PHYSICAL Geology

SIXTEENTH EDITION

Charles C. Plummer
Diane H. Carlson
Lisa Hammersley

Mc Graw Hill Education

Sixteenth Edition

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About the Cover

The cover photo shows the Moeraki Boulders found on Koekohe Beach in New Zealand. These large, almost spherical boulders are concretions that formed in marine mud just below the sea floor approximately 60 million years ago. Over millions of years, the loose mud was differentially cemented into solid rock (see chapter 6). Where the cement was concentrated, hard, spherical concretions formed.

Later, the region was uplifted and wave action (see chapter 14) eroded away the softer sandstone beds, leaving the harder concretions exposed at the beach. The Moeraki Boulders are not unique; similar spherical concretions can be found in a number of locations around the world, including Bowling Ball Beach in Northern California.

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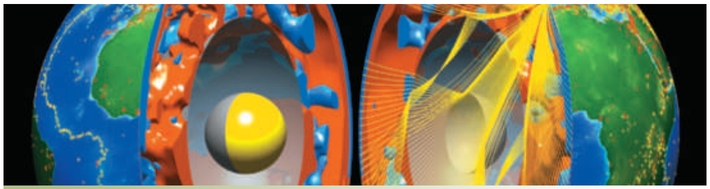

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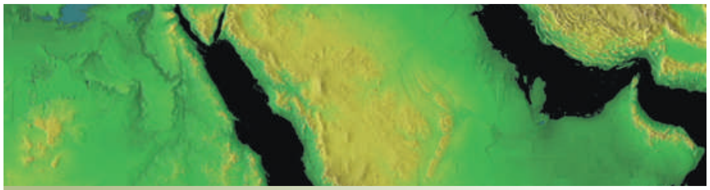

Source: NOAA/NGDC

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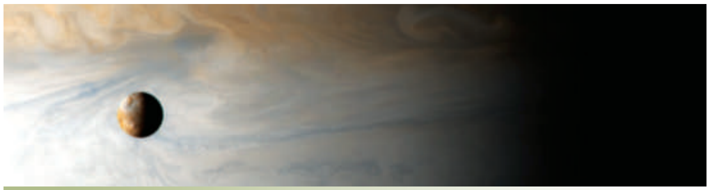


Source: JPL/NASA/University of Arizona

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 sixteenth 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 SIXTEENTH EDITION

New to the Sixteenth 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 the current status of the U.S. petroleum industry. A new photo in box 1.3 shows a more modern image of geologists at work. We have added groundwater to the discussion of the hydrosphere. The section on the Earth's interior has been rewritten to include the concepts of mechanical layers and compositional layers.

Chapter 2 includes some new figures and updated text. The discussion of asbestos in Box 2.4 has been completely rewritten with a new emphasis on mineralogy and health hazards, and new photos have been added.

Chapter 3 has been updated and new web links added. Changes made to figures 3.3 and 3.14B will make them clearer for the reader.

Chapter 4 has been updated with new photos and web links.

Chapter 5 includes a new photo of scenic cliffs formed by differential weathering, and the figure illustrating spheroidal weathering has been revised. Questions at the end of the chapter have been revised and reorganized to better reflect the learning objectives and more clearly follow the flow of the chapter.

Chapter 6 includes a new photo of rounded sediment, and the discussion of how detrital rocks are classified and identified has been expanded. The end-of-chapter questions have been revised to more closely follow the learning objectives.

Chapter 7 has been updated with new photos and web links. A new section on metamorphic facies has been added to the section on plate tectonics and metamorphism. This section shows how the mineral assemblages in metamorphic rocks can provide information on the tectonic setting in which the rock formed.

Chapter 8 has been updated to improve readability, and new web links have been added.

Chapter 9 has minor rewrites to improve readability. Figure 9.3 is a new image showing an example of a landslide triggered by an earthquake. Figure 9.13 shows the effects of a recent mudslide.

Chapter 10 contains new photos of alluvial fans, stream terraces, high-discharge streams, and the recent flooding in Louisiana. Box 10.1 has been updated to include the latest controlled floods on the Colorado River, and the tables and graphs in box 10.3 have been revised to include the past 10 years of peak discharges along the Cosumnes River. The difficulty of estimating the size of a 100-year flood due to the lack of long-term records and the extreme weather events associated with climate change are discussed. Questions at the end of the chapter were revised to more closely follow the learning objectives.

Chapter 11 includes a new photo of groundwater contamination at a landfill, and a new photo of the Geysers Field in California. The fracking box has been updated and revised, and figure 1 of box 11.1 now more accurately reflects hydraulic gradient. We have also included new figures and a discussion of renewed subsidence in the Central Valley of California due to overpumping of deep aquifers during the recent historic drought. New web links have also been added.

Chapter 12 has been updated and new photos have been added. Box 12.1 has been rewritten to incorporate the potential impact of climate change on water availability. New web links have also been added to box 12.1.

Chapter 13 includes a revised discussion of flash floods and mudflows in deserts and a new photo of the catastrophic mudflow in southern California that buried more than 100 vehicles on Highway 58 in the Tehachapi Mountains. Box 13.2 includes minor revisions, and figure 13.12 has been replaced with a new photo of alluvial fans and playa lakes. Box 13.4 has been updated to include the first up-close study of sand dunes on a planet other than Earth. The Mars Science Laboratory rover, *Curiosity*, found miniature sand dunes that are attributed to the thin atmosphere on Mars. Similar large ripples preserved in 3.7-billion-year-old sandstone on Mars suggest the planet may have lost its atmosphere early in its history.

Chapter 14 has been updated and includes new photos of a barrier island along the Atlantic Coast and effects of rising sea level along the Gulf Coast. Web Resources at the end of the chapter have been updated.

Chapter 15 contains minor edits throughout the chapter to help clarify material for the student and improve readability. New photos of deformation along the San Andreas fault and a panoramic photo of Chief Mountain and the Lewis thrust fault in Montana have been added.

Chapter 16 has been updated to include the 2016 Kaikoura, New Zealand, and Amatrice, Italy, earthquakes as well as the human-induced earthquakes in Oklahoma caused by the deep injection of wastewater from oil and gas drilling operations. Spectacular new photos and drone footage of the ground rupture from the Kaikoura earthquake that ripped across the South Island of New Zealand have been added to the Earthquake-Related Hazards section. We have also added a new photo of a trench wall exposing offset layers of sediment along the San Andreas fault. The box "Waiting for the Big One in California" has been revised and updated to include new earthquake probabilities from the 2015 Uniform California Rupture Forecast (UCERF3). New web links detailing the earthquake forecast and simulations of ground motion during earthquakes in northern and southern California have also been added to box 16.3.

Chapter 17 opens with a new seismic tomography image of Earth that shows a large slab of subducted plate that sank through the entire mantle and is preserved below the Indian Ocean. The chapter has been updated to include the new attempt to drill through the oceanic crust to reach the mantle in the southeast Indian Ocean, and also the discovery of a possible new stiff layer in the upper part of the lower mantle based on high-pressure mineral experiments and on seismic tomography showing subducted plates pooling at 1500 km.

Chapter 18 has been updated and contains new photos and web links. Box 18.1 contains new research on tidal-triggered earthquakes on the East Pacific Rise, and the correlation of shallow earthquakes and tidal forces before the 2011 Tohoku earthquake in Japan and the Sumatra-Andaman earthquake in 2004. The "Turbidity Currents" section now contains web links to dramatic new video footage of turbidity currents in submarine canyons along the Baja and Mendocino coasts, and also turbidity currents modeled in laboratory settings. We have also expanded the discussion of submarine cable breaks caused by turbidity currents and the potential risk to the global economy caused by broken telecommunication cables that carry almost all of the digital and voice communications worldwide.

Chapter 19 has minor editing throughout the chapter to update content and improve clarity. The "Continent-Continent Convergence" section has been revised to reflect new mass balance calculations that suggest half of the Indian continent was subducted back into the mantle. The "What Causes Plate Motions?" section has been updated to include recent studies on mantle plumes.

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, and 21.18 have been updated to include the most recent data available. New web links have been added throughout.

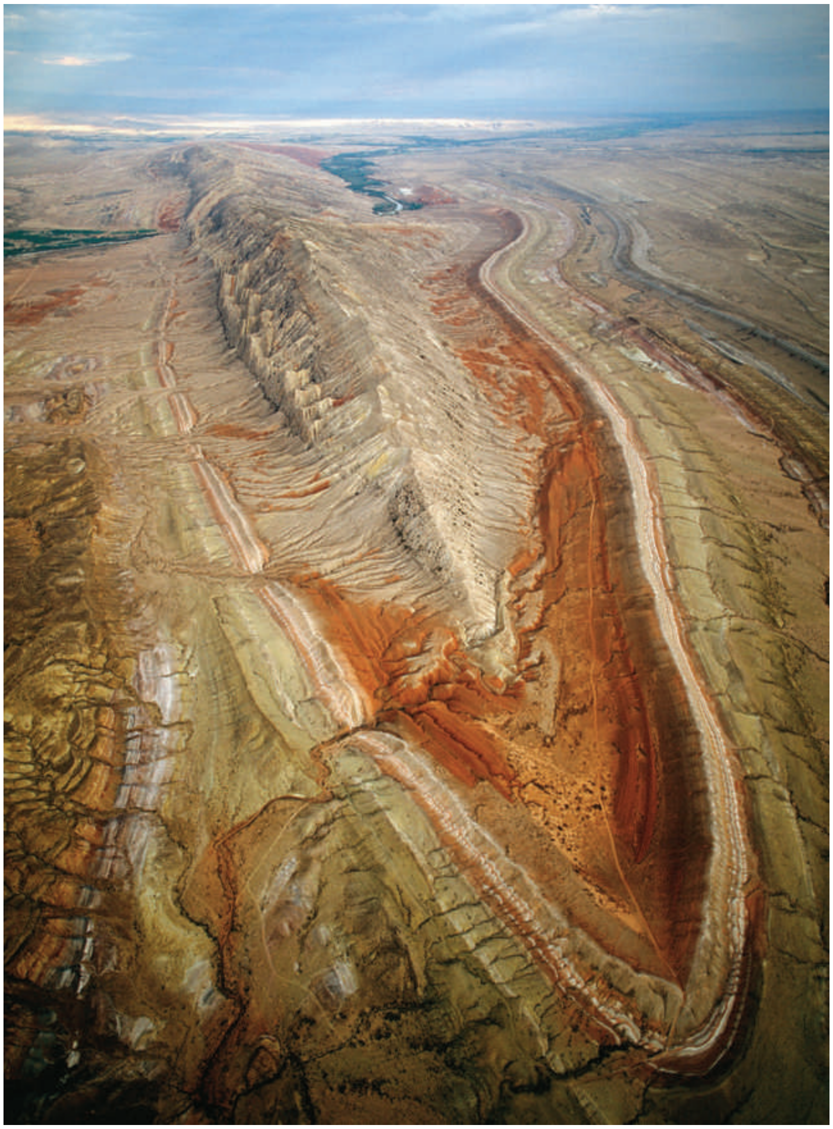
Chapter 22 has been updated to reflect changes in the demand for, and price of, various resources. New photos and web links have been added.

Chapter 23 has been revised to reflect the current state of knowledge of the solar system. New images have been added where recent missions have produced improved imagery of the planets.

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.



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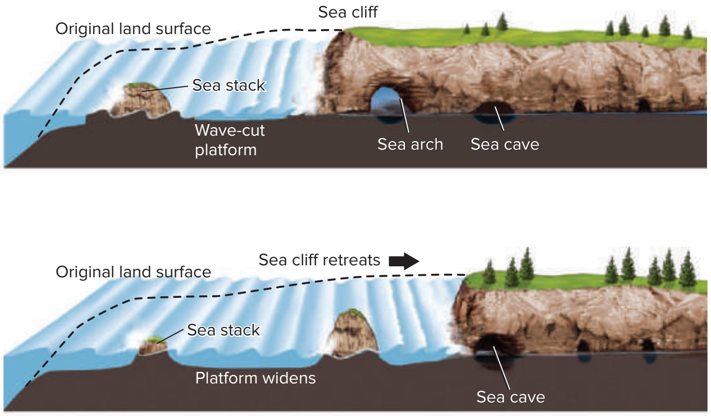


©David McGeary

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 (e.g., “Radon—A Radioactive Health Hazard”).

In Greater Depth Boxes

Discuss phenomena that are not necessarily covered in a geology course (e.g., “Precious Gems”) or present material in greater depth (e.g., “Calculating the Age of a Rock”).

Earth Systems Boxes

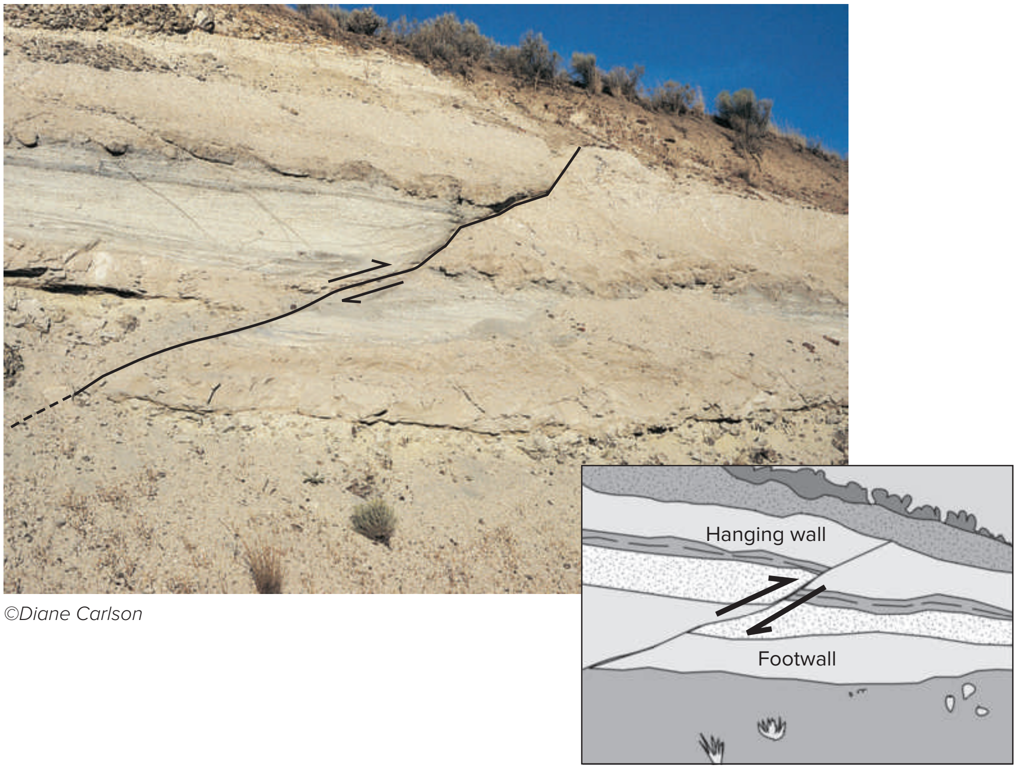
Highlight the interrelationships between the geosphere, the atmosphere, and other Earth systems (e.g., "Oxygen Isotopes and Climate Change").

Planetary Geology Boxes

Compare features elsewhere in the solar system to their Earthly counterparts (e.g., "Stream Features on the Planet Mars").

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.



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Animations

Figures representing key concepts such as plate tectonics, fault movement, earthquakes, isostasy, groundwater movement, sediment transport, glacial features, Earth movement, and other processes enhanced by animation are included online at McGraw-Hill Connect.

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.
- *Exploring Web Resources* describe some of the best sites on the Web that relate to the chapter.

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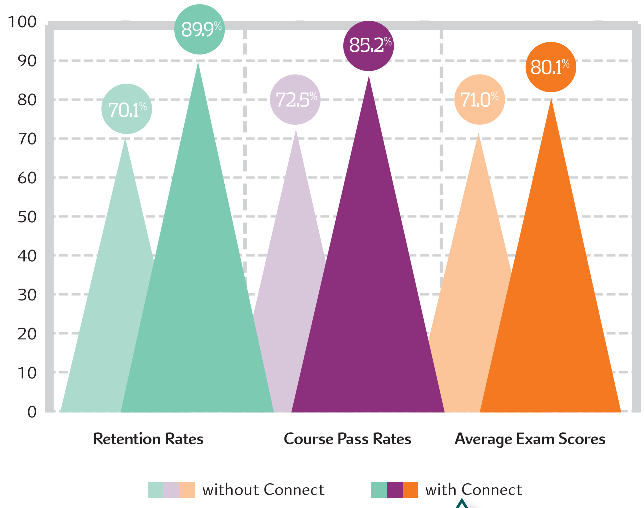

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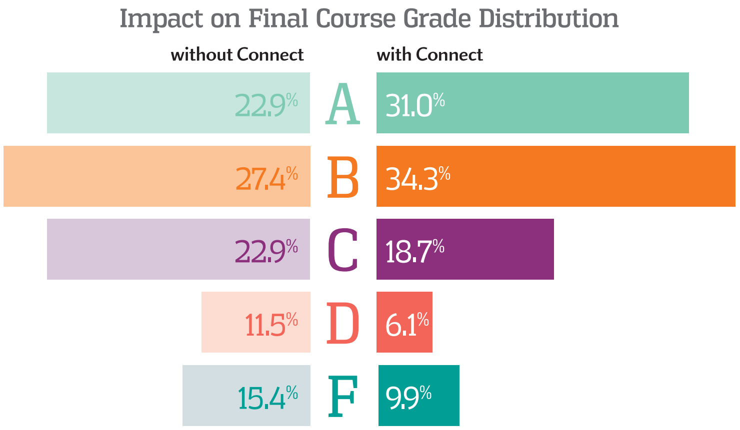

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- Connect offers comprehensive service, support, and training throughout every phase of your implementation.
- If you're looking for some guidance on how to use Connect, or want to learn tips and tricks from super users, you can find tutorials as you work. Our Digital Faculty Consultants and Student Ambassadors offer insight into how to achieve the results you want with Connect.

Instructor Resources

The following resources can be found on Connect:

- ***Presentation Tools*** Everything you need for outstanding presentations.
  - Animations—Numerous full-color animations illustrating important processes are provided. Harness the visual impact of concepts in motion by importing these files into classroom presentations or online course materials.
  - Lecture PowerPoints—with animations fully embedded.
  - JPEG images—Full-color digital files of all illustrations that can be readily incorporated into presentations, exams, or custom-made classroom materials.
  - Tables—Tables from the text are available in electronic format.
- ***Google Earth and Virtual Vista Exercises***—Descriptions and questions to help students visualize and analyze geologic features.
- ***Instructor's Manual***—The instructor's manual contains chapter outlines, lecture enrichment ideas, and critical thinking questions.
- ***Computerized Test Bank***—A comprehensive bank of test questions is provided within a computerized test bank. Instructors can select questions from multiple McGraw-Hill test banks or author their own, and then either print the test for paper distribution or give it online.

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 revised chapter 21 for the fifteenth edition. 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.

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.

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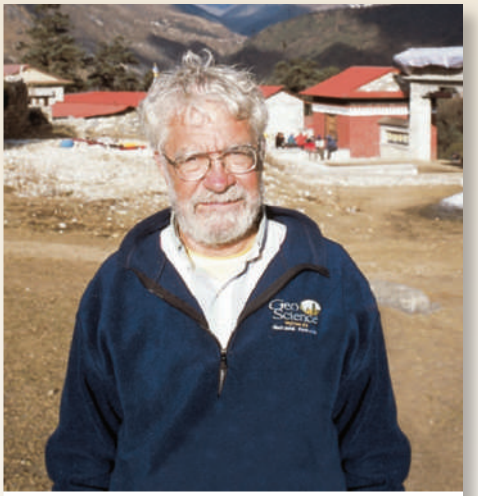
MEET THE AUTHORS



Courtesy of C.C. Plummer

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

Courtesy of Reid Buell

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

Courtesy of Christopher Cappa

Lisa Hammersley on the coast of Northern California

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.

At CSUS, he taught optical mineralogy, metamorphic petrology, and field courses as well as introductory courses. He retired from teaching in 2003. He skis, has a private pilot license, and is certified for open-water SCUBA diving. (plummercc@csus.edu)

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)

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 Associate 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.
- Do not get overwhelmed by terms. (Every discipline has its own language.) Don't just memorize each term and its definition. 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.)
- Explore the web links provided in this book. You will find they provide additional useful information.
- 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 a pencil (figure 1.1). The Earth, at work for billions of years, has 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 geology.

The economic systems of Western civilization currently depend 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. When fuel prices jump, people who are not aware that petroleum is a nonrenewable resource become upset and are quick to blame oil companies, politicians, and oil-producing countries. (The Gulf Wars of 1991 and 2003 were at least partially fought because of the industrialized nations' petroleum requirements.) 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 forces.

Just how much of our resources do we use? According to the Minerals Education Coalition, approximately 17,936 kilograms (39,543 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 4,115 kilograms stone, 3,093 kilograms sand and gravel, 279 kilograms limestone for cement, 66 kilograms clays, 191 kilograms salt, 243 kilograms other nonmetals, 150 kilograms iron ore, 30 kilograms aluminum ore, 6 kilograms copper, 8 kilograms lead and zinc, 3 kilograms manganese, and 11 kilograms other metals. Americans' yearly per capita consumption of energy resources includes 3,463 liters (915 gallons) of petroleum, 2,609 kilograms of coal, 2,389 cubic meters (84,348 cubic feet) of natural gas, and 0.08 kilograms of uranium.

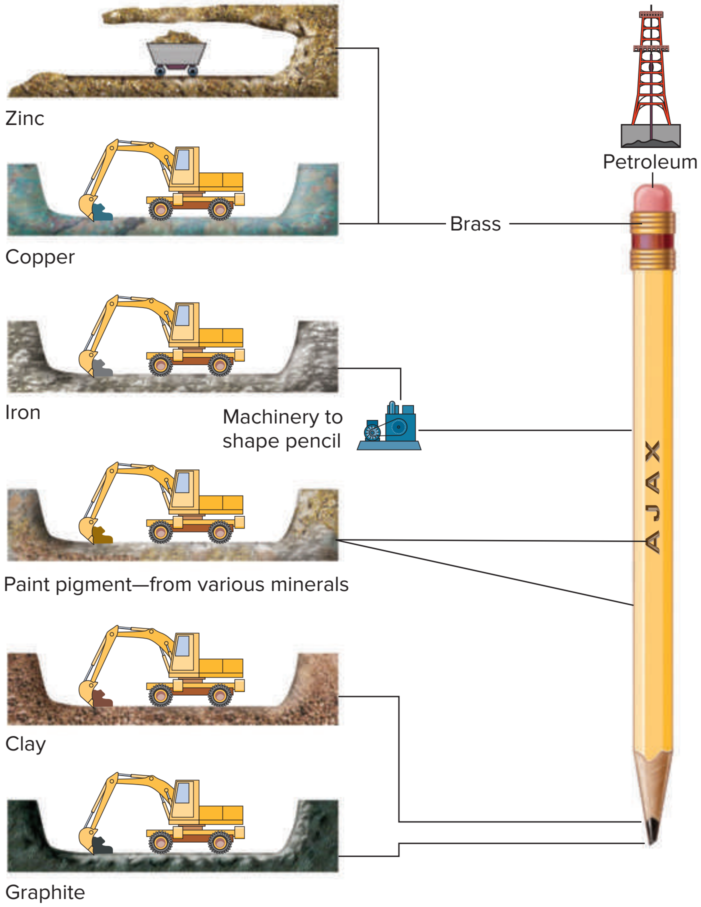


FIGURE 1.1

Earth's resources needed to make a wooden pencil.

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 balance of nature within the Earth and therefore on us, Earth's residents. 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

ENVIRONMENTAL GEOLOGY 1.1

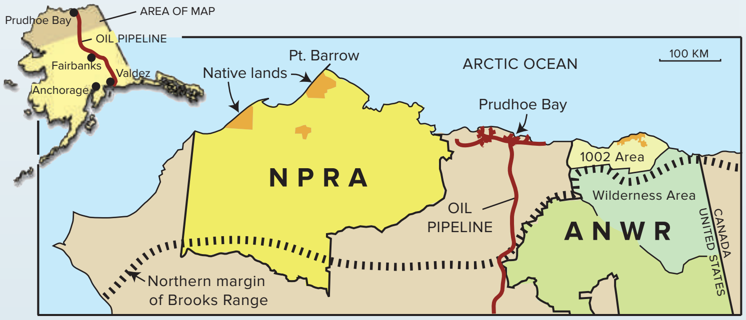
Delivering Oil—The Environment versus the Economy

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 United States' third largest oil field. 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%.

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 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

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).

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

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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.

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 geologic hazards.

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. Go to http://pubs.usgs.gov/fs/2003/fs014-03/pipeline.html for more information.
Source: Alyeska Pipeline Service Company/U.S. Geological Survey

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.

Additional Resources

The Alyeska pipeline company's site.

- www.alyeska-pipe.com/

U.S. Geological Survey fact sheet on the Arctic National Wildlife Refuge.

- http://pubs.usgs.gov/fs/2002/fs045-02/

Geotimes article on the 2006 oil spill. Links at the end of this and other articles lead to older articles published by the magazine.

- www.geotimes.org/aug06/WebExtra080706.html

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 over 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.

Just one month later, on February 10, a magnitude 8.8 earthquake hit off the coast of central Chile. The earthquake

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) Source: Tech. Sgt. James L. Harper, Jr., U.S. Air Force (B) Source: Walter D. Mooney, U.S. Geological Survey

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.

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

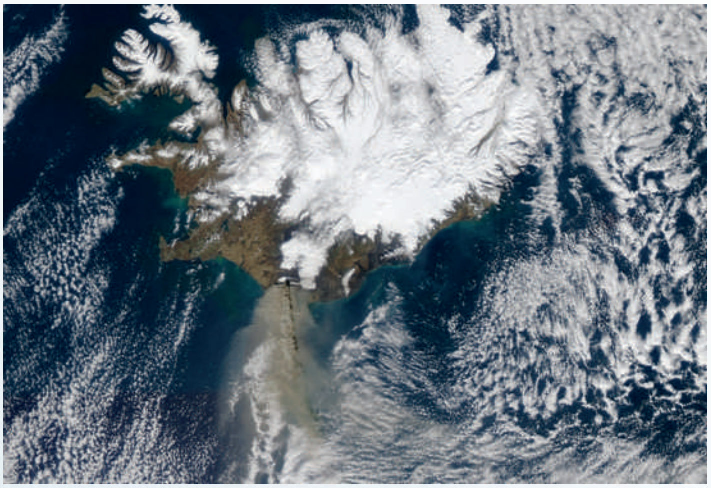
ENVIRONMENTAL GEOLOGY 1.2

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.

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.



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.
Source: Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC

Additional Resources

Amazing images of the eruption can be found at

- http://www.boston.com/bigpicture/2010/04/more_from_eyjafjallajokull.html

The Institute of Earth Sciences Nordic Volcanological Center, University of Iceland—lots of great information about the eruptions

- http://earthice.hi.is/eruption_eyjafjallajokull_2010

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.

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

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

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.
©Jacques Langevin/Corbis/Getty Images

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.

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.

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 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, such as we find in farms, gardens, and forests. The solid "dirt" 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 GREATER DEPTH 1.3

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 most geologists have in common is that they were attracted to the outdoors. Most of us enjoyed hiking, skiing, climbing, or other outdoor activities before getting interested in geology. We 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). A petroleum geologist can make over $90,000 a year but may have to spend months at a time on an offshore drilling platform. 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 work in Antarctica studying the dynamics of glacier movement or collecting ice cores through drilling to determine climate changes that have taken place over the past 100,000 years or more. Other geologists who work in Antarctica might be deciphering the history of a mountain range, working on skis and living in tents. Volcanologists sometimes are killed or injured while trying to collect gases or samples of lava from a volcano. Some sedimentologists scuba dive in places like the Bahamas, skewering lobsters for lunch while they collect sediment samples. One geologist was the only scientist to work on the Moon. 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/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.

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. Usually, a geologist engages in a combination of field work, lab work, and computer analysis.

Geologists tend to be happy with their jobs. In surveys of job satisfaction in a number of professions, geology rates near or at 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.

Additional Resource

For more information, go to the American Geological Institute's career site at

- www.earthscienceworld.org/careers/brochure.html

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.