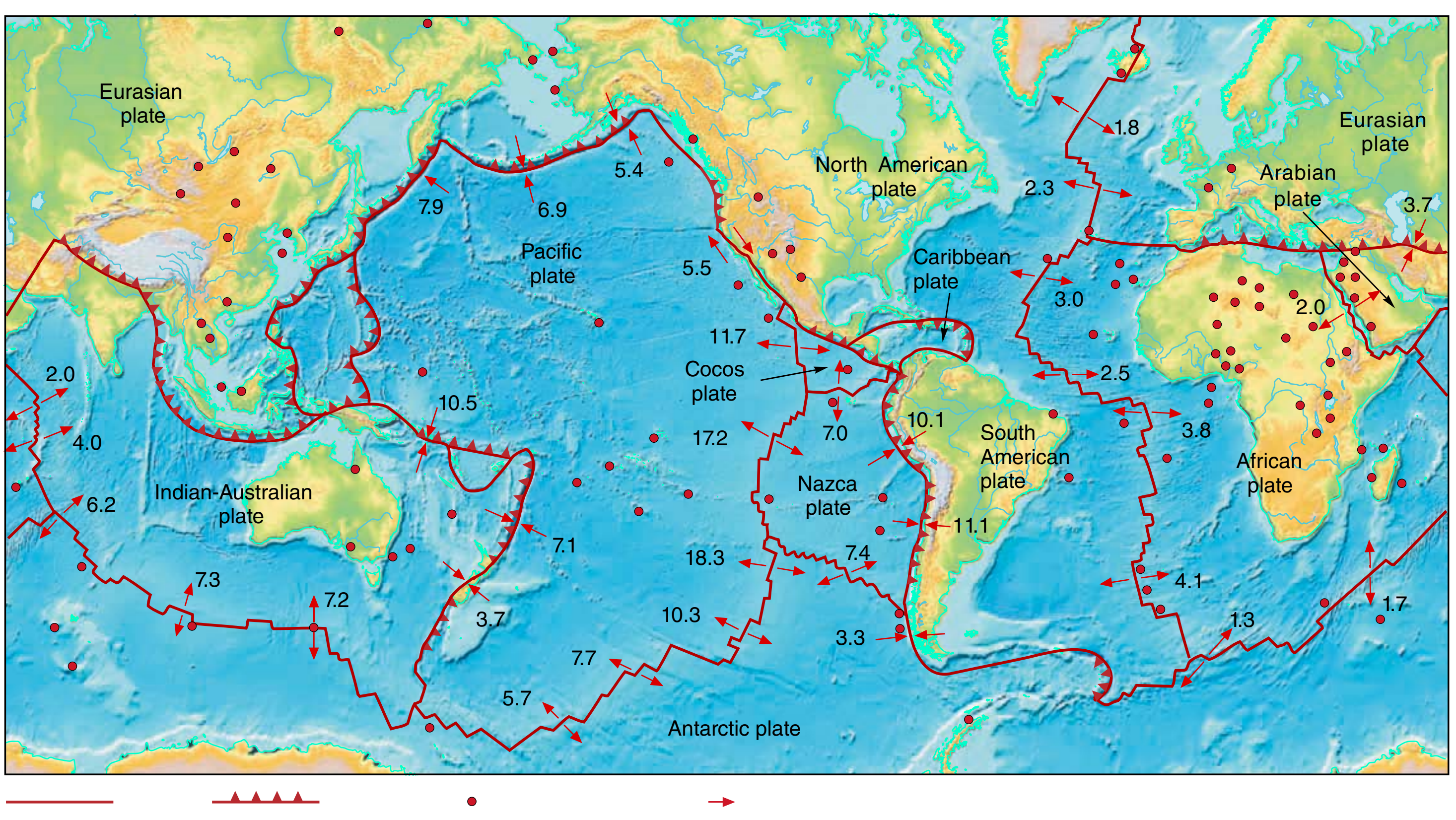


Figure 2.10 The major lithospheric plates, showing their directions of relative movement and the location of the principal hot spots. Note the correspondence of plate boundaries and earthquake locations—compare this figure with Figure 2.9. Most of the million or so earthquakes and volcanic events each year occur along plate boundaries.

- Convergent plate boundaries (two plates move toward each other and interact)
- Transverse (or transform) plate boundaries (two plates slide laterally past each other)

Look for these boundaries in **Figure 2.11**.

Ocean Basins Form at Divergent Plate Boundaries

Imagine the effect a rising plume of heated mantle might have on overlying continental crust. Pushed from below, the relatively brittle continental crust would arch and fracture. The broken pieces would be pushed apart by the diverging asthenosphere, and spaces between the blocks of continental crust would be filled with newly formed (and relatively dense) oceanic crust. As the broken plate separated at this new spreading center, molten rock called **magma** would rise into the crustal fractures. (Magma is called *lava* when found aboveground.) Some of the magma would solidify in the fractures; some would erupt from volcanoes. A **rift valley** would form (**Figure 2.12**).

The East African Rift, one of the newest and largest of Earth's rift valley systems, was formed in this way. It extends from Ethiopia to Mozambique, a distance of nearly 3,000 kilometers (1,860 miles). In the south, long, linear depressions have partially filled with water to form large freshwater lakes. To the north, the rift widens to form the Red Sea and the Gulf of Aden. Between the freshwater lakes to the south and the gulfs to the north, seawater is leaking through the fractured crust to fill small depressions—the first evidence of an ocean-basin-to-be in central eastern Africa.

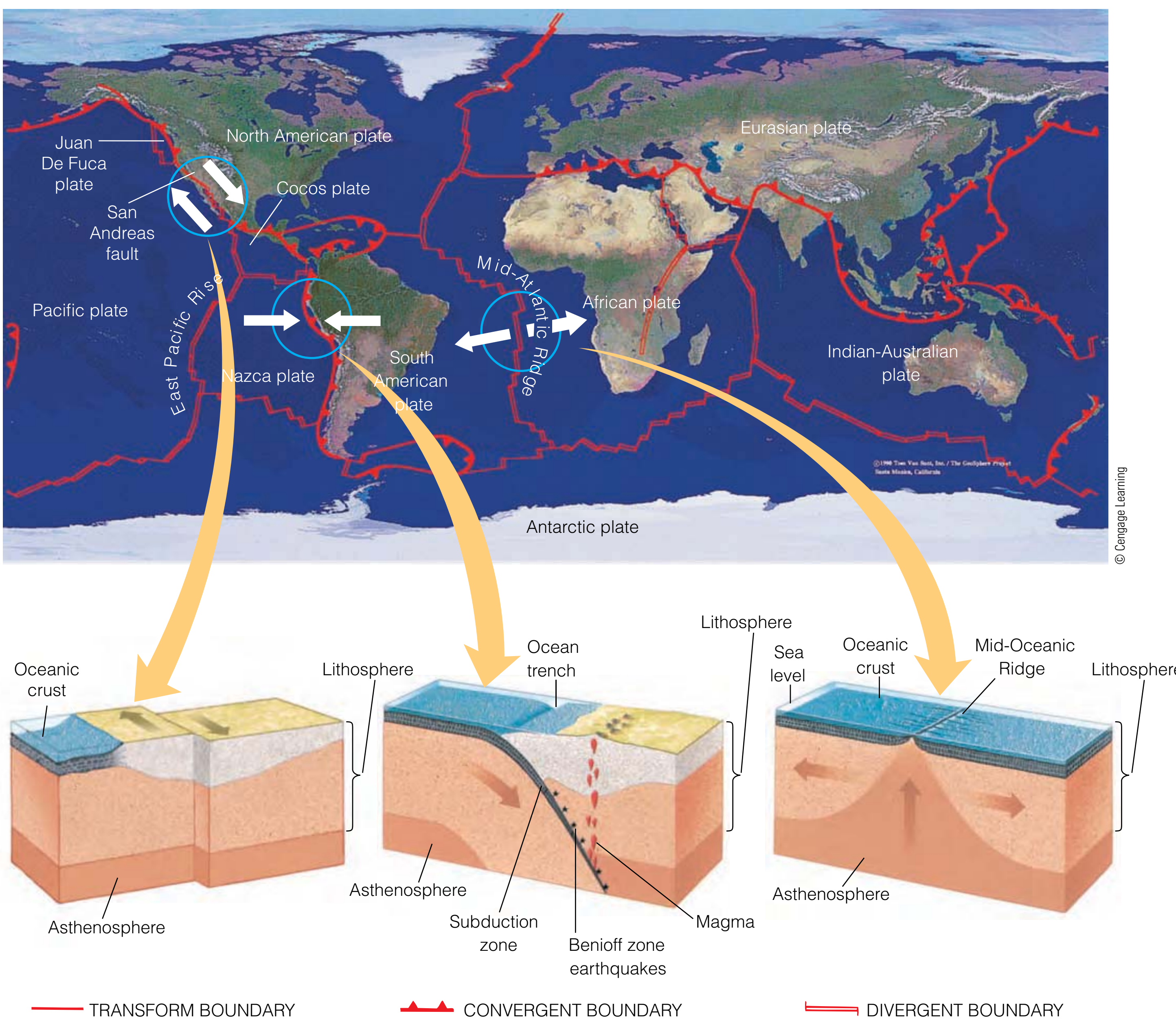


Figure 2.11 Plate boundaries in action. Lateral movement at *transform* boundaries causes shear, compression at *convergent* boundaries produces buckling and shortening, and extension of *divergent* boundaries causes splitting and rifting.

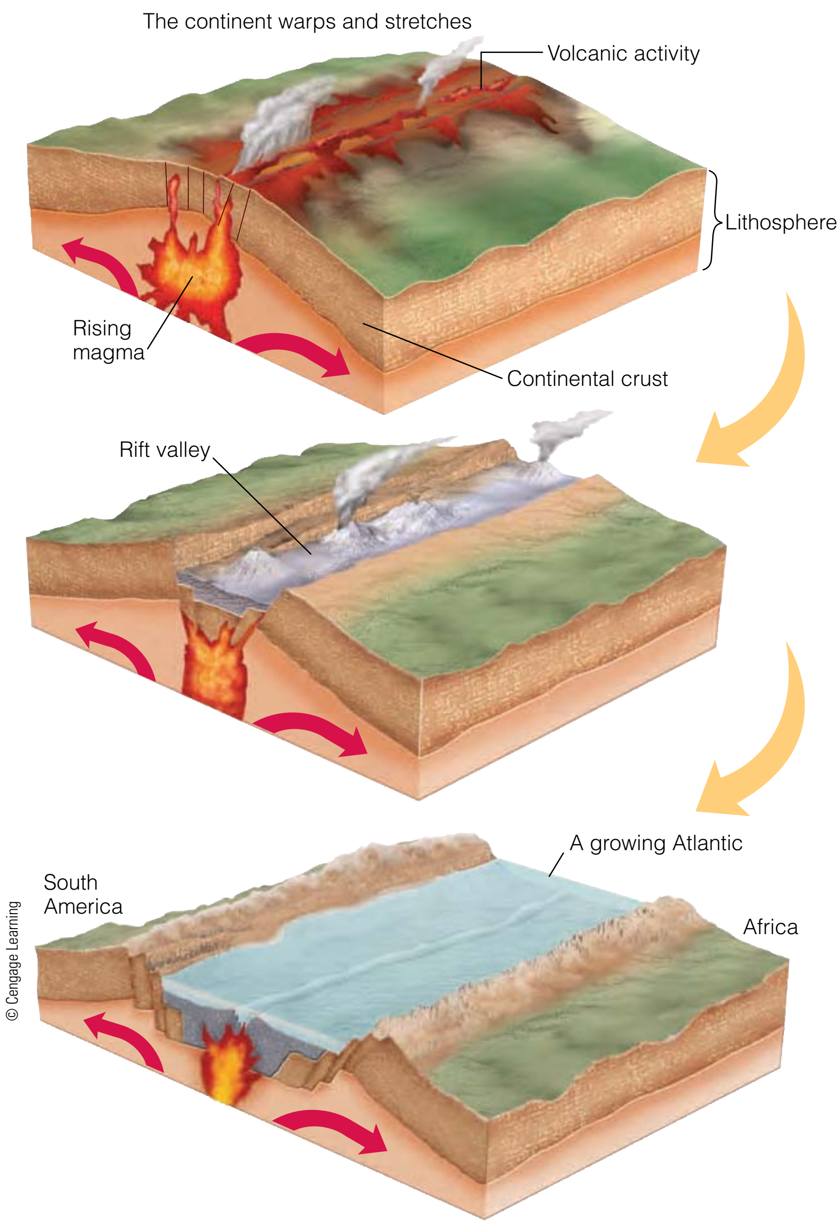


Figure 2.12 A model for the formation of a new plate boundary: the formation of the Atlantic.

a As the lithosphere began to crack, a rift formed beneath the continent, and molten magma began to rise to form a new basaltic ocean floor.

b As the rift continued to open, the two new continents were separated by a growing ocean basin. Volcanoes and earthquakes occur along the active rift area, which is the mid-ocean (mid-Atlantic) ridge. The East African Rift Valley, although not yet submerged, currently resembles this stage.

c A new ocean basin forms beneath a new ocean.

The Atlantic Ocean experienced a similar youth. Like the East African Rift, the spreading center of the Mid-Atlantic Ridge is a **divergent plate boundary**, a line along which two plates are moving apart and at which oceanic crust forms. The growth of the Atlantic began about 210 million years ago when heat caused the asthenosphere to expand and rise, lifting and fracturing the lighter, solid lithosphere above.[1] **Figure 2.13** shows the Atlantic, a large new ocean basin that formed between the diverging plates when the rift became deep enough for water to collect. A long mid-ocean ridge divided by a central rift valley traverses the ocean floor roughly equidistant from the shorelines in both the North and South Atlantic, terminating north of Iceland.

Plate divergence is not confined to East Africa or the Atlantic, nor has it been limited to the last 200 million years. The Mid-Atlantic Ridge has counterparts in the Pacific and Indian oceans. A section of the Pacific floor, for example, diverges along the East Pacific Rise and the Pacific-Antarctic Ridge, spreading centers that form the eastern and southern boundaries of the great Pacific Plate. In East Africa, rift valleys have formed relatively recently as plate divergence begins to separate another continent. As happened in the Red Sea, the ocean will invade when the rift becomes deep enough.

Island Arcs Form, Continents Collide, and Crust Recycles at Convergent Plate Boundaries

Since Earth is not getting larger, divergence in one place must be offset by convergence in another. Oceanic crust is destroyed at **convergent plate boundaries**, regions of violent geological activity where plates push together.

Ocean–Continent Convergence

South America, embedded in the westward-moving South American Plate, encounters the Pacific's Nazca Plate as it moves eastward. The relatively thick and light continental lithosphere of South America rides up and over the heavier

[1] How do we know the age of rocks? Appendix 3 explains the process.

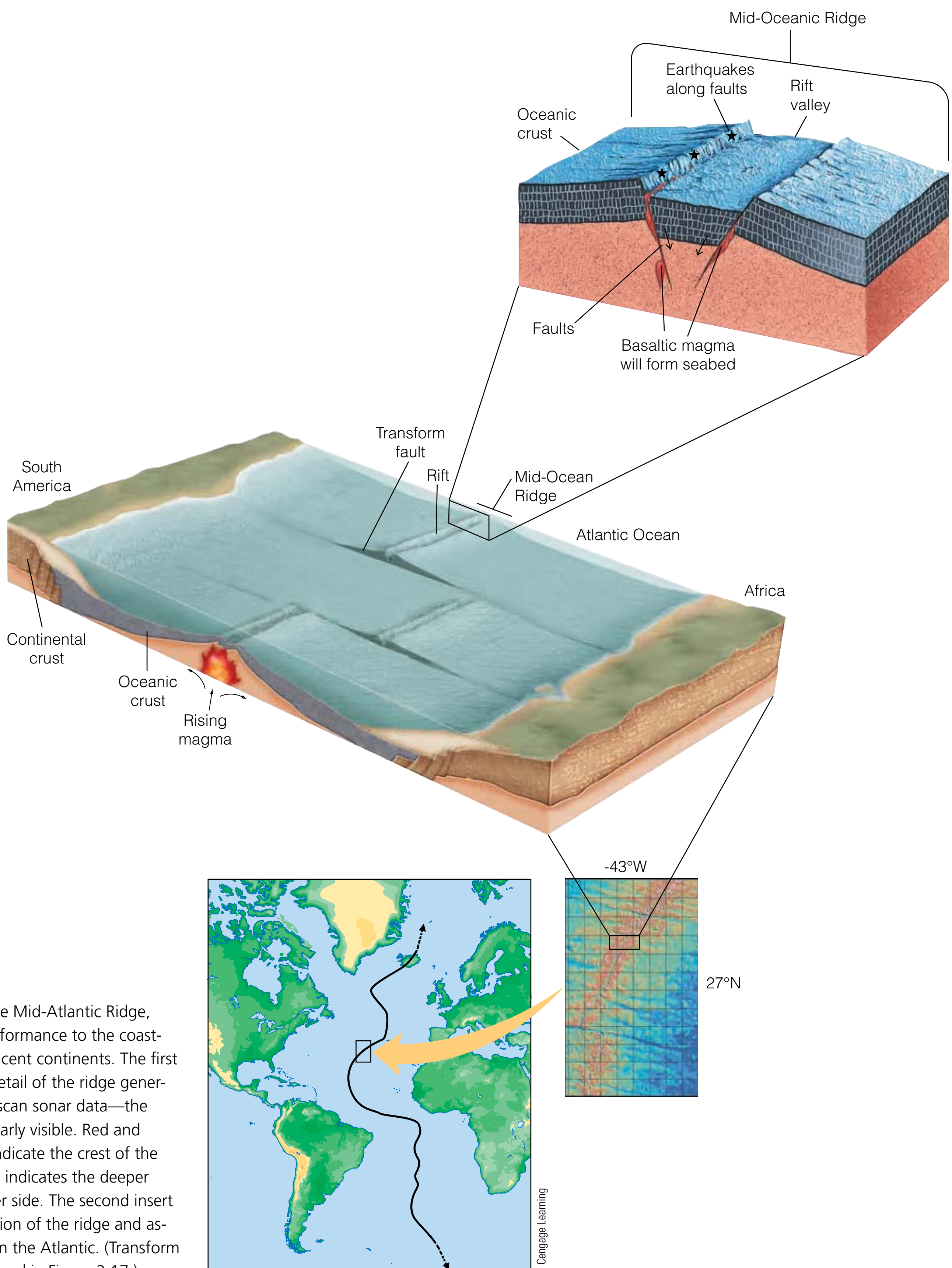


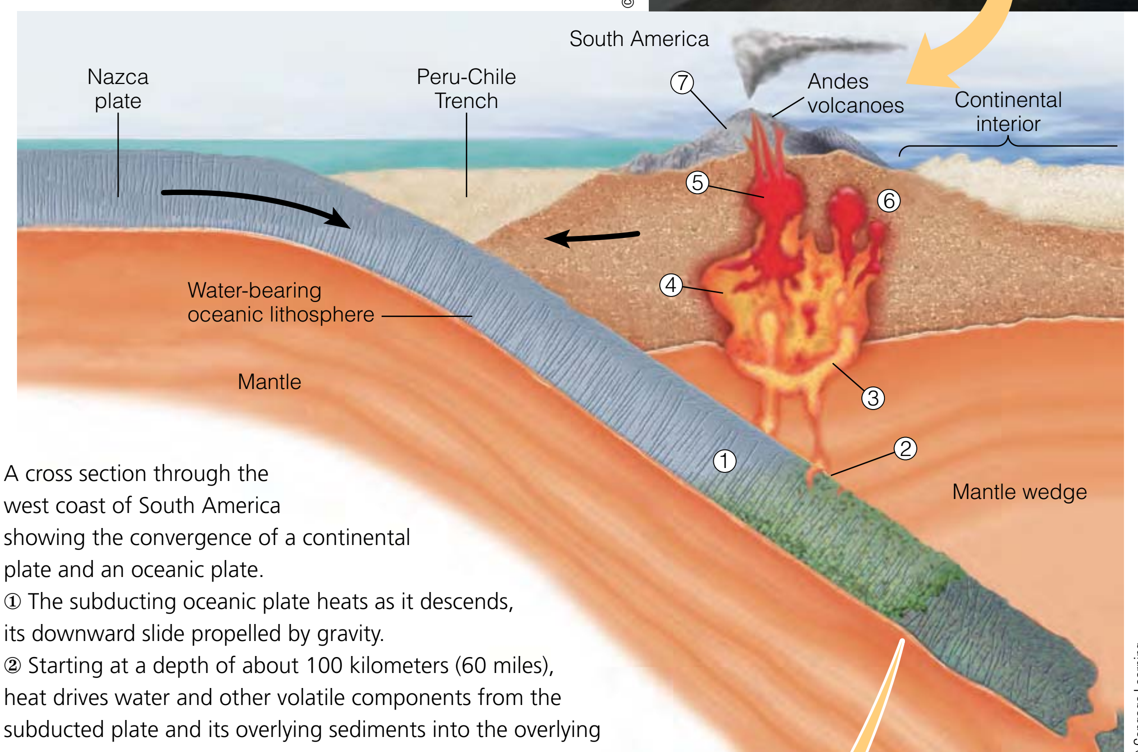
Figure 2.13 The Mid-Atlantic Ridge, showing its conformance to the coastlines of the adjacent continents. The first inset shows a detail of the ridge generated from side-scan sonar data—the central rift is clearly visible. Red and orange colors indicate the crest of the ridge; dark blue indicates the deeper seabed on either side. The second insert shows the location of the ridge and associated valley in the Atlantic. (Transform faults are explained in Figure 2.17.)

oceanic lithosphere of the Nazca Plate, which is subducted along the deep trench that parallels the west coast of South America. **Figure 2.14** is a cross section through these plates.

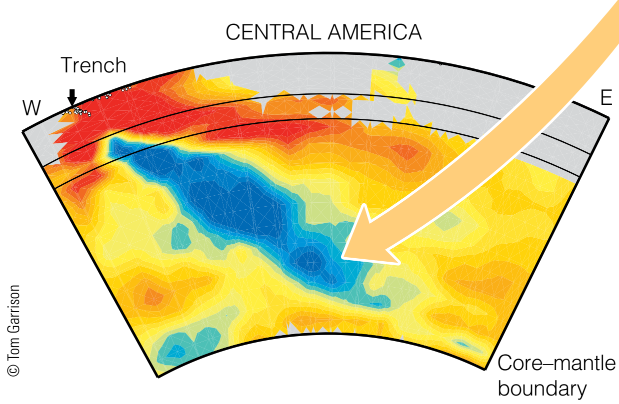
Some of the oceanic crust and its sediments will melt as the plate plunges downward and its temperature rises. Volatile components—mostly water and carbon dioxide—are driven off and rise toward the overriding plate. This, in turn, lowers the melting temperature of the surrounding mantle, forming magma rich in dissolved gases. In places this magma then rises through overlying layers to the surface and causes

Figure 2.14 Subduction.

b An Andean volcano in full blast in 2006. The 5,000-meter (16,400 feet) high volcano Tungurahua, located in Equador, becomes active roughly every 90 years.



a A cross section through the west coast of South America showing the convergence of a continental plate and an oceanic plate.
① The subducting oceanic plate heats as it descends, its downward slide propelled by gravity.
② Starting at a depth of about 100 kilometers (60 miles), heat drives water and other volatile components from the subducted plate and its overlying sediments into the overlying mantle, lowering its melting point.
③ Masses of the melted material rise and "underplate" the continental crust in places.
④ Heat from the rising material melts the continental crust and
⑤ mixes with it.
Some of this mixture solidifies in place ⑥,
but some can rise to the surface and power Andean volcanoes ⑦.



c A vertical slice through Earth's mantle beneath Central America showing the distribution of warmer (red) and colder (blue) material. The configuration of colder material suggests that the subducting slab has penetrated to the core–mantle boundary, which is at a depth of about 2,900 kilometers (1,800 miles).

volcanic eruptions. The high volumes of gas contained in these melts can be explosively released as the magma nears the surface. The violent volcanoes of Central America and South America's Andes Mountains are a product of this activity, as are the area's numerous earthquakes. The North American Cascade volcanoes, including Mount St. Helens, result from similar processes.

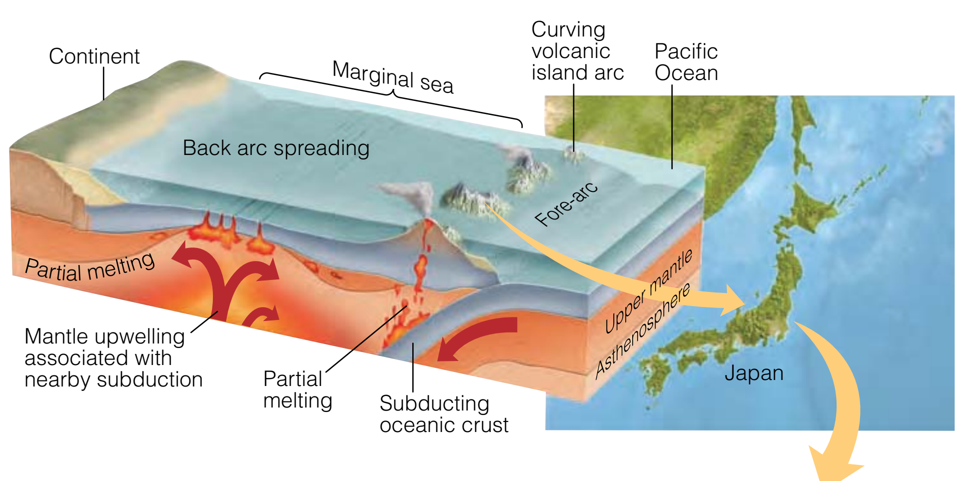
Most of the subducted crust mixes with the mantle. As shown in **Figure 2.14c**, some of it continues downward through the mantle, eventually reaching the mantle–core boundary 2,800 kilometers (1,740 miles) beneath the surface! Subduction at converging oceanic plates was responsible for the great Alaska earthquake of 1964 and the devastating tsunami-generating Indian Ocean earthquake of 2004. Plate convergence (and divergence) is faster in the Pacific than in the Atlantic, in a few places reaching a rate of 18 centimeters (7 inches) a year. You can now clearly see the source of the aptly named "**Pacific Ring of Fire**," the violent circle of seismic activity surrounding the Pacific Plate.

Ocean–Ocean Convergence

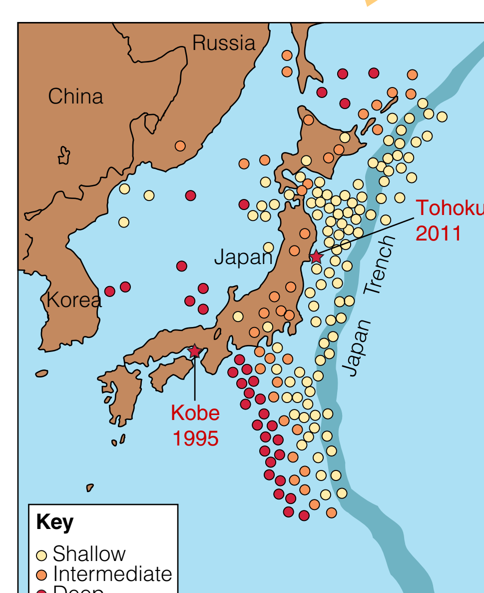
In the previous example, continental crust met oceanic crust. What happens when two *oceanic* plates converge? One of the colliding plates will usually be older, and therefore cooler and denser, than the other. Pulled by gravity, this heavier plate will slip steeply below the lighter one into the asthenosphere. The ocean bottom distorts in these areas to form deep trenches, the ocean's greatest depths. Again, the temperature of the descending plate rises, and water and carbon dioxide trapped with the melting rock of the subducting plate rise into the overlying mantle, lowering its melting point. As before, this fluid melt of magma and subducted material forms a relatively light magma that powers vigorous volcanoes, but the volcanoes emerge from the seafloor rather than from a continent. These volcanoes appear in patterns of curves on the overriding oceanic crust; when they emerge above sea level they form curving arcs of islands as seen in the Caribbean island chain, the Aleutian Islands in Alaska, or the Japanese islands (**Figure 2.15**).

Convergent margins are vast "continent factories," where materials from the surface descend and are heated, compressed, partially liquefied, separated, mixed with surrounding materials, and recycled to the surface. Relatively light continental crust is the main product, and it is produced at a rate of about 1 cubic kilometer (0.24 cubic mile) per year. Some geophysicists believe all of Earth's continental crust may have originated from granitic rock produced in this way. The island arcs may have coalesced to form larger and larger continental masses.

Figure 2.15 The formation of island arcs.



a The formation of an island arc along a trench as two oceanic plates converge. The volcanic islands form as masses of magma reach the seafloor. The Japanese islands were formed in this way.



b The distribution of shallow, intermediate, and deep earthquakes for part of the "Pacific Ring of Fire" in the vicinity of the Japan trench. Note that earthquakes occur only on one side of the trench, the side on which the plate subducts. The sites of the catastrophic 1995 Kobe and 2011 Tohoku subduction earthquakes are marked.

Continent–Continent Convergence

Two plates bearing continental crust can also converge. Because both plates are of approximately equal density, neither plate edge is subducted; instead, both are compressed, folded, and uplifted, to form mountains as **Figure 2.16** shows. These mountains—Earth's largest land features—are composed of the remains of sedimentary rocks originally formed from seabed sediments. The most spectacular example of such a collision, between the India-Australian and Eurasian Plates some 45 million years ago, formed the Himalayas. The lofty top of Mount Everest is made of rock formed from sediments deposited long ago in a shallow sea!

Crust Fractures and Slides at Transform Plate Boundaries

Remember, movement of lithospheric plates over the mantle is occurring on the surface of a sphere, not on a flat plane. The axis of spreading is not a smoothly curving line but a jagged trace abruptly offset by numerous faults. These features are called **transform faults** (**Figure 2.17**. Look for these features on the mid-ocean ridges of Figure 2.13). Transform faults are named from the fact that the relative plate motion is changed, or transformed, along them. We will discuss transform faults in more detail in Chapter 3 in our discussion of the mid-ocean ridge system (see, for example, Figure 3.12), but the concept is important in our discussion of plate boundaries because lithospheric plates shear laterally past one another at **transform plate boundaries**. Crust is neither produced nor destroyed at this type of junction.

The potential for earthquakes at transform plate boundaries can be great as the plate edges slip past each other. The eastern boundary of the Pacific Plate is a long transform fault system. Shown in **Figure 2.17c**, California's San Andreas Fault is merely the most famous of the many faults that mark the junction between the Pacific and North American plates. The Pacific Plate moves steadily, but its movement is stored elastically at the North American Plate boundary until friction is overcome. Then the Pacific Plate lurches in abrupt jerks to the northwest along much of its shared border with the North American Plate, an area that includes the major population centers of California. These jerks cause California's famous earthquakes. Because of this movement, coastal southwestern California is gradually sliding north along the rest of North America; some 50 million years from now, it will encounter the Aleutian Trench near Alaska.

2.4 The Confirmation of Plate Tectonics

The theory of plate tectonics has had the same revolutionary effect on geology that the theory of evolution has had on biology. In each case a catalog of seemingly unrelated facts was unified by a powerful unifying idea. Many discoveries contributed to our present understanding of plate tectonics, but the most compelling evidence is locked within the floors of the young ocean basins themselves.

History of Plate Movement Has Been Captured in Residual Magnetic Fields

Earth's persistent magnetic field is caused by the movement of molten metal in the outer core. A compass needle points toward the magnetic north pole because it aligns with Earth's magnetic field (**Figure 2.18**). Tiny particles of an iron-bearing magnetic mineral called *magnetite* occur naturally in basaltic magma. When this magma erupts at mid-ocean ridges, it cools to form solid rock. The magnetic minerals act like miniature compass needles. As they cool to form new seafloor, the minerals' magnetic fields align with Earth's magnetic field. Thus, the orientation of Earth's magnetic field at that particular time becomes frozen in the rock as it solidifies. Any later change in the strength or direction of Earth's magnetic field will not significantly change the characteristics of the field trapped within the solid rocks. **Figure 2.19** shows the process. The "fossil," or remanent, magnetic field of a rock is known as **paleomagnetism** (*palaios*, "ancient").

A magnetometer measures the amount and direction of residual magnetism in a rock sample. In the late 1950s, geophysicists towed sensitive magnetometers just above the ocean floor to detect the weak magnetism frozen in the rocks. When plotted on charts, the data revealed a pattern of symmetrical

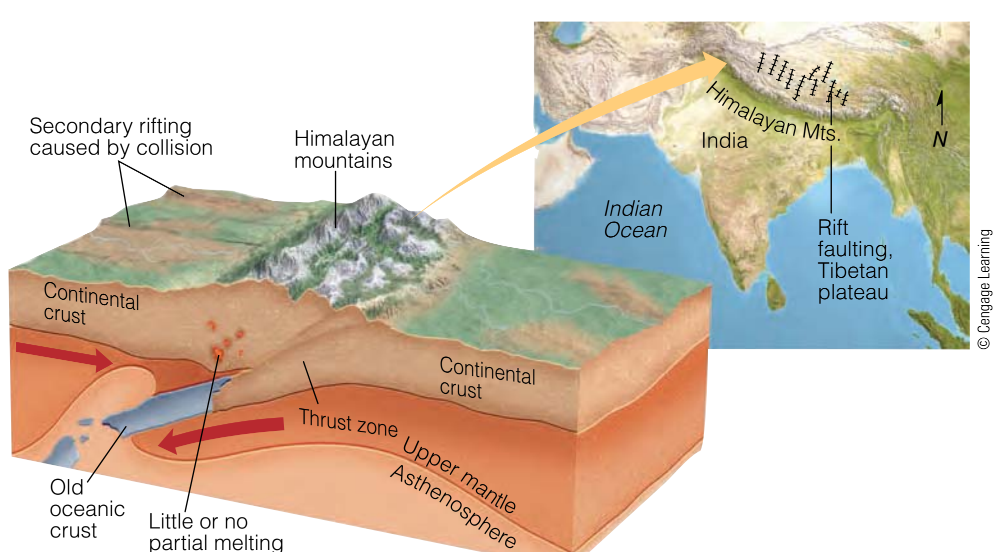
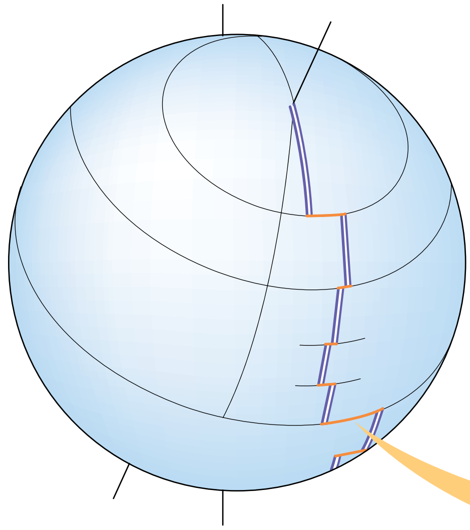
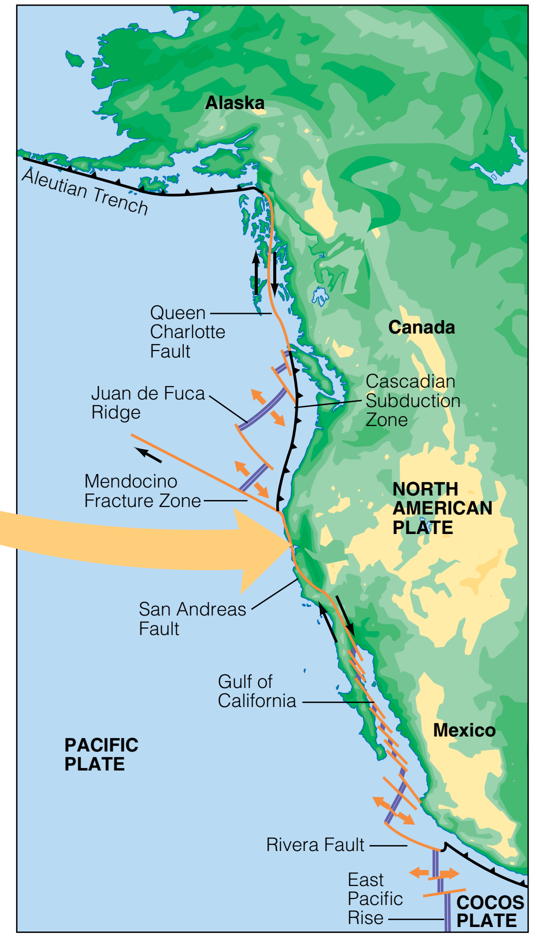


Figure 2.16 A cross section through the Himalayan plateau, showing the convergence of two continental plates. Neither plate is dense enough to subduct; instead, their compression and folding uplift the plate edges to form the Himalayan Mountains. Notice the massive supporting "root" beneath the emergent mountain needed for isostatic equilibrium. The devastating 2015 earthquake in Nepal was triggered by isostatic readjustment.

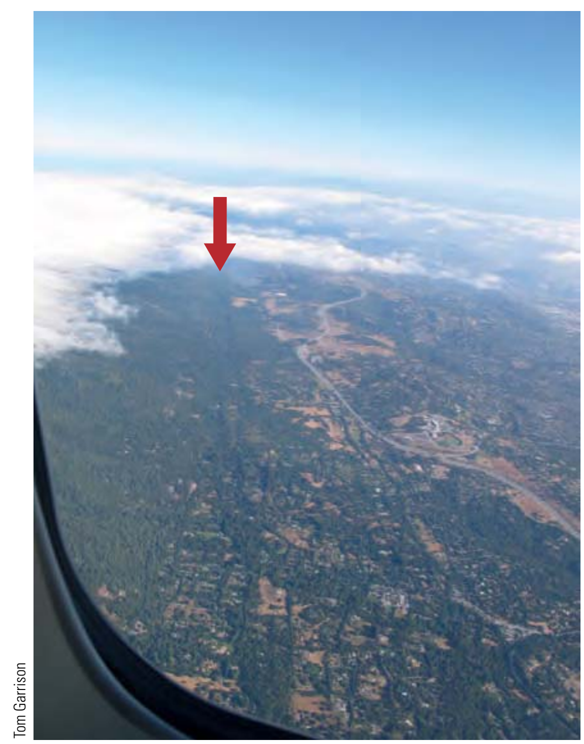
Figure 2.17



a Transform faults (orange) form because the axis of seafloor spreading on the surface of a sphere cannot follow a smoothly curving line. The motion of two diverging lithospheric plates (*arrows*) rotates about an imaginary axis extending through Earth.



b A long transform plate boundary, which includes California's San Andreas Fault. Note the offset plate boundaries caused by divergence on a sphere.



c California's San Andreas Fault, a transform fault. The fault trace is clearly visible beneath the arrow in this photograph taken south of San Francisco.

magnetic stripes or bands on both sides of a spreading center (**Figure 2.20**). The magnetized minerals contained in the rocks of some stripes add to Earth's present magnetic orientation to enhance the strength of the local magnetic field, but the magnetism in rocks in adjacent stripes weakens it. What could cause such a pattern?

In 1963, geologists Drummond Matthews, Frederick Vine, and Lawrence Morley proposed a clever interpretation. They knew similar magnetic patterns had been found in layered lava flows on land that had been independently dated by other means. They also knew that Earth's magnetic field reverses at irregular intervals of a few hundred thousand years. In a time of reversal a compass needle would point south instead of north, and any particles of cooling magnetic material in fresh seafloor basalt at a spreading center would be imprinted with the reversed field. The alternating magnetic stripes represent rocks with alternating magnetic polarity—one band having normal polarity (magnetized in the same direction as today's magnetic field direction), and the next band having reversed polarity (opposite from today's direction). These researchers realized that the pattern of alternating weak and strong magnetic fields was symmetrical because freshly magnetized rocks born at the ridge are spread apart and carried away from the ridge by plate movement.

By 1974, scientists had compiled charts showing the paleomagnetic orientation—and the age—of the seafloors of the eastern Pacific and the Atlantic for about the last 200 million years (**Figure 2.21**). Plate tectonics beautifully explains these patterns, and the patterns themselves are among the most compelling of all arguments for the theory.