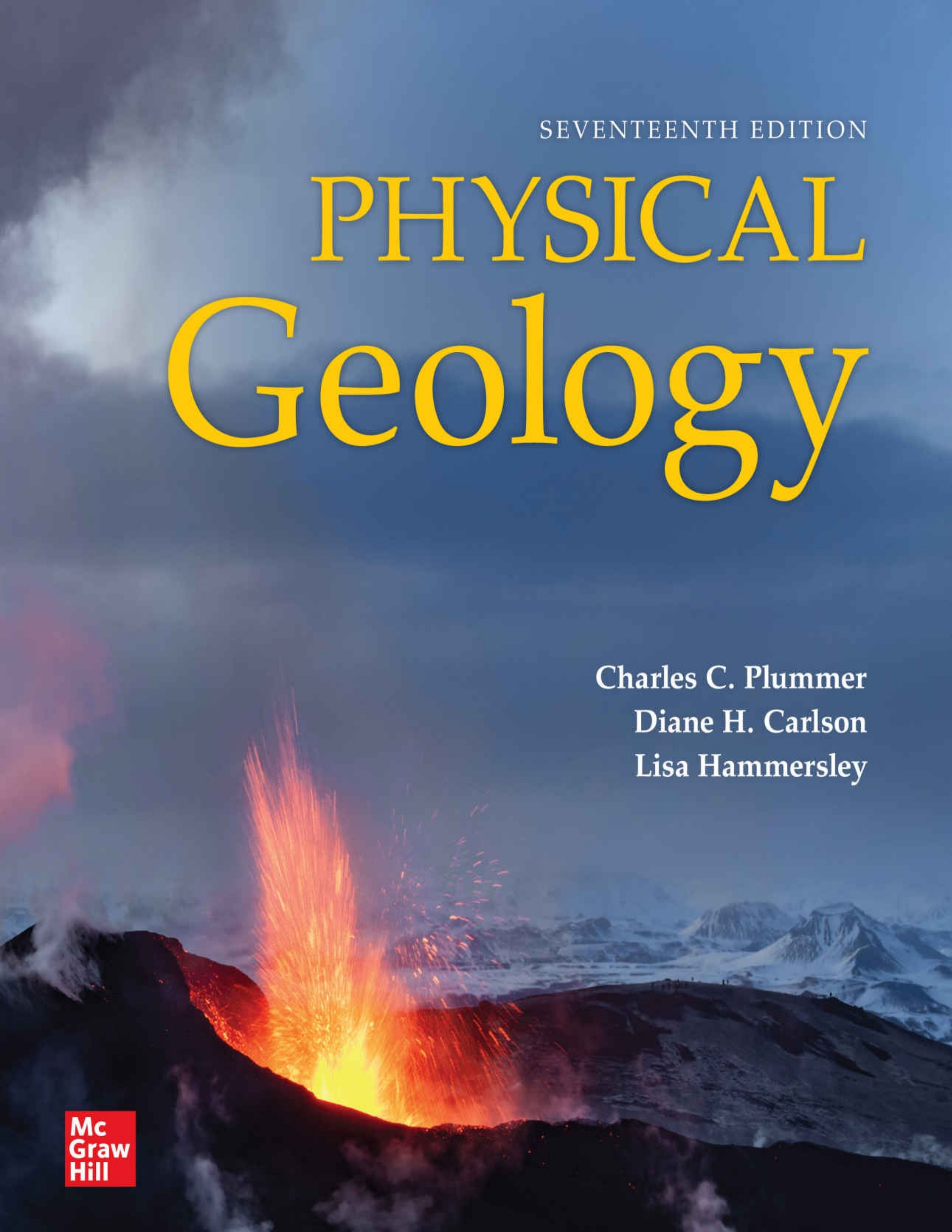
SEVENTEENTH EDITION

PHYSICAL Geology

Charles C. Plummer
Diane H. Carlson
Lisa Hammersley



Mc Graw Hill

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Charles C. Plummer

Emeritus of California State University at Sacramento

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Published by McGraw Hill LLC, 1325 Avenue of the Americas, New York, NY 10121.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 24 23 22 21

ISBN 978-1-260-72224-6 (bound edition)

MHID 1-260-72224-4 (bound edition)
ISBN 978-1-266-07356-4 (loose-leaf edition)
MHID 1-266-07356-6 (loose-leaf edition)

Portfolio Manager: *Marah Bellegarde*

Product Developer: *Melisa Seegmiller*
Marketing Manager: *Kelly Brown*
Content Project Managers: *Kelly Hart, Rachael Hillebrand*
Buyer: *Susan K. Culbertson*
Designer: *Beth Blech*
Content Licensing Specialist: *Melissa Homer*
Cover Image: *J. Helgason/Shutterstock*
Compositor: *SPi Global*

Library of Congress Cataloging-in-Publication Data

Names: Plummer, Charles C., 1937- author. | Carlson, Diane H., author. | Hammersley, Lisa, author.
Title: Physical geology / Charles C. Plummer, Diane H. Carlson, Lisa Hammersley.
Description: Seventeenth edition. | New York, NY : McGraw-Hill Education, 2021. | Includes index.
Identifiers: LCCN 2020022087 | ISBN 9781260722246 (paperback)
Subjects: LCSH: Physical geology—Textbooks.
Classification: LCC QE28.2 .P58 2021 | DDC 551—dc23
LC record available at https://lccn.loc.gov/2020022087

mheducation.com/highered

About the Cover

The cover photo shows an effusive eruption of basaltic lava (see chapters 3 and 4) at Eyjafallajökull (pronounced ay-uh-fyat-luh-yoe-kuutl-ul) volcano in Iceland. The 2010 eruption at Eyjafallajökull lasted only a few months and was relatively small, but it still caused significant disruption to air travel. Ash from the eruption closed down airspace over much of Europe for a week, costing the airline industry more than $1 billion. Iceland owes its existence to a unique set of geologic circumstances. The volcanic island is located over a hotspot that coincides with the Mid-Atlantic Ridge, a divergent plate boundary separating the North American tectonic plate from the Eurasian plate. It was hot spot volcanism that generated enough magma to build Iceland and raise the Mid-Atlantic Ridge above sea level, where you can visit it today.

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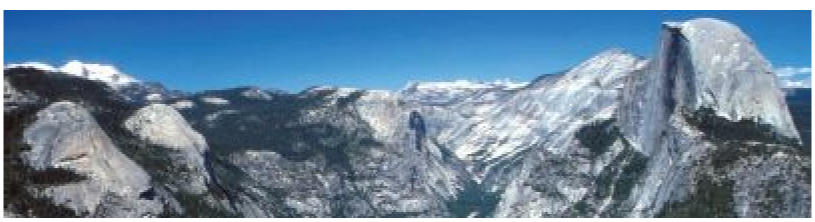

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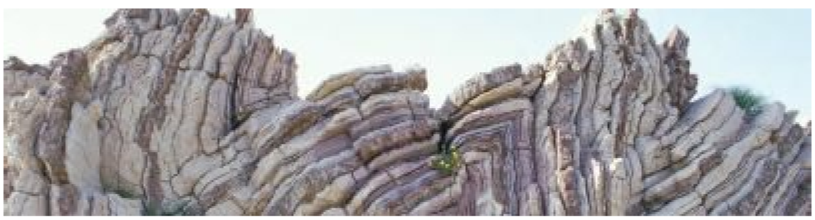

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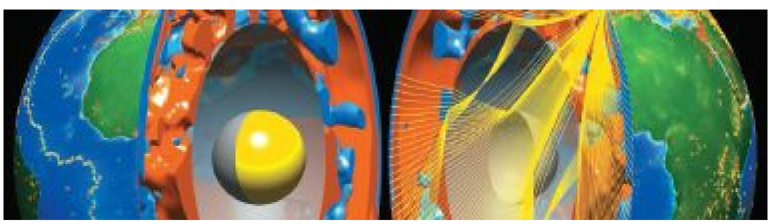
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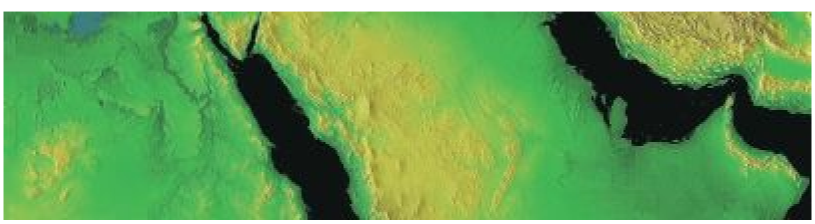

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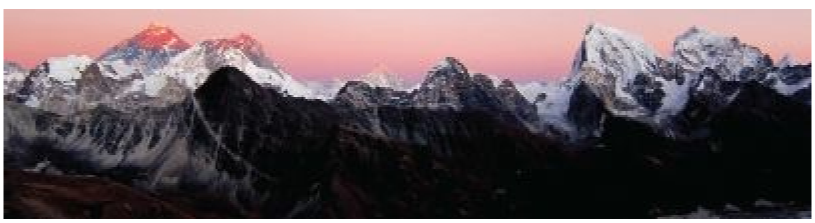

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PREFACE

WHY USE THIS BOOK?

One excellent reason is that it's tried and true. Since the book was first published in 1979, over 1,000,000 students have read this text as an introduction to physical geology. Proportionately, geology instructors have relied on this text for over 5,000 courses to explain, illustrate, and exemplify basic geologic concepts to both majors and non-majors. Today, the seventeenth edition continues to provide contemporary perspectives that reflect current research, recent natural disasters, unmatched illustrations, and unparalleled learning aids. We have worked closely with contributors, reviewers, and our editors to publish the most accurate and current text possible.

APPROACH

Our purpose is to clearly present the various aspects of physical geology so that students can understand the logic of what scientists have discovered, as well as the elegant way the parts are interrelated to explain how Earth, as a whole, works.

This approach is epitomized by our treatment of plate tectonics. Plate tectonics is central to understanding how the Earth works. Rather than providing a full-fledged presentation of plate tectonics at the beginning of the textbook and overwhelming students, *Physical Geology* presents the essentials of plate tectonics in the first chapter. Subsequent chapters then detail interrelationships between plate tectonics and major geologic topics.

For example, chapter 3, on igneous activity, includes a thorough explanation of how plate tectonics accounts for the generation of magma and resulting igneous rocks. Chapter 19, typically covered late in the course, presents a full synthesis of plate tectonics. By this time, students have learned the many aspects of physical geology and can appreciate the elegance of plate tectonics as a unifying paradigm.

CHANGES TO THE SEVENTEENTH EDITION

New to the Seventeenth Edition

Each chapter has been revised and updated, and an overview of notable changes made to each chapter is given below:

Chapter 1 has been updated to reflect current resource usage and to improve readability. The information on careers in geology contained in box 1.3 has been updated.

Chapter 2 has been updated to improve readability. Figure 2.2 has been edited to improve clarity. The web box has been removed.

Chapter 3 includes an updated rock cycle figure that incorporates hand sample images of rocks rather than sketches. Changes have been made to section 3.3 to improve comprehension. Figure 3.25 has been replaced with a more modern image. The section on igneous activity and plate tectonics has been reorganized to improve flow.

Chapter 4 has been updated to reflect the change in eruption status at Kilauea, and a new box (4.2) has been added that describes the dramatic end of the Kilauea eruption.

Chapter 5 includes a revised rock cycle diagram that includes photos of rocks rather than sketches. The section on solution weathering and table 5.1 have been modified to more clearly show the solution of calcite. The effect of increased surface area on weathering processes has been revised to emphasize its importance.

Chapter 6 contains minor changes to increase clarity. A revised rock cycle figure has also been added to this chapter.

Chapter 7 has been updated to improve readability.

Chapter 8 has been updated to improve readability and clarify the Precambrian as a supereon. Box 8.2 has been updated to reflect the change in name of the K-T boundary to the K-Pg boundary.

Chapter 9 has minor rewrites to improve readability, and landslide fatality statistics have been updated.

Chapter 10 has undergone significant revision. Numerous sections have been updated and revised to improve readability and clarity. Figure 10.5 now includes aerial photos of rivers paired with sketches to illustrate the different types of drainage patterns. Box 10.1 on the controlled floods in the Grand Canyon has been replaced with a new box on the environmental consequences of the Three Gorges Dam in China. We have also added a new alluvial fan photo and replaced figure 10.37 with a new graph that more clearly shows how urbanization affects discharge rate. The summary and questions at the end of the chapter have also been revised.

Chapter 11 includes an extensively revised “fracking” box and new figure that more clearly explains the process of hydraulically fracturing a confined aquifer during horizontal drilling, and an updated discussion of possible environmental problems. Figure 11.16 has also been revised to more accurately illustrate a gasoline plume.

Chapter 12 has been edited to improve readability and contains new images of a U-shaped valley and a hanging valley. Box 12.2 has been updated to reflect more recent research on glacial surges and evidence for life in subglacial lakes in the Antarctic.

Chapter 13 includes an expanded discussion of deserts around the world and a revision of figure 13.3.

Chapter 14 has been extensively edited to improve readability. Box 14.1 has been revised and now includes a sea-level curve showing fluctuation from past glaciations and also a sea-level curve illustrating more recent variation and projected future sea-level rise based on IPCC emission scenarios. Box 14.2 has been updated to include category 5 Hurricanes Michael and Dorian. The summary has been revised to reflect the relationship between coastal landforms and processes and sea-level changes.

Chapter 15 contains edits of text and figures throughout the chapter to help clarify material for the student and improve readability.

Chapter 16 has been updated to include the largest, most deadly liquefaction event ever recorded after the 2018 Sulawesi, Indonesia, earthquake and associated tsunami that was intensified by submarine landslides and offshore morphology. Minor edits were made throughout the chapter to improve clarity.

Chapter 17 has been extensively revised. Many sections have been rewritten to improve clarity and make the subject more approachable. We have added photos of geologists using geophysical equipment in the field. The gravity section now includes a geoid image from NASA’s GRACE mission. We replaced figure 17.2 with a new seismic reflection profile from the SHIRE research project at the Hikurangi plate margin that shows intensely folded and faulted sediments. We added a new planetary geology box (17.2) that discusses the interiors of other planets. We also replaced the “Earth’s Spinning Core” box with a new box (17.3) describing “Geophysical Methods of Exploration: How a Geologist Sees Underground.” The summary has been expanded and completely rewritten in a more narrative style.

Chapter 18 has undergone minor edits of text and photo captions. We have adopted *Wadati–Benioff zone* to more accurately name this important tectonic feature.

Chapter 19 begins with a rewritten introduction that more clearly states how the plate tectonic theory has unified the study of geology. The "Early Case for Continental Drift" section has also been rewritten, and the entire chapter has been extensively revised to improve readability and clarity.

Chapter 20 has undergone minor editing for improved readability.

Chapter 21 has been updated to reflect the rapid changes in the study of climate change. Figures 21.11, 21.12, 21.14, and 21.18 have been updated to include the most recent data available. Figures 21.22 and 21.20 have been updated to reflect current understanding of the impacts of climate change.

Chapter 22 has been updated to reflect changes in the demand for, and price of, various resources, as well as changes in global production and estimates of total reserves remaining.

Chapter 23 has been edited to significantly improve readability. Multiple images of planets and moons have been replaced with newer images that have become available in recent years. The section on Mars has been updated to reflect new results from the *InSight* mission, and the section on Pluto has been completely rewritten to reflect new knowledge gained from the *New Horizons mission*.

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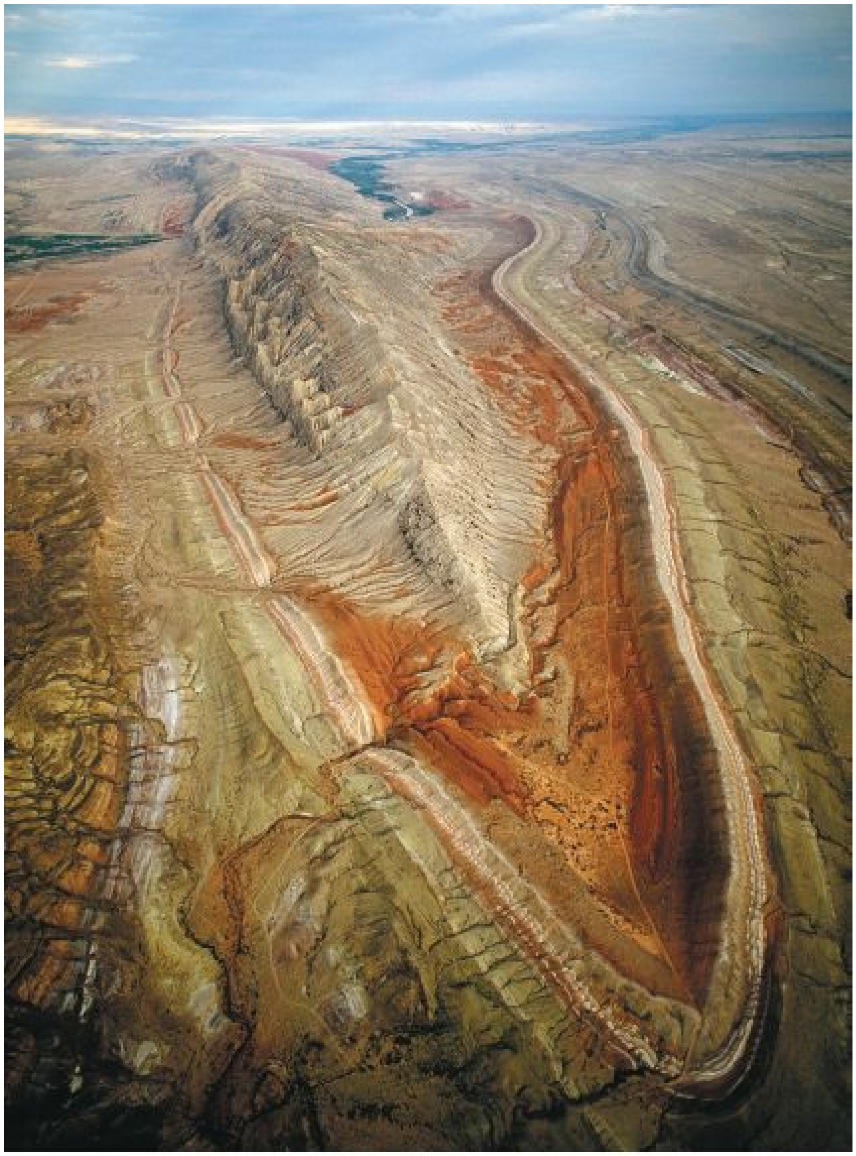
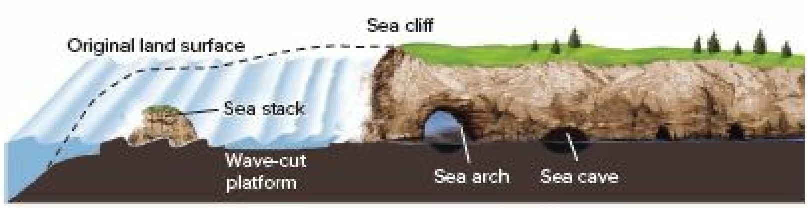
KEY FEATURES

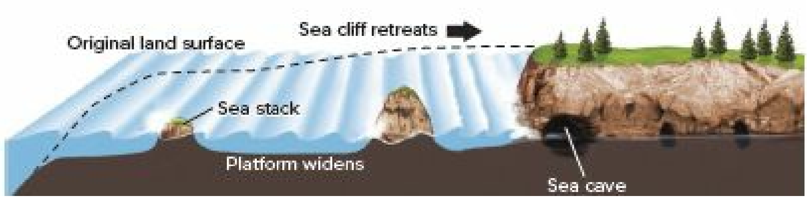
Superior Photo and Art Programs

Geology is a visually oriented science, and one of the best ways to learn it is by studying illustrations and photographs. The outstanding photo and art programs in this text feature accuracy in scale, realism, and aesthetic appeal that provides students with the best visual learning tools available in the market. We strive to have the best photographs possible so that they are the next best thing to seeing geology on a field trip. We are again pleased to feature aerial photography from award-winning photographer/geologist Michael Collier, who gives students a birds-eye view of spectacular geology from western North America.



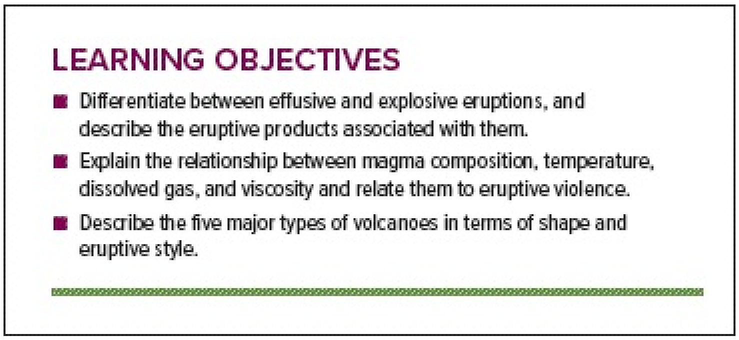
Michael Collier





Learning Objectives

Each chapter begins with a bulleted list of learning objectives to help students focus on what they should know and understand after reading the chapter.


LEARNING OBJECTIVES

- Differentiate between effusive and explosive eruptions, and describe the eruptive products associated with them.
- Explain the relationship between magma composition, temperature, dissolved gas, and viscosity and relate them to eruptive violence.
- Describe the five major types of volcanoes in terms of shape and eruptive style.

Environmental Geology Boxes

Discuss topics that relate the chapter material to environmental issues, including impact on humans (For example: “Radon—A Radioactive Health Hazard”, “Coasts in Peril—The Effects of Rising Sea Level,” “Sinkholes as a Geologic Hazard,” “The Gulf of Mexico Spill—The Cost of Oil Exploration in Ever More Difficult-to-Reach Areas,” and “The Nuclear Crisis in Japan—The Future of Nuclear Power Put to the Test”).

BOX 22.3: ENVIRONMENTAL GEOLOGY

The Nuclear Crisis in Japan—The Future of Nuclear Power Put to the Test

The magnitude 9.0 earthquake and tsunami that hit eastern Japan on March 11, 2011, was devastating. Entire coastal towns and villages were destroyed, leaving hundreds of thousands of people homeless. As of 2012, the official death toll was 15,854 with another 3,203 missing. The disaster also caused a nuclear crisis that has global implications for the future of nuclear power.

Nuclear power has been viewed as a way to reduce reliance on foreign sources of fossil fuels, but there are many risks associated with nuclear reactors that have been highlighted by the events in Japan. Prior to the earthquake and tsunami, Japan relied on nuclear power for 30% of its electricity and had plans to expand its nuclear capacity to 50% by 2030. Located in a region known for powerful earthquakes and tsunami, the Fukushima Daiichi plant was designed with many safety features. When the earthquake hit, the plant's electricity was cut off, but backup generators quickly kicked in and began an emergency shutdown of the active reactors. Cooling systems pumping water around the fuel rods kept the reactors from overheating. One hour later, a 14-meter (46-foot) tsunami reached the plant, which was protected by a seawall. Unfortunately, while planners had assumed a 10-meter seawall would provide adequate protection against tsunami, they did not anticipate an event of this magnitude or the 1-meter drop in elevation of the coast caused by the massive earthquake. The seawall was easily overtopped by the massive wave. Water flooded the facility and disabled the backup generators, which were all located at or below ground level. All power was lost, and without cooling water circulating through them, the reactors began to overheat and partially melt down. In the following weeks, efforts to get the reactors under control were hampered by explosions and fires as well as flooding with radioactive water (box figure 1). Spent fuel rods stored in pools in each reactor building also began to overheat as water levels in the pools dropped. It took months to fully stabilize the plant, and it could take decades to remove the melted core material and complete a cleanup of the area.

Radiation leaked from the plant as a result of explosions, planned steam releases to relieve pressure in the reactors, and discharge of coolant water into the sea. The Japanese government evacuated people living within 30 km (18 miles) of the plant (box figure 2). Radiation was detected in milk and food produced in the area as well as in water in Tokyo. Trace amounts of radiation were observed around the world, although the levels were extremely low and were not considered to pose any threat. Cleanup efforts continue as of this writing at Fukushima and will likely take decades to complete. Of grave concern is the continued leak of radioactive waters into the ocean and the groundwater.

The crisis at Fukushima caused many countries to reconsider the benefits of nuclear power. Japan is moving to reduce its dependence on nuclear energy. Germany made a decision to close the last of its seventeen nuclear reactors. The Swiss government also recommended phasing out its nuclear power plants. Italy put an indefinite hold on plans to build new power plants. France, which currently relies on nuclear power for 75% of its electricity, recently announced plans to cut nuclear output by a third in twenty years. In the United States, plans to expand nuclear power capacity may be slowed or even halted.

What will be the implications of a worldwide decrease in nuclear power production? Without a decrease in demand for energy, it will most likely lead to increased reliance on fossil fuels like coal and oil. What will be the impact on the climate of increased use of carbon-based fuel? How do we weigh the risk of a nuclear disaster against long-term climate change?

BOX 22.3 ■ FIGURE 1

Smoke from the damaged Fukushima Daiichi nuclear plant in Okuma, Japan

BOX 22.3 ■ FIGURE 2

A man being screened for radiation exposure

In Greater Depth Boxes

Discuss phenomena that are not necessarily covered in a geology course (For example: “Geophysical Methods of Exploration: How a Geologist Sees Underground”, “Precious Gems,” “Is There Oil Beneath My Property? First Check the Geologic Structure,” and “Valuable Sedimentary Rocks”) or present material in greater depth such as “Darcy’s Law and Fluid Potential” and “Calculating the Age of a Rock”.

BOX 6.1: IN GREATER DEPTH

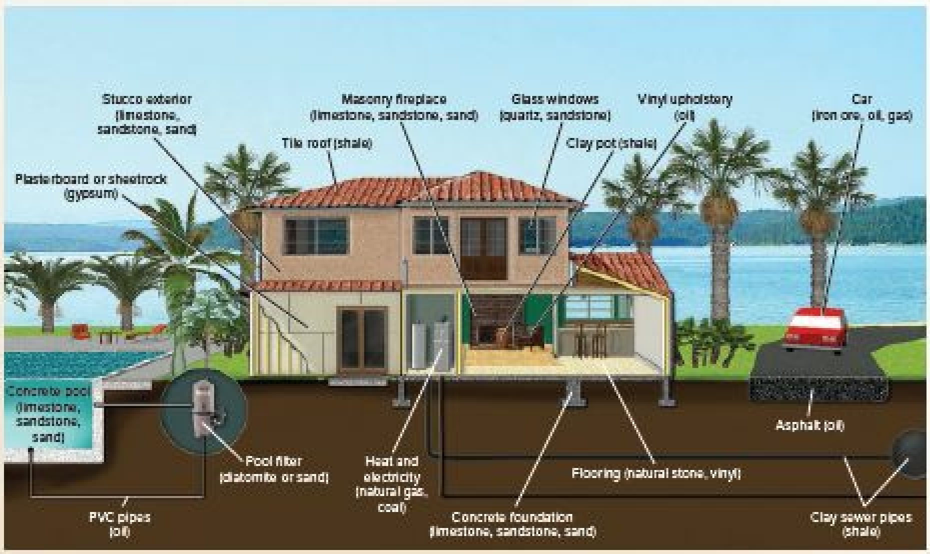
Valuable Sedimentary Rocks

Many sedimentary rocks have uses that make them valuable. *Limestone* is widely used as building stone and is also the main rock type quarried for crushed rock for road construction. Pulverized limestone is the main ingredient of cement for mortar and concrete and is also used to neutralize acid soils in the humid regions of the United States. *Coal* is a major fuel, used widely for generating electrical power and for heating. Plaster and plasterboard for home construction are manufactured from *gypsum*, which is also used to stabilize the shrink-swell characteristics of clay-rich soils in some areas. Huge quantities of *rock salt* are consumed by industry, primarily for the manufacture of hydrochloric acid. More familiar uses of rock salt are for table salt and melting ice on roads.

Some *chalk* is used in the manufacture of blackboard chalk, although most classroom chalk is now made from pulverized limestone. The filtering agent for beer brewing and for swimming pools is likely to be made of *diatomite*, an accumulation of the siliceous remains of microscopic diatoms.

Clay from *shale* and other deposits supplies the basic material for ceramics of all sorts, from hand-thrown pottery and fine porcelain to sewer pipe. *Sulfur* is used for matches, fungicides, and sulfuric acid; and *phosphates* and *nitrates* for fertilizers are extracted from natural occurrences of special sedimentary rocks (although other sources also are used). Potassium for soap manufacture comes largely from *evaporites*, as does boron for heat-resistant cookware and fiberglass and sodium for baking soda, washing soda, and soap. *Quartz sandstone* is used in glass manufacturing and for building stone.

Many *metallic ores*, such as the most common iron ores, have a sedimentary origin. The pore space of sedimentary rocks acts as a reservoir for groundwater (chapter 11), crude oil, and natural gas. In chapter 22, we take a closer look at these resources and other useful Earth materials.

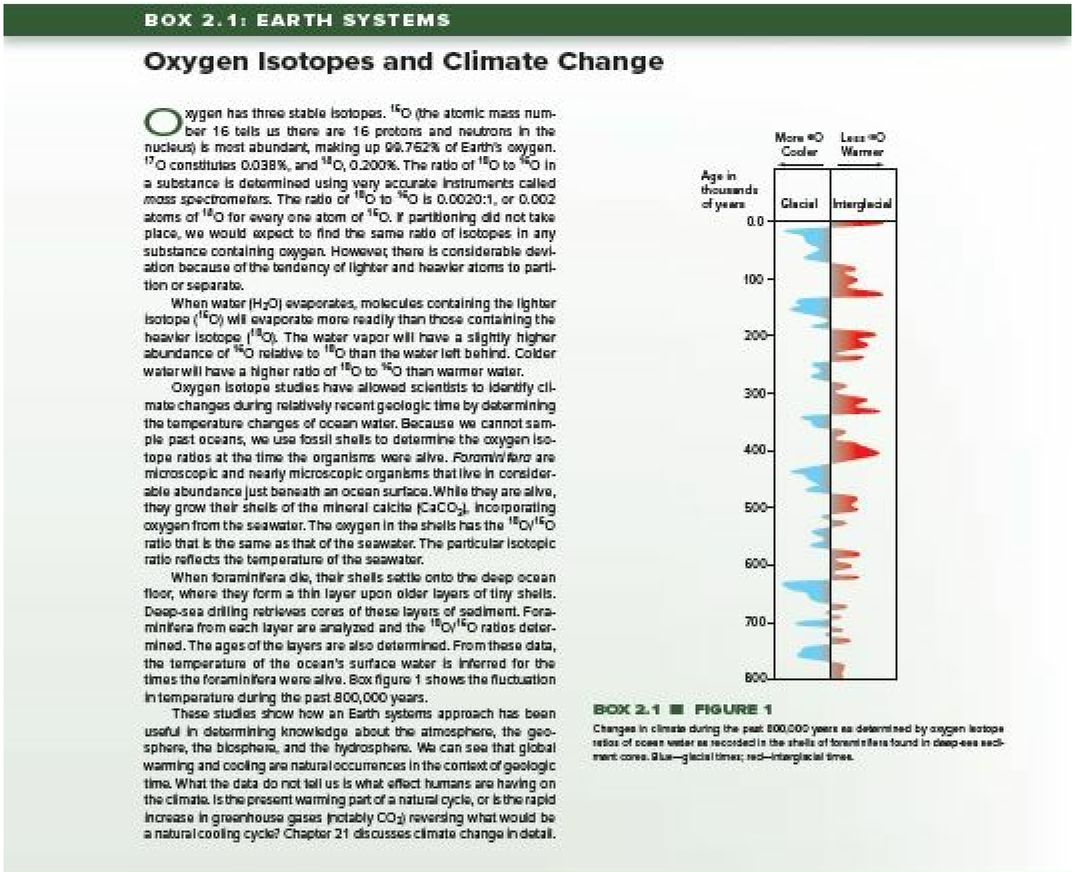


BOX 6.1 ■ FIGURE 1

Common uses of materials that are sedimentary in origin.

Earth Systems Boxes

Highlight the interrelationships between the geosphere, the atmosphere, and other Earth systems (For example: "Global Warming and Glaciers" and "Oxygen Isotopes and Climate Change").



BOX 2.1: EARTH SYSTEMS

Oxygen Isotopes and Climate Change

Oxygen has three stable isotopes. ^{16}O (the atomic mass number 16 tells us there are 16 protons and neutrons in the nucleus) is most abundant, making up 99.762% of Earth's oxygen. ^{17}O constitutes 0.038%, and ^{18}O, 0.200%. The ratio of ^{18}O to ^{16}O in a substance is determined using very accurate instruments called *mass spectrometers*. The ratio of ^{18}O to ^{16}O is 0.0020:1, or 0.002 atoms of ^{18}O for every one atom of ^{16}O. If partitioning did not take place, we would expect to find the same ratio of isotopes in any substance containing oxygen. However, there is considerable deviation because of the tendency of lighter and heavier atoms to partition or separate.

When water (H_2O) evaporates, molecules containing the lighter isotope (^{16}O) will evaporate more readily than those containing the heavier isotope (^{18}O). The water vapor will have a slightly higher abundance of ^{16}O relative to ^{18}O than the water left behind. Colder water will have a higher ratio of ^{18}O to ^{16}O than warmer water.

Oxygen isotope studies have allowed scientists to identify climate changes during relatively recent geologic time by determining the temperature changes of ocean water. Because we cannot sample past oceans, we use fossil shells to determine the oxygen isotope ratios at the time the organisms were alive. *Foraminifera* are microscopic and nearly microscopic organisms that live in considerable abundance just beneath an ocean surface. While they are alive, they grow their shells of the mineral calcite ($CaCO_3$), incorporating oxygen from the seawater. The oxygen in the shells has the $^{18}O/^{16}O$ ratio that is the same as that of the seawater. The particular isotopic ratio reflects the temperature of the seawater.

When foraminifera die, their shells settle onto the deep ocean floor, where they form a thin layer upon older layers of tiny shells. Deep-sea drilling retrieves cores of these layers of sediment. Foraminifera from each layer are analyzed and the $^{18}O/^{16}O$ ratios determined. The ages of the layers are also determined. From these data, the temperature of the ocean's surface water is inferred for the times the foraminifera were alive. Box figure 1 shows the fluctuation in temperature during the past 800,000 years.

These studies show how an Earth systems approach has been useful in determining knowledge about the atmosphere, the geosphere, the biosphere, and the hydrosphere. We can see that global warming and cooling are natural occurrences in the context of geologic time. What the data do not tell us is what effect humans are having on the climate. Is the present warming part of a natural cycle, or is the rapid increase in greenhouse gases (notably CO_2) reversing what would be a natural cooling cycle? Chapter 21 discusses climate change in detail.

BOX 2.1 ■ FIGURE 1

Changes in climate during the past 800,000 years as determined by oxygen isotope ratios of ocean water as recorded in the shells of foraminifera found in deep-sea sediment cores. Blue—glacial times; red—interglacial times.

Planetary Geology Boxes

Compare features elsewhere in the solar system to their Earthly counterparts (For example: “Interior of Other Planets”, “Extraterrestrial Volcanic Activity”, and “Sedimentary Rocks: The Key to Mars’ Past”).

BOX 6.2: PLANETARY GEOLOGY

Sedimentary Rocks: The Key To Mars' Past

Sedimentary rocks on Mars are currently being studied by planetary geologists to decipher its early history and determine if Mars was once a warmer, wetter planet. Currently, the atmosphere on Mars is too thin and its surface too cold to allow liquid water to exist (see chapter 23). But recent evidence shows that Mars was once wet enough to host lakes and seas. New observations from robotic spacecraft exploring Mars show evidence for extensive deposits of water-lain sedimentary rock. In orbit around Mars, the *Mars Global Surveyor*, *Mars Express*, and *Mars Reconnaissance Orbiter* spacecraft have taken thousands of high-resolution photographs, many of which reveal widespread, laterally continuous layers that appear to be sedimentary rock. For example, hundreds of layers of rock are exposed in parts of the walls of the Valles Marineris, a large chasm on Mars that resembles the Grand Canyon but is almost 4,000 kilometers (2,700 miles) long! In the Mawrth Vallis, the rock layers have been identified as thick beds of clay. Because clay minerals can form only in the presence of liquid water and because the clay beds are thick and cover such a wide geographic area, one interpretation is that large bodies of standing water may have existed on Mars. These extensive lakes would have formed very early in the planet's history and probably lasted for millions of years.

While the Mars Orbiters search from the sky, Mars Rovers and Landers have been exploring the surface of the planet. The Mars Exploration Rover named *Opportunity* landed inside a small crater with exposures of layered rock and later traversed the Martian surface to enter a larger crater with more layered rock (box figure 1). Detailed photographic and spectrographic analyses of these layered rocks have revealed sedimentary features such as cross-beds, hematite mineral concretions, and the presence of minerals such as jarosite that typically form in water. More recently, the *Phoenix Mars Lander* set down near the polar region and found frozen water in the soil under the landing site. During the *Phoenix* mission, the first wet chemical analyses done on any planet other than Earth found more evidence for the possible past occurrence of water on Mars in the form of magnesium, sodium, potassium, and chloride salts (evaporites). Subsequent analyses indicate the presence of calcium carbonate (limestone), an important discovery because carbon-containing compounds are necessary for life as we know it on Earth.

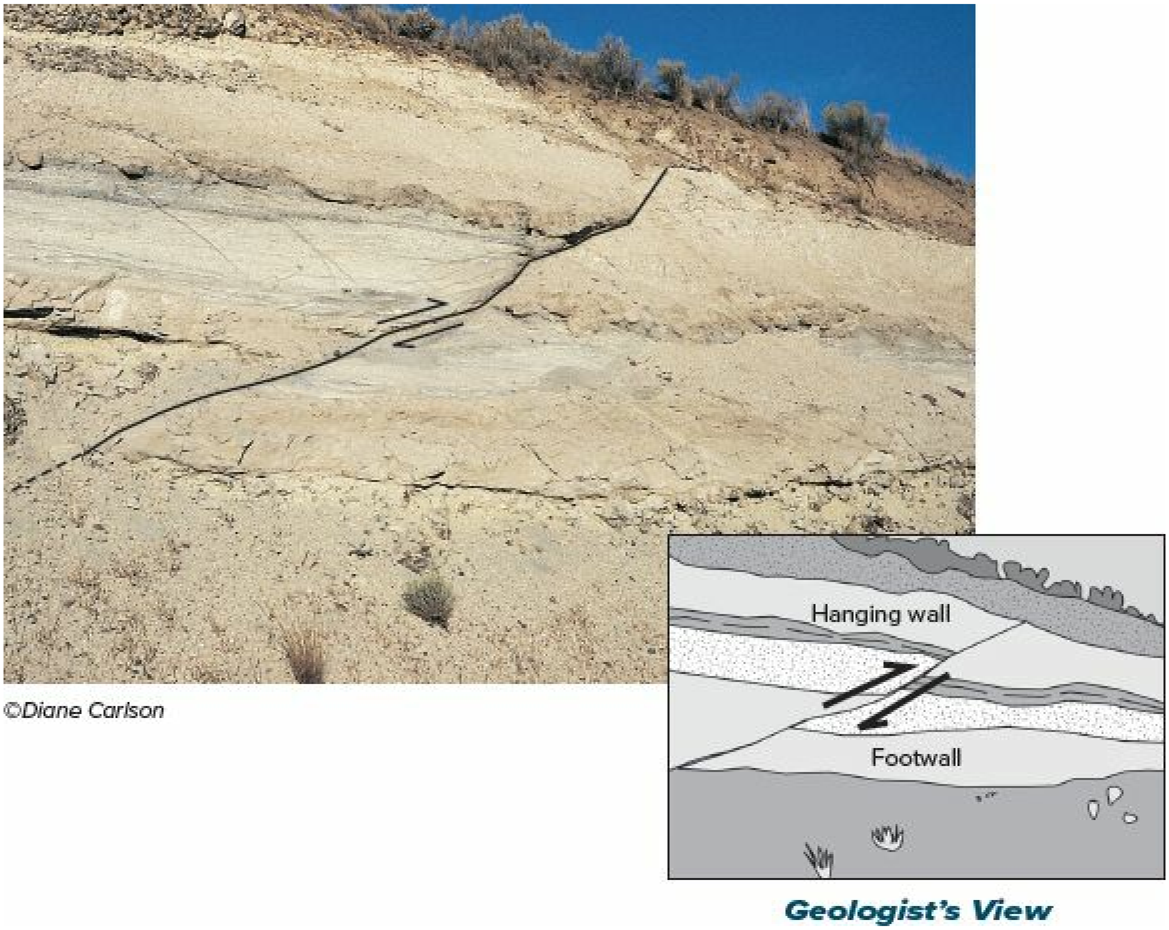
The most recent rover, the *Mars Science Laboratory* (also known as Curiosity), is exploring Gale Crater with a complex array of new capabilities. Gale was selected from high-resolution *Mars Reconnaissance Orbiter* images showing a long-lived and varied geologic history that included potential lake deposits. Curiosity has in fact found and characterized strong evidence for the long-lived existence of water at Gale, including a mudstone (lithified clay deposit) and other sedimentary materials deposited by water (box figure 2). Curiosity will continue to drill, sample, and analyze rocks in its trek through Mars' geologic history, and it will collaborate with *MAVEN* (*Mars Atmospheric and Volatile EvolutioN*) to investigate how the atmosphere has evolved from one dense enough to support a wetter climate to the thin atmosphere present today. More exciting discoveries are anticipated as Mars continues to be one of the most promising places to look for evidence of extraterrestrial life in our solar system.

BOX 6.2 ■ FIGURE 1

BOX 6.2 ■ FIGURE 2

A Geologist's View

Photos accompanied by an illustration depicting how a geologist would view the scene are featured in the text. Students gain experience understanding how the trained eye of a geologist views a landscape in order to comprehend the geologic events that have occurred.



Study Aids are found at the end of each chapter and include:

Summaries bring together and summarize the major concepts of the chapter.

Terms to Remember include all the boldfaced terms covered in the chapter so that students can verify their understanding of the concepts behind each term.

Testing Your Knowledge Quizzes allow students to gauge their understanding of the chapter and are aligned with the learning objectives presented at the beginning of each chapter. (The answers to the multiple choice portions are posted on Connect.)

Expanding Your Knowledge Questions stimulate a student's critical thinking by asking questions with answers that are not found in the textbook.

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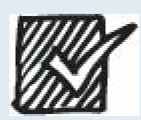
Solutions for your challenges 

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Acknowledgments

We have tried to write a book that will be useful to both students and instructors. We would be grateful for any comments by users, especially regarding mistakes within the text or sources of good geological photographs.

Although he is no longer listed as an author, this edition bears a lot of the writing style and geologic philosophy of the late David McGeary. He was coauthor of the original edition, published in 1979. His authorship continued through the seventh edition, after which he retired and turned over revision of his half of the book to Diane Carlson. We greatly appreciate his role in making this book successful way beyond what he or his original coauthor ever dreamed of.

Tom Arny wrote the planetary geology chapter for the tenth edition. This chapter was revised and updated by Steve Kadel for the eleventh and twelfth editions and by Mark Boryta for the fifteenth edition. Chris Cappa and Delphine Farmer wrote the chapter on climate change for the fourteenth edition, and Professor Cappa has continued to revise chapter 21 in subsequent editions. We greatly appreciate the publisher's "book team" whose names appear on the copyright page. Their guidance, support, and interest in the book were vital for the completion of this edition.

Thank you also to Cindy Shaw for her contribution to the superior art program of the eleventh and twelfth editions.

Diane Carlson would like to thank her husband Reid Buell for his tireless support, and for his technical assistance with engineering geology and hydrogeology material, in several chapters. Charles Plummer thanks his wife Beth Strasser for assistance with photography in the field, and for her perspective as a paleontologist and anthropologist. Lisa Hammersley would like to thank her husband Chris Cappa for his support, and for agreeing to find time to write the climate change chapter for this book.

We are appreciative of the following contributing authors for their work on the seventeenth edition:

Mark Boryta, *Mt, San Antonio College*
Elizabeth Catlos, *The University of Texas at Austin*
Daniel Hauptvogel, *University of Houston*
Sarah Heinlein, *University of Houston-Downtown*
Amelia Vankeuren, *California State University, Sacramento*

The following individuals helped write and review learning goal–oriented content for LearnSmart for Geology:

Sylvester Allred, *Northern Arizona University*
Lisa Hammersley, *California State University, Sacramento*

Arthur C. Lee, *Roane State Community College*

Through each edition of *Physical Geology*, we have had outstanding feedback from reviewers who have provided careful evaluations and useful suggestions for improvement.

Prajukti (juk) Bhattacharyya, *University of Wisconsin–Whitewater*
Elizabeth J. Catlos, *The University of Texas at Austin*
Ellen A. Cowan, *Appalachian State University*
Carl N. Drummond, *Purdue University Fort Wayne*
James R. Jones, *Del Mar College*
David T. King, Jr., *Auburn University*
Paul Lowrey, *NorthWest Arkansas Community College*
Prabhat C Neupane, PhD, *University of New Orleans*
Jeff Simpson, *Chandler-Gilbert Community College*
Megan Sjoblom, *Brigham Young University–Idaho*
LeAnne Teruya, *San Jose State University*
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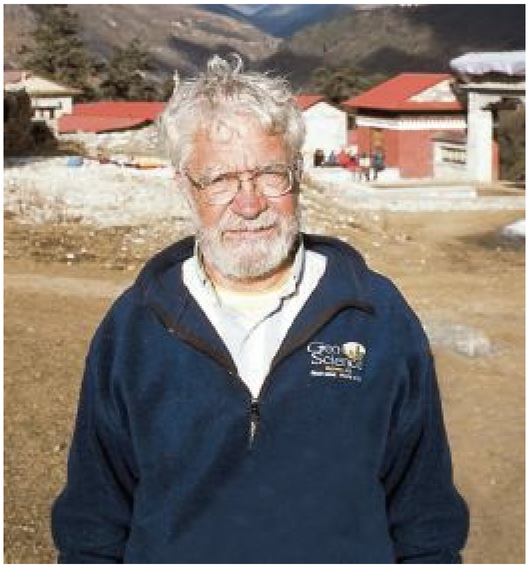
MEET THE AUTHORS



Courtesty of Charles Plummer

Charles Plummer at Tengboche, in the Himalayan Mountains of Nepal.

CHARLES PLUMMER Professor Charles "Carlos" Plummer grew up in the shadows of volcanoes in Mexico City. There, he developed a love for mountains and mountaineering that eventually led him into geology. He received his B.A. degree from Dartmouth College. After graduation, he served in the U.S. Army as an artillery officer. He resumed his geological education at the University of Washington, where he received his M.S. and Ph.D. degrees. His geologic work has been in mountainous and polar regions, notably Antarctica (where a glacier is named in his honor). He taught at Olympic Community College in Washington and worked for the U.S. Geological Survey before joining the faculty at California State University, Sacramento.

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Courtesty of Reid Buell

Diane Carlson at Convict Lake in the Sierra Nevada Mountains of California.

DIANE CARLSON Professor Diane Carlson grew up on the glaciated Precambrian shield of northern Wisconsin and received an A.A. degree at Nicolet College in Rhinelander and a B.S. in geology at the University of Wisconsin at Eau Claire. She continued her studies at the University of Minnesota–Duluth, where she focused on the structural complexities of high-grade metamorphic rocks along the margin of the Idaho batholith for her master's thesis. The lure of the West and an opportunity to work with the U.S. Geological Survey to map the Colville batholith in northeastern Washington led her to Washington State University for her Ph.D. Dr. Carlson accepted a position at California State University, Sacramento, after receiving her doctorate and taught physical geology, structural geology, environmental geology, field techniques, and field geology. Professor Carlson is a recipient of the Outstanding Teacher Award from the CSUS School of Arts and Sciences. She is also engaged in researching the structural and tectonic evolution of part of the Foothill Fault System in the northern Sierra Nevada of California. (carlsondh@csus.edu)

Courtesty of Christopher Cappa

Lisa Hammersley on the coast of Northern California

LISA HAMMERSLEY Dr. Lisa Hammersley hails originally from England and received a B.Sc. in geology from the University of Birmingham. After graduating, she traveled the world for a couple of years before returning to her studies and received a Ph.D. in geology from the University of California at Berkeley. She joined the faculty at California State University, Sacramento in 2003, where she taught natural disasters, physical geology, geology of Mexico, mineralogy, and metallic ore deposits, receiving the Outstanding Teacher Award from the College of Natural Sciences and Mathematics in 2011. Dr. Hammersley specializes in igneous petrology with an emphasis on geochemistry. Her interests involve understanding magma chamber processes and how they affect the evolution of volcanic systems. She has worked on volcanic systems in Ecuador, Mexico, and the United States. Dr. Hammersley has also worked in the field of geoarcheology, using geologic techniques to identify the sources of rocks used to produce stone grinding tools found near the pyramids of Teotihuacan in Mexico. She is currently serving as the Dean of the College of Natural Sciences and Mathematics. (hammersley@csus.edu)

CHAPTER 1

Introducing Geology, the Essentials of Plate Tectonics, and Other Important Concepts

Mount Robson, 3,954 meters (12,972 feet) above sea level, is the highest peak in the Canadian Rocky Mountains.

J. A. Kraulis/Masterfile

LEARNING OBJECTIVES

Know what physical geology is, and describe some of the things it is used for.

Define a system, and describe the four Earth systems (spheres).

Distinguish between the Earth's internal and external heat engines and list the processes driven by them.

List the three major internal zones of the Earth.

Describe the lithosphere and the asthenosphere.

Sketch and label the different types of plate boundaries.

Summarize the scientific method, and define the meaning of the word *theory*.

Know the age of the Earth.

Have you ever looked out of the window of an airplane and wondered about the landforms that you see below you, or examined a pebble on a beach and wondered how it got there? Have you ever listened to a news report about a major natural disaster such as an earthquake, flood, or volcanic eruption, and asked yourself why it happened and what you would do if you found yourself in such a situation? What about the materials used to manufacture the electronics you use every day or the gasoline used to fuel your car—have you ever thought about where they come from, how they formed, and how we exploit them? These topics are all parts of **geology**—the scientific study of the Earth. Geologists use the scientific method to explain natural aspects of the Earth, such as what it is made of and the processes that affect it, and to interpret Earth's history. This chapter is an introduction to geology. We will first explore the uses of geology before introducing some of the important concepts such as the modern theory of plate tectonics and geologic time. These concepts form a framework for the rest of the book. Understanding the "big picture" presented here will aid you in comprehending the chapters that follow.

Strategy for Using This Textbook

As authors, we try to be thorough in our coverage of topics so the textbook can serve you as a resource. Your instructor may choose, however, to concentrate only on certain topics for *your* course. Find out which topics and chapters you should focus on in your studying and concentrate your energies there.

Your instructor may present additional material that is not in the textbook. Take good notes in class.

Try not to get overwhelmed by terms. (Every discipline has its own language.) If you associate a term with a concept or mental picture, remembering the term comes naturally when you understand the concept. (You remember names of people you know because you associate personality and physical characteristics with a name.) You may find it helpful to learn the meanings of frequently used prefixes and suffixes for geological terms. These can be found in appendix G.

Boldfaced terms are ones you are likely to need to understand because they are important to the entire course.

Italicized terms are not as important but may be necessary to understand the material in a particular chapter.

Pay particular attention to illustrations. Geology is a visually oriented science, and the photos and artwork are at least as important as the text. You should be able to sketch important concepts from memory.

Find out to what extent your instructor expects you to learn the material in the boxes. They offer an interesting perspective on geology and how it is used, but much of the material might well be considered optional for an introductory course and not vital to your understanding of major topics. Many of the In Greater Depth boxes are meant to be challenging—do not be discouraged if you need your instructor's help in understanding them.

Read through the appropriate chapter before going to class. Reread it after class, concentrating on the topics covered in the lecture or discussion. Especially concentrate on concepts that you do not fully understand. Return to previously covered chapters to refresh your memory on necessary background material.

Use the end-of-chapter material for review. The Summary is just that, a summary. Don't expect to get through an exam by only reading the summary and not the rest of the chapter. Use the Terms to Remember to see if you can visually or verbally associate the appropriate concept with each term. Answer the Testing Your Knowledge questions in writing. Be honest with yourself. If you are fuzzy on an answer, return to that portion of the chapter and reread it. Remember that these are just a sampling of the kinds of questions that might be on an exam.

Geology, like most science, builds on previously acquired knowledge. You must retain what you learn from chapter to chapter. If you forget or did not learn significant concepts covered early in your course, you will find it frustrating later in the course. (To verify this, turn to chapter 20 and you will probably find it intimidating; but if you build on your knowledge as you progress through your course, the chapter material will fall nicely into place.)

Be curious. Geologists are motivated by a sense of discovery. We hope you will be, too.

1.1 WHO NEEDS GEOLOGY?

Geology benefits you and everyone else on this planet. The clothes you wear, the food you eat, your smart phone, and your car exist because of what geologists have discovered about the Earth. The Earth can also be a killer. You might have survived an earthquake, flood, or other natural disaster thanks to action taken based on what scientists have learned about these hazards. Before getting into important scientific concepts, we will look at some of the ways geology has benefited you and will continue to do so.

Supplying Things We Need

We depend on the Earth for energy resources and the raw materials we need for survival, comfort, and pleasure. Every manufactured object relies on Earth's resources—even something as simple as a pencil (figure 1.1). Earth processes, at work for millions of years, have localized material into concentrations that humans can mine or extract. By learning how the Earth works and how different kinds of substances are distributed and why, we can intelligently search for metals, sources of energy, and gems. Even maintaining a supply of sand and gravel for construction purposes depends on an understanding of geology.

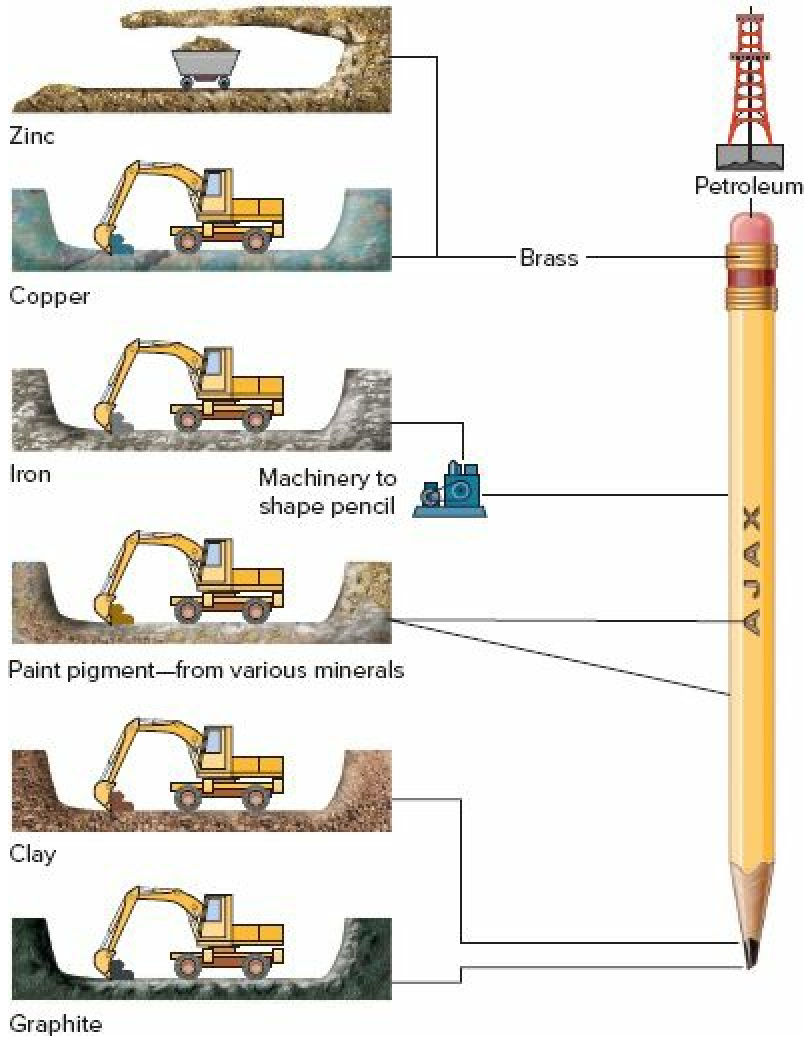


FIGURE 1.1

Earth’s resources needed to make a wooden pencil.

Modern society currently depends on abundant and cheap energy sources. Nearly all our vehicles and machinery are powered by petroleum, coal, or nuclear power and depend on energy sources concentrated unevenly in the Earth. The U.S. economy, in particular, is geared to petroleum and natural gas as cheap sources of energy. It is important to remember, however, that these resources took hundreds of millions of years to form, and they are being rapidly depleted. In recent years, the United States has been able to reduce its reliance on imported oil by developing technology to access oil that was previously too difficult or too expensive to extract. Finding more of this diminishing resource will require more money and increasingly sophisticated knowledge of geology. Although many people are not aware of it, we face similar problems with diminishing resources of other materials, notably metals such as iron, aluminum, copper, and tin, each of which has been concentrated in a particular environment by the action of the Earth's geologic processes.

Just how much of our resources do we use? According to the Minerals Education Coalition, approximately 18,430 kilograms (40,633 pounds; for metric conversions, go to appendix E) of resources, including energy resources, must be mined annually to provide for every person in the United States. The amount of each commodity mined per person per year is 4,501 kilograms stone, 3,332 kilograms sand and gravel, 306 kilograms limestone for cement, 70 kilograms clays, 174 kilograms salt, 283 kilograms other nonmetals, 116 kilograms iron ore, 12 kilograms aluminum ore, 3 kilograms copper, 8 kilograms lead and zinc, 3 kilograms manganese, and 5 kilograms other metals. Americans' yearly per capita consumption of energy resources includes 3,626 liters (958 gallons) of petroleum, 1,908 kilograms of coal, 2,775 cubic meters (97,988 cubic feet) of natural gas, and 0.06 kilograms of uranium.

Protecting the Environment

Our demands for more energy and metals have, in the past, led us to extract them with little regard for effects on the environment and therefore, on ourselves. Mining of coal, if done carelessly, for example, can release acids into water supplies. Understanding geology can help us lessen or prevent damage to the environment—just as it can be used to find the resources in the first place.

The environment is further threatened because these are nonrenewable resources. Petroleum and metal deposits do not grow back after being harvested. As demands for these commodities increase, so does the pressure to disregard the ecological damage caused by the extraction of the remaining deposits. As the supply of resources decreases, we are forced to exploit them from harder-to-reach locations. The Deepwater Horizon oil spill in the Gulf of Mexico in 2010 was due in part to the very deep water in which drilling was taking place (see box 22.2).

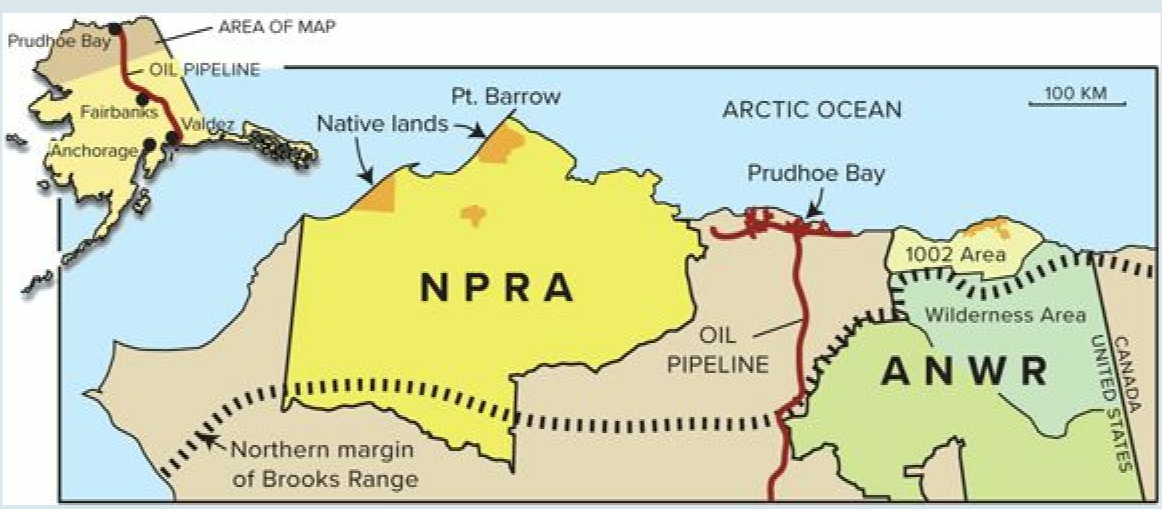
Geology has a central role in these issues. Oil companies employ geologists to discover new oil fields, while the public and government depend on other geologists to assess the potential environmental impact of petroleum's removal from the ground, the transportation of petroleum (see box 1.1), and disposal of any toxic wastes from petroleum products.

The consumption of resources, in particular energy resources, is also affecting the Earth's climate. chapter 21 covers the evidence for global climate change and its connection to greenhouse gases released by burning fossil fuels.

BOX 1.1: ENVIRONMENTAL GEOLOGY

Delivering Oil—The Environment versus the Economy

In the 1960s, geologists discovered oil beneath the coast of the Arctic Ocean on Alaska's North Slope at Prudhoe Bay (box figure 1). It is now the largest oil field in North America. Thanks to the Trans-Alaska pipeline, completed in 1977, Alaska has at times supplied as much as 25% of the United States' domestic oil, although it currently supplies only 7%.



BOX 1.1 ■ FIGURE 1

Map of northern Alaska showing locations and relative sizes of the National Petroleum Reserve in Alaska (NPRA) and the Arctic National Wildlife Refuge (ANWR). “1002 Area” is the portion of ANWR being proposed for oil exploitation. Current oil production is taking place at Prudhoe Bay.

Source: U.S.G.S. Fact Sheet 045-02 and U.S.G.S. Fact Sheet 014-03

In the late 1970s before Alaskan oil began to flow, the United States was importing almost half its petroleum, at a loss of billions of dollars per year to the national economy. At its peak, over 2 million barrels of oil a day flowed from the Arctic oil fields. Despite its important role in the American economy, some considered the Alaska pipeline and the use of oil tankers to be unacceptable threats to the area’s ecology.

The 1,287-kilometer-long pipeline crosses regions of ice-saturated, frozen ground and major earthquake-prone mountain ranges that geologists regard as serious hazards to the structure.

Building anything on frozen ground creates problems. The pipeline presented enormous engineering problems. If the pipeline were placed on the ground, the hot oil flowing through it could melt the frozen ground. On a slope, mud could easily slide and rupture the pipeline. Careful (and costly) engineering minimized these hazards. Much of the pipeline is elevated above the ground (box figure 2). Radiators conduct heat out of the structure. In some places, refrigeration equipment in the ground protects against melting.

BOX 1.1 ■ FIGURE 2

The Alaska pipeline.

David Applegate

Records indicate that a strong earthquake can be expected every few years in the earthquake belts crossed by the pipeline. An earthquake could rupture a pipeline—especially a conventional pipe as in the original design. When the Alaska pipeline was built, however, in several places sections were specially jointed and placed on slider beams to allow the pipe to shift as much as 6 meters without rupturing. In 2002, a major earthquake (magnitude 7.9—the same strength as the May 2008 earthquake in China, described in chapter 16, that killed more than 87,000 people) caused the pipeline to shift several meters, resulting in minor damage to the structure, but the pipe did not rupture (box figure 3).

BOX 1.1 ■ FIGURE 3

The Alaska pipeline where it was displaced along the Denali fault during the 2002 earthquake. The pipeline is fastened to teflon shoes, which are sitting on slider beams.

USGS Fact Sheet 014-03

The original estimated cost of the pipeline was $900 million, but the final cost was $7.7 billion, making it, at that time, the costliest privately financed construction project in history. The redesigning and construction that minimized the potential for an environmental disaster were among the reasons for the increased cost. Some spills from the pipeline have occurred. In January 1981, 5,000 barrels of oil were lost when a valve ruptured. In 2001, a man fired a rifle bullet into the pipeline, causing it to rupture and spill 7,000 barrels of oil into a forested area. In March 2006, a British Petroleum Company (BP) worker discovered a 201,000 gallon spill from that company's feeder pipes to the Trans-Alaska Pipeline. This was the largest oil spill on the North Slope to date. Subsequent inspection by BP of its feeder pipes revealed much more corrosion than expected. As a result, it made a very costly scaling back of its oil production to replace pipes and make major repairs.

Recently, two other large oil pipeline projects have caused much debate. The Keystone Pipeline delivers oil from Canada to refineries in the Midwest and the Gulf Coast of Texas. Although parts of the pipeline system are already operational, a proposed extension from Canada to Nebraska with a shorter route and larger-diameter pipe faced strong criticism from environmentalists, and in 2015, the plan was rejected by the U.S. government. In 2017, however, the U.S. government changed course and approved the pipeline.

In August 2016, Native American protests in North Dakota halted construction of a section of the Dakota Access pipeline, which is intended to span over 1,000 miles between North Dakota and Illinois. The protests were sparked by concerns about negative impacts on the environment and damage to sites of cultural importance.

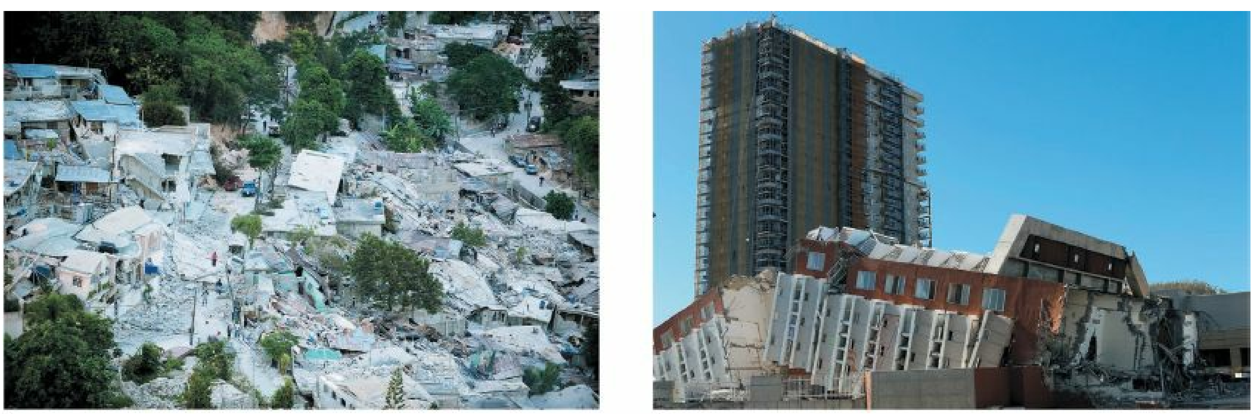
The alternative to pipelines is transporting oil by rail, which can be hazardous. On December 30, 2013, a train carrying crude oil collided with another train in North Dakota. The collision caused a large explosion and fire, leading to a partial evacuation of the nearby town of Casselton. Earlier in 2013, a train carrying crude oil derailed in Quebec, Canada, killing more than 40 people in the town of Lac-Megantic.

Oil can also be transported by sea. When the tanker *Exxon Valdez* ran aground in 1989, more than 240,000 barrels of crude oil were spilled into the waters of Alaska's Prince William Sound. The spill, with its devastating effects on wildlife and the fishing industry, dramatically highlighted the conflicts between maintaining the energy demands of the American economy and conservation of the environment. Statistical studies of tanker accidents worldwide revealed the frequency with which large oil spills could be expected. The *Exxon Valdez* spill should not have been a surprise.

Avoiding Geologic Hazards

Almost everyone is, to some extent, at risk from natural hazards, such as earthquakes or hurricanes. Earthquakes, volcanic eruptions, landslides, floods, and tsunami are the most dangerous *geologic hazards.* Each is discussed in detail in appropriate chapters. Here, we will give some examples to illustrate the role that geology can play in *mitigating* (reducing the impact of) geologic hazards.

On Tuesday, January 12, 2010, a magnitude 7 earthquake struck close to Port-au-Prince, the capital city of Haiti. The city and other parts of Haiti were left in ruins (figure 1.2*A*). Responses to the emergency were severely hampered because roads were blocked by debris, hospitals were heavily damaged, the seaport in Port-au-Prince was rendered unusable, and the control tower at the airport was damaged. This not only made it difficult for Haitian emergency workers to rescue those trapped or injured, but also made it difficult for international relief to reach the country quickly. The Haitian government estimates that as many as 300,000 people were killed and a million were left homeless. However, due to the immense damage and the difficulties involved in the response, the true impact in terms of casualties may never be known.



A B

FIGURE 1.2

Damage caused by earthquakes in (*A*) Haiti and (*B*) Chile in 2010. Notice how many of the buildings in Haiti were reduced to rubble. Although many buildings were destroyed in Chile, strict building codes meant that many, such as the high-rise apartment building in the background of (*B*), survived the massive magnitude 8.8 earthquake.

(A) U.S. Air Force photo by Tech. Sgt. James L. Harper Jr (B) USGS photo

Just one month later, on February 10, a magnitude 8.8 earthquake hit off the coast of central Chile. The earthquake was the sixth largest ever recorded, releasing 500 times as much energy as the Haitian earthquake, and was felt by 80% of the population. Movement of the sea floor due to the earthquake generated a tsunami that caused major damage to some coastal communities and prompted the issuance of a Pacific-wide tsunami warning. It is estimated that 525 people were killed and 1.5 million people were displaced.

Although the impact on Chile was significant (figure 1.2*B*), this enormous earthquake killed far fewer people than the earthquake that struck Haiti. Why is this, and could the deaths in Haiti have been avoided? As described later in this chapter, geologists understand that the outer part of the Earth is broken into large slabs known as *tectonic plates* that are moving relative to each other. Most of the Earth's geologic activity, such as earthquakes and volcanic eruptions, occurs along boundaries between tectonic plates. Both Chile and Haiti are located on plate boundaries, and both have experienced large earthquakes in the past. In fact, the largest earthquake ever recorded happened in Chile in 1960. The impact of earthquakes can be reduced, or mitigated, by engineering buildings to withstand shaking. Chile has strict building codes, which probably saved many lives. Haiti, however, is one of the poorest countries in the Western Hemisphere and does not have the stringent building codes of Chile and other wealthy nations. Because of this, thousands of buildings collapsed and hundreds of thousands lost their lives.

page 6

Japan is seen as a world leader in earthquake engineering, but nothing could prepare the country for the events of March 11, 2011. At 2:46 P.M., a devastating magnitude 9.0 earthquake hit the east coast of Japan. The earthquake was the largest known to have hit Japan. Soon after the earthquake struck, tsunami waves as high as 38.9 meters (128 feet) inundated the coast. Entire towns were destroyed by waves that in some cases traveled up to 10 kilometers (6 miles) inland. The death toll from this disaster was almost 16,000, and almost half a million people were left homeless. Things could have been much worse. Due to the high building standards in Japan, the damage from the earthquake itself was not severe. Japan has an earthquake early warning system, and after the earthquake struck, a warning went out to millions of people. In Tokyo, the warning arrived one minute before the earthquake was felt. This early warning is believed to have saved many lives. Japan also has a tsunami warning system, and coastal communities have clearly marked escape routes and regular drills for their citizens. Concrete seawalls were built to protect the coast. Unfortunately, the walls were not high enough to hold back a wave of such great height, and some areas designated as safe areas were not on high enough ground. Still, without the safety precautions in place, many more thousands of people could have lost their lives. In some communities, lives were saved by the actions of their ancestors. Ancient stone markers along the coastline, some more than 600 years old, warn people of the dangers of tsunami. In the hamlet of Aneyoshi, one of these stone markers reads, “Remember the calamity of the great tsunami. Do not build any homes below this point.” The residents of Aneyoshi heeded the warning, locating their homes on higher ground, and the community escaped unscathed.

Volcanic eruptions, like earthquakes and tsunami, are products of Earth’s sudden release of energy. Unlike earthquakes and tsunami, however, volcanic eruptions can last for extended periods of time. Volcanic hazards include lava flows, falling debris, and ash clouds (see box 1.2). The most deadly volcanic hazards are pyroclastic flows and volcanic mudflows. As described in chapter 4, a *pyroclastic flow* is a hot, turbulent mixture of expanding gases and volcanic ash that flows rapidly down the side of a volcano. Pyroclastic flows often reach speeds of over 100 kilometers per hour and are extremely destructive. A *mudflow* is a slurry of water and rock debris that flows down a stream channel.

Mount Pinatubo’s eruption in 1991 was the second largest volcanic eruption of the twentieth century. Geologists successfully predicted the climactic eruption (figure 1.3) in time for Philippine officials to evacuate people living near the mountain. Tens of thousands of lives were saved from pyroclastic flows and mudflows.

FIGURE 1.3

The major eruption of Mount Pinatubo on June 15, 1991, as seen from Clark Air Force Base, Philippines.

Source: Robert LaPointe, U.S. Air Force

By contrast, one of the worst volcanic disasters of the twentieth century took place after a relatively small eruption of Nevado del Ruiz in Colombia in 1985. Hot volcanic debris blasted out of the volcano and caused part of the ice and snow capping the peak to melt. The water and loose debris turned into a mudflow. The mudflow overwhelmed the town of Armero at the base of the volcano, killing 23,000 people (figure 1.4). Colombian geologists had previously predicted such a mudflow could occur, and they published maps showing the location and extent of expected mudflows. The actual mudflow that wiped out the town matched that shown on the geologists' map almost exactly. Unfortunately, government officials ignored the map and the geologists' report; otherwise, the tragedy could have been averted.

FIGURE 1.4

Most of the town of Armero, Colombia, and its residents are buried beneath up to 8 meters of mud from the 1985 mudflow.

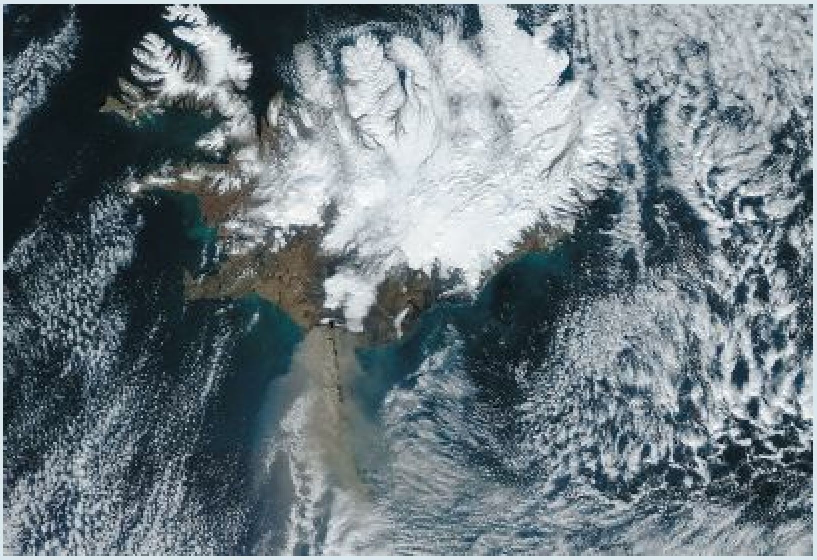
Langevin Jacques/Contributor/Getty Images

BOX 1.2: ENVIRONMENTAL GEOLOGY

A Volcanic Eruption in Iceland Shuts Down European Airspace for Over a Week

The hazards associated with volcanic eruptions are not necessarily localized. Volcanic ash spewed into the atmosphere presents a hazard to air traffic. Particles of ash can sandblast the windows and clog a plane's sensors. When fine particles of ash are sucked into jet engines, they melt and fuse onto the blades, causing the engines to fail. In 1985, a British Airways flight from London, England, to Auckland, New Zealand, flew into a cloud of ash flung up from Mount Galunggung in Indonesia. All four engines failed, and the plane dropped 14,000 feet before the engines could be restarted. This and other incidents have shown aviation authorities that extreme caution must be taken during a volcanic eruption.

In March 2010, Eyjafjallajökull (pronounced ay-uh-fyat-luh-yoe-kuutl-ul), a relatively small volcano in Iceland, began erupting lava from fissures on the side of the mountain. On the morning of April 14, the eruption shifted to new vents buried under the ice cap that covers the summit of the volcano and increased in intensity. The ice melted, adding cold water to the hot lava, causing it to cool rapidly and to fragment into ash particles. The ash was carried up into the atmosphere by an eruption plume where it encountered the jet stream, a band of high-speed winds that blow from west to east (box figure 1). The jet stream carried the ash cloud over much of northern Europe. Because of the hazard to air traffic, much of Europe's airspace was closed from April 15 to April 23, the largest disruption to air traffic since World War II. Flights into and out of Europe were canceled, leaving millions of passengers stranded around the world.



BOX 1.2 ■ FIGURE 1

An ash plume from Iceland's Eyjafjallajökull volcano spreads south toward Europe. Notice that the southern end of the plume is being blown eastward by the polar jet stream.

Image by Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC

The cost to the airline industry is estimated to have been around $200 million a day. Total losses are estimated at $1.7 billion. The industry complained that the restrictions were too tight and that ash levels were low enough for safe flight.

Understanding Our Surroundings

It is a uniquely human trait to want to understand the world around us. Most of us get satisfaction from understanding our cultural and family histories, or learning how things such as car engines or computers work. Music and art help link our feelings to that which we have discovered through our life. The natural sciences involve understanding the physical and biological universe in which we live. Most scientists get great satisfaction from their work because, besides gaining greater knowledge from what has been discovered by scientists before them, they can find new truths about the world around them. Even after a basic geology course, you can use what you learn to explain and be able to appreciate what you see around you, especially when you travel. If, for instance, you were traveling through the Canadian Rockies, you might see the scene in this chapter's opening photo and wonder how the landscape came to be.

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You might wonder: (1) why there are layers in the rock exposed in the cliffs; (2) why the peaks are so jagged; (3) why there is a glacier in a valley carved into the mountain; (4) why this is part of a mountain belt that extends northward and southward for thousands of kilometers; (5) why there are mountain ranges here and not in the central part of the continent. After completing a course in physical geology, you should be able to answer these questions as well as understand how other kinds of landscapes formed.

1.2 EARTH SYSTEMS

The awesome energy released by an earthquake or volcano is a product of forces within the Earth that move firm rock. Earthquakes and volcanoes are only two consequences of the ongoing changing of Earth. Ocean basins open and close. Mountain ranges rise and are then very slowly worn back down to plains. Studying how the Earth works can be as exciting as watching a great theatrical performance. The purpose of this book is to help you understand how and why those changes take place. More precisely, we concentrate on *physical geology*, which is the division of geology concerned with Earth materials, changes in the surface and interior of the Earth, and the dynamic forces that cause those changes. Put another way, physical geology is about how the Earth works.

But to understand geology, we must also understand how the solid Earth interacts with water, air, and living organisms. For this reason, it is useful to think of the Earth as being part of a system. A *system* is an arbitrarily isolated portion of the universe that can be analyzed to see how its components interrelate. For example, the *solar system* is a part of the much larger universe. The solar system includes the Sun, planets, the moons orbiting planets, and asteroids (see chapter 23).

The **Earth system** is a small part of the larger solar system, but it is, of course, very important to us. The Earth system has its components, which can be thought of as its subsystems. We refer to these as *Earth systems* (plural). These systems, or "*spheres*," are the atmosphere, the hydrosphere, the biosphere, and the geosphere. You, of course, are familiar with the **atmosphere**, the gases that envelop the Earth. The **hydrosphere** is the water on or near Earth's surface. The hydrosphere includes the oceans, rivers, lakes, and glaciers of the world. It also includes **groundwater**, which is water that lies beneath the ground surface. Earth is unique among the planets in that two-thirds of its surface is covered by oceans. The **biosphere** is all of the living or once-living material on Earth. The **geosphere**, or solid Earth system, is the rock and other inorganic Earth material that make up the bulk of the planet. This book mostly concentrates on the geosphere; to understand geology, however, we must understand the interaction between the solid Earth and the other systems (spheres).

The 2011 Japanese tsunami involved the interaction of the geosphere and the hydrosphere. The earthquake took place in the geosphere. Energy was transferred into giant waves in the hydrosphere. The hydrosphere and geosphere again interacted when waves inundated the shores. Can you think of other ways in which the four spheres interacted, either during or as a result of the tsunami?

All four of the Earth systems interact with each other to produce soil, which is a mixture of decomposed and disintegrated rock and organic matter. The organic matter is from decayed plants—from the biosphere. The geosphere contributes the rock that has broken down while exposed to air (the atmosphere) and water (the hydrosphere). Air and water also occupy pore space between the solid particles in soil.

1.3 AN OVERVIEW OF PHYSICAL GEOLOGY—IMPORTANT CONCEPTS

The remainder of this chapter is an overview of physical geology that should provide a framework for most of the material in this book. Although the concepts probably are new to you, it is important that you comprehend what follows. You may want to reread portions of this chapter while studying later chapters when you need to expand or reinforce your comprehension of this basic material. You will especially want to refresh your understanding of plate tectonics when you learn about the plate-tectonic setting for the origin of rocks in chapters 3 through 7.

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BOX 1.3: IN GREATER DEPTH

Geology as a Career

If someone says that she or he is a geologist, that information tells you almost nothing about what he or she does. This is because geology encompasses a broad spectrum of disciplines. Perhaps what many geologists have in common is that they were attracted to the outdoors. Geologists like having one of our laboratories being Earth itself.

Geology is a collection of disciplines. When someone decides to become a geologist, she or he is selecting one of those disciplines. The choice is very large. Some are financially lucrative; others may be less so but might be more satisfying. Following are a few of the areas in which geologists work.

Petroleum geologists work at trying to determine where existing oil fields might be expanded or where new oil fields might exist (box figure 1). Mining geologists might be concerned with trying to determine where to extend an existing mine to get more ore or trying to find new concentrations of ore that are potentially commercially viable. Environmental geologists might work at mitigating pollution or preventing degradation of the environment. Marine geologists are concerned with understanding the sea floor. Some go down thousands of meters in submersibles to study geologic features on the sea floor. Hydrogeologists study surface and underground water and assist in either increasing our supply of clean water or isolating or cleaning up polluted water. Glaciologists study the dynamics of glacier movement or collect ice cores through drilling to determine climate changes that have taken place over the past 100,000 years or more. Volcanologists collect gases or samples of lava from a volcano. Geophysicists interpret earthquake waves or gravity measurements to determine the nature of Earth’s interior. Seismologists are geophysicists who specialize in earthquakes.

BOX 1.3 ■ FIGURE 1

Petroleum geologists examine geological information.

Monty Rakusen/Cultura/Getty Images

Engineering geologists determine whether the rock or soil upon which structures (dams, bridges, buildings) are built can safely support those structures. Paleontologists study fossils and learn about when extinct creatures lived and the environment in which they existed. One geologist was the only scientist to work on the Moon!

Teaching is an important field in which geologists work. Some teach at the college level and are usually involved in research as well. Some teach Earth science (which includes meteorology, oceanography, and astronomy as well as geology) at the middle or high school level.

Many geologists enjoy the challenge and adventure of field work, but some work comfortably behind computer screens or in laboratories with complex analytical equipment.

Geologists tend to be happy with their jobs. In surveys of job satisfaction in a number of professions, geology rates near the top. A geologist is likely to be a generalist who solves problems by bringing in information from beyond his or her specialty. Chemistry, physics, and life sciences are often used to solve problems. Problems geologists work on tend to be ones in which there are few clues. So the geologist works like a detective, piecing together the available data to form a plausible solution. In fact, some geologists work at solving crimes—forensic geology is a branch of geology dedicated to criminal investigations.

Not all people who major in geology become professional geologists. Physicians, lawyers, and businesspeople who have majored in geology have felt that the training in how geologists solve problems has benefited their careers.

The Earth can be visualized as a giant machine driven by two engines, one internal and the other external. Both are *heat engines*, devices that convert heat energy into mechanical energy. Two simple heat engines are shown in figure 1.5. A more complex example is a car engine. When gasoline is ignited in the engine's cylinders, the resulting hot gases expand, driving pistons to the far ends of their cylinders. In this way, the heat energy of the expanding gas has been converted to the mechanical energy of the moving pistons, then transferred to the wheels, where the energy is put to work moving the car.

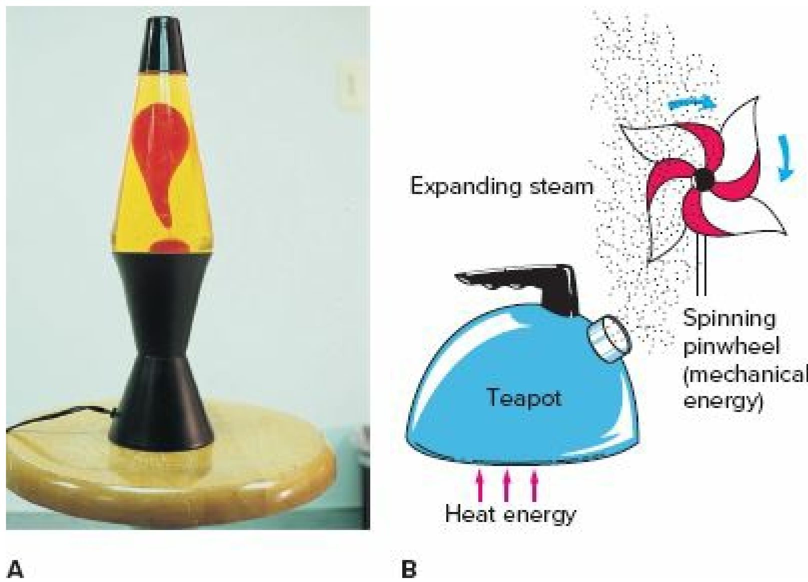

FIGURE 1.5

Two examples of simple heat engines. (*A*) A lava lamp. Blobs are heated from below and rise. Blobs cool off at the top of the lamp and sink. (*B*) A pinwheel held over steam. Heat energy is converted to mechanical energy.

(A) Charles Plummer

Earth's *internal* heat engine is driven by heat moving from the hot interior of the Earth toward the cooler exterior. Volcanic eruptions and earthquakes are products of this heat engine.

Earth's *external* heat engine is driven by solar energy. Heat from the Sun provides the energy for circulating the atmosphere and oceans. Water, especially from the oceans, evaporates because of solar heating. When moist air cools, we get rain or snow.

Over long periods of time, moisture at the Earth's surface helps rock disintegrate. Water washing down hillsides and flowing in streams loosens and carries away the rock particles. In this way, mountains originally raised by the Earth's internal heat engine are worn away by processes driven by the external heat engine.

We will look more closely at how the Earth's heat engines work and show how some of the major topics of physical geology are related to the *internal* and *surficial* (on the Earth's surface) processes powered by the heat engines.

Internal Processes: How the Earth's Internal Heat Engine Works

The Earth's internal heat engine works because hot, buoyant material deep within the Earth moves slowly upward toward the cool surface and cold, denser material moves downward—a process called **convection**. Visualize a vat of hot wax, heated from below (figure 1.6). As the wax immediately above the fire gets hotter, it expands, becomes less dense (that is, a given volume of the material will weigh less), and rises. Wax at the top of the vat loses heat to the air, cools, contracts, becomes denser, and sinks. A similar process takes place in the Earth's interior. Rock that is deep within the Earth and is very hot rises slowly toward the surface, while rock that has cooled near the surface is denser and sinks downward. Instinctively, we don't want to believe that rock can flow like hot wax. However, experiments have shown that under the right conditions, deeply buried rock that is hot and under high pressure can deform, like taffy or putty. But the deformation takes place very slowly. If we were somehow able to strike a rapid blow to the deeply buried rock with a hammer, it would fracture, just as rock at Earth's surface would.

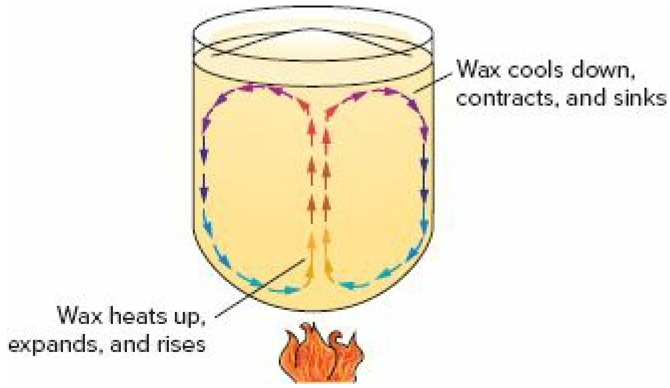

FIGURE 1.6

Convection of wax due to density differences caused by heating and cooling (shown schematically).

Earth's Interior

We divide the Earth's interior into *compositional layers* based upon changes in chemical composition and density, and into *mechanical layers* based upon changes in mechanical behavior, or strength. These layers are shown in figure 1.7. The three compositional layers of the earth are the **crust**, the **mantle**, and the **core**. The Earth's core and mantle and the lower parts of the crust are inaccessible to direct observation. No mine or oil well has penetrated through the crust, so our concept of the Earth's interior is based on indirect evidence. chapter 17 explores the evidence used to understand the interior of the Earth.

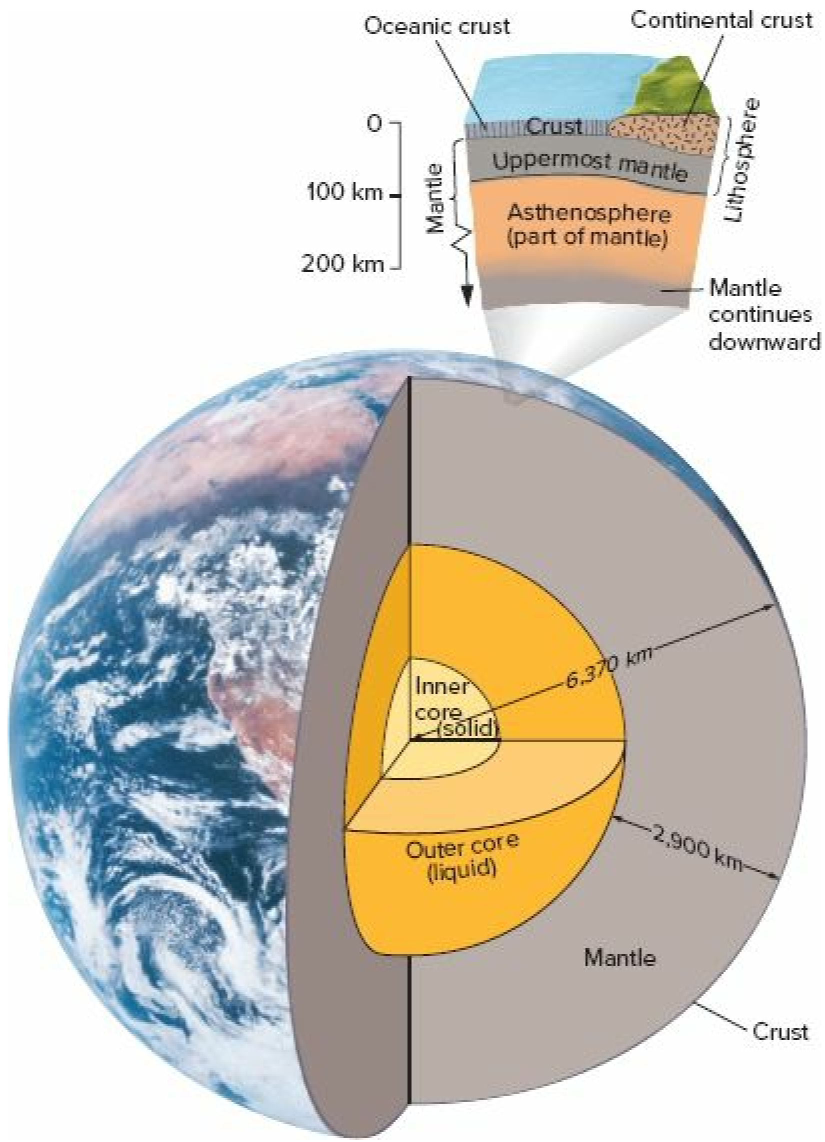

FIGURE 1.7

Cross section through the Earth. Expanded section shows the relationship between the two types of crust, the lithosphere and the asthenosphere, and the mantle. The crust ranges from 5 to 75 kilometers thick.

NASA

The crust, the thin, outermost layer of the Earth, is analogous to the skin on an apple. The thickness of the crust is insignificant compared to the whole Earth. We have direct access to only the crust, and not much of the crust at that. We are like microbes crawling on an apple, without the ability to penetrate its skin. Because it is our home and we depend on it for resources, we are concerned more with the crust than with the inaccessible mantle and core.

The two major types of crust are *oceanic crust* and *continental crust.* Oceanic crust underlies the oceans and is relatively thin (on average, approximately 7 km thick). It is made of basalt, a volcanic rock that is somewhat denser than the rock that underlies the continents. Continental crust is much thicker than oceanic crust, averaging approximately 35 kilometers thick. Unlike oceanic crust, continental crust is made up of many different types of rock. Its average composition is equal to that of granite, a rock you may have seen in many kitchens because it is a popular material used to make countertops.

As described in more detail in chapter 17, the mantle is the thickest and most voluminous of these zones, making up more than 80% of the Earth’s volume. The mantle is composed of rock that contains more iron and magnesium than crustal rocks and thus is more dense. Although the mantle is solid rock, parts of it flow slowly, generally upward or downward, depending on whether it is hotter or colder than adjacent mantle.

The core, the innermost and densest layer of the Earth, is believed to be made of metal—not rock like the mantle and crust—mostly iron and nickel. The core is divided into two mechanical layers, the solid inner core and the liquid outer core. It is the convection of liquid iron in the outer core that generates the Earth’s magnetic field.

The expanded section of figure 1.7 shows two very important mechanical layers of the Earth. The crust and the uppermost part of the mantle are relatively rigid. Collectively, they make up the **lithosphere**. (To help you remember terms, the meanings of commonly used prefixes and suffixes are given in appendix G. For example, *lith* means “rock” in Greek. You will find *lith* to be part of many geologic terms.) The uppermost mantle underlying the lithosphere, called the **asthenosphere**, is soft and therefore flows more readily than the underlying mantle. It provides a “lubricating” layer over which the lithosphere moves (*asthenos* means “weak” in Greek). Where hot mantle material wells upward, it will uplift the lithosphere. Where the lithosphere is coldest and densest, it will sink down through the asthenosphere and into the deeper mantle, just as the wax does in figure 1.6. The effect of this internal heat engine on the crust is of great significance to geology. The forces generated inside the Earth, called **tectonic forces**, cause deformation of rock as well as vertical and horizontal movement of portions of the Earth's crust. The existence of mountain ranges indicates that tectonic forces are stronger than gravitational forces. (Mount Everest, the world's highest peak, is made of rock that formed beneath an ancient sea.) Mountain ranges are built over extended periods as portions of the Earth's crust are squeezed, stretched, and raised.

Most tectonic forces are mechanical forces. Some of the energy from these forces is put to work deforming rock, bending and breaking it, and raising mountain ranges. The mechanical energy may be stored (an earthquake is a sudden release of stored mechanical energy) or converted to heat energy (rock may melt, resulting in volcanic eruptions). The working of the machinery of the Earth is elegantly demonstrated by plate tectonics.

The Theory of Plate Tectonics

From time to time a theory emerges within a science that revolutionizes that field. (In common usage, the word *theory* is used for what scientists call a *hypothesis*—that is, a tentative answer to a question or solution to a problem. In science, however, as explained in box 1.4, a *theory* is a concept that has been highly tested and in all likelihood is true.) The theory of plate tectonics is as important to geology as the theory of relativity is to physics, the atomic theory to chemistry, or evolution to biology. It is a unifying theory that accounts for many seemingly unrelated geologic phenomena. Some of the disparate phenomena that plate tectonics explains are where and why we get earthquakes, volcanoes, mountain belts, deep ocean trenches, and mid-oceanic ridges.

Plate tectonics was seriously proposed as a hypothesis in the early 1960s, though the idea was based on earlier work—notably, the hypothesis of *continental drift.* In the chapters on igneous, sedimentary, and metamorphic rocks, as in the chapter on earthquakes, we will expand on what you learn