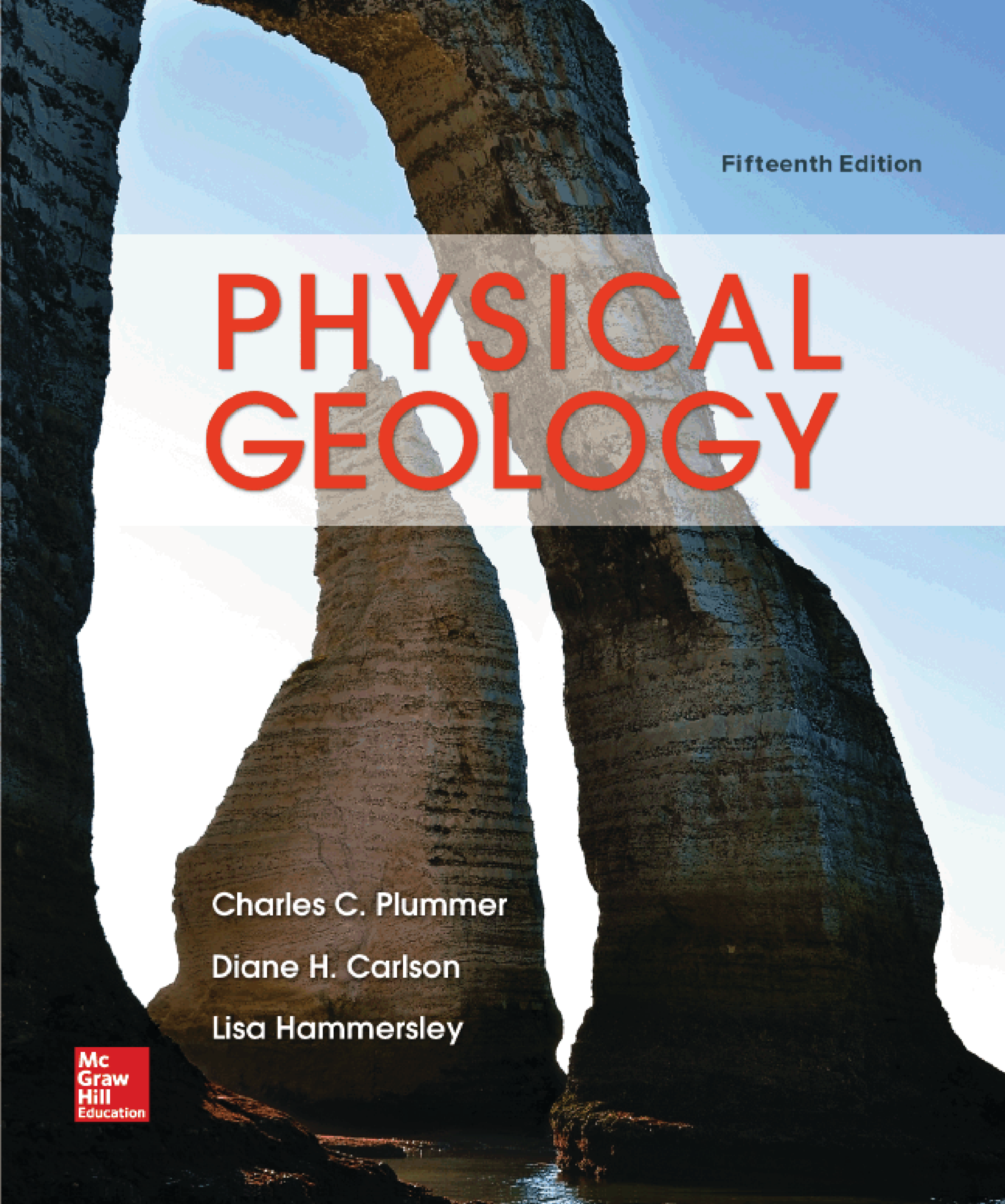


Fifteenth Edition

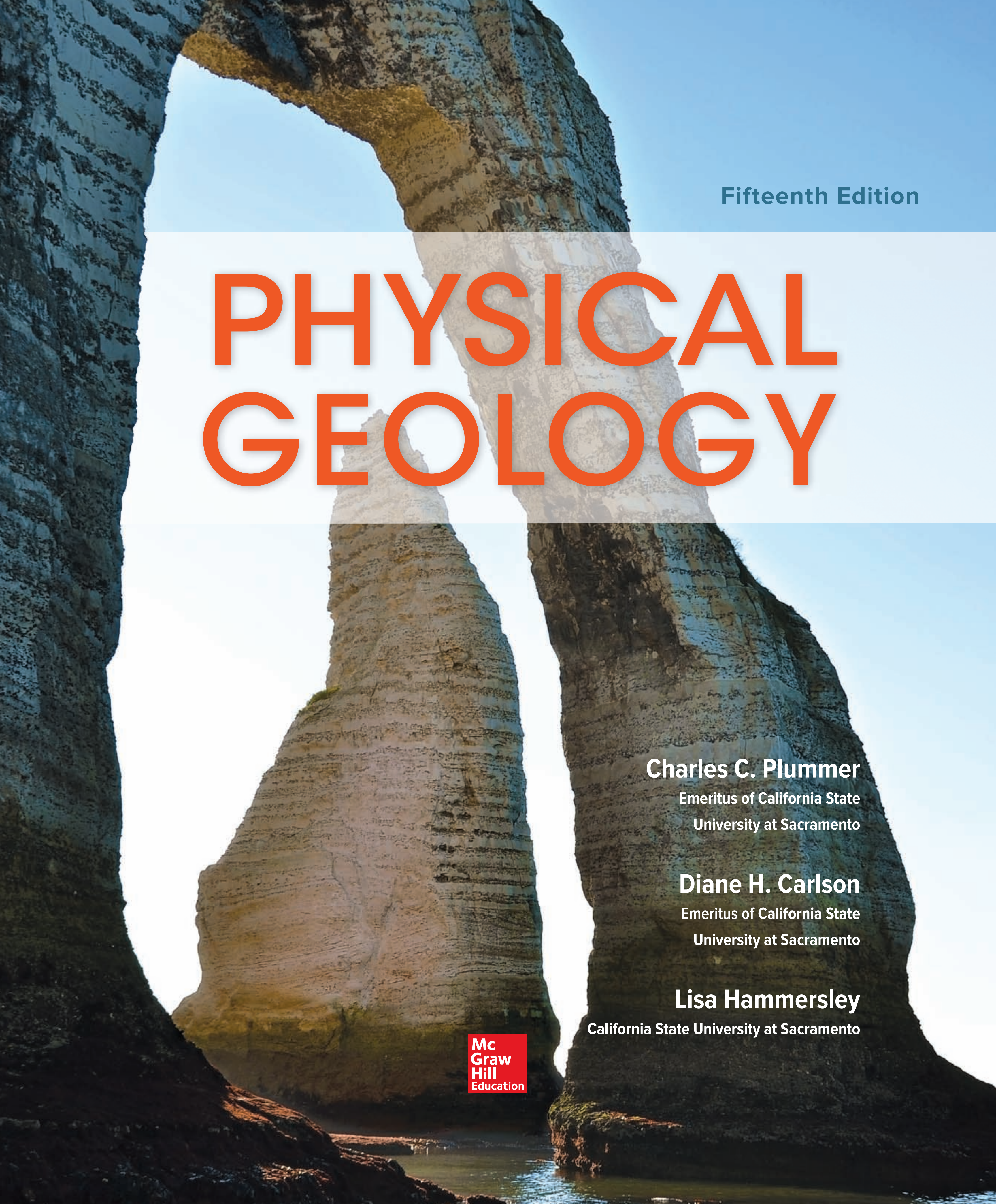
PHYSICAL GEOLOGY

Charles C. Plummer

Diane H. Carlson

Lisa Hammersley

Mc Graw Hill Education



Fifteenth Edition

PHYSICAL GEOLOGY

Charles C. Plummer
Emeritus of California State University at Sacramento

Diane H. Carlson
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PHYSICAL GEOLOGY, FIFTEENTH EDITION

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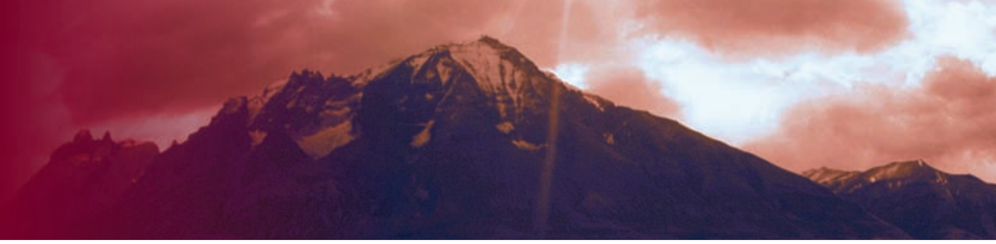
About the Cover

The cover photo is of a portion of France's western coastline in the province of Normandy. The sea is the English Channel, the portion of the Atlantic Ocean between France and England.

The layered bedrock exposed on the cliffs is sedimentary rock (see chapter 6). Originally, layers of sediment settled on the floor of a shallow sea. In time, the loose sediment solidified into sedimentary rock. Most of the white layers are chalk, a variety of limestone made up of tiny fossils that require a microscope to be seen. Fossils in the rocks indicate that deposition of sediment took place during the Cretaceous period, which ended around 65 million years ago (see chapter 8).

Later, the region was uplifted above sea level and erosion of the rock began and continues to take place. Wave action along the new shoreline carved the coast into sea cliffs, arches and stacks, as explained in chapter 14. The steep, rugged island seen through the arch is a sea stack.



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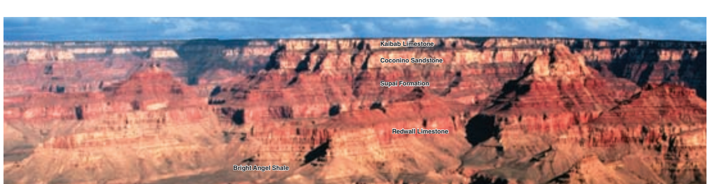

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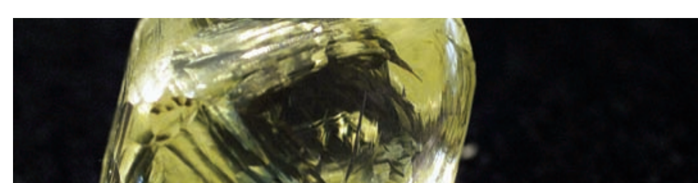

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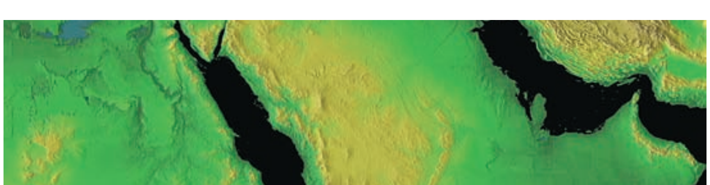

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PREFACE

WHY USE THIS BOOK?

One excellent reason is that it's tried and true. Since the book was 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 fifteenth 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 FIFTEENTH EDITION

New to the Fifteenth Edition

We are pleased to announce that Dr. Lisa Hammersley has taken on a much larger role as an author of *Physical Geology,* as Charles Plummer assumes a less active role. To mark this change, the fifteenth edition has been **redesigned** to give it a fresher look that is more inviting to students. Bolder colors, clearer layout, and single-page chapter openers are all part of this redesign. Each chapter now opens with an introductory paragraph that first engages the reader with the topic through questions or observations and then outlines the approach that will be taken as students work through the chapter. This introductory material is no longer divided between the chapter opener page and the main text, which will provide more encouragement for students to read it.

As part of the fifteenth edition's redesign, we have added **learning objectives** to the beginning of each chapter. Learning objectives are a useful tool to help students focus their study of the material and to understand the kinds of questions they should be able to answer once they have mastered the material in the chapter. Learning objectives emphasize the synthesis of information over the basic recollection of terminology, something many introductory-level students struggle with.

The fifteenth edition also features major updates to the **questions** at the end of each chapter. The authors have worked to ensure that the questions reflect the learning objectives and follow the flow of the chapter more clearly. In addition, new questions have been added to refresh the pool of questions available to instructors. The fifteenth edition has clearly benefitted from Dr. Hammersley's work as lead author of LearnSmart™ for *Physical Geology* and for multiple other McGraw-Hill texts.

This edition also contains new boxes, sections, and photos detailing **recent geologic events** such as the damage to coastal areas from 2012 Superstorm Sandy; the deadly 2014 landslide near Oso, Washington; the devastating 2013 flash floods in Colorado; the catastrophic collapse of sinkholes that have taken houses, cars, and lives; dust storms (haboobs) in Phoenix, Arizona, and elsewhere in drought-stricken areas; and the meteorite impact in Chelyabinsk, Russia. Environmental issues are also addressed in this edition, such as hydraulic fracturing "fracking" for natural gas in shale and the consequences to groundwater supply and contamination (box 11.3). New to the previous edition, chapter 21 has been updated by a scientist working in the field to reflect the rapid changes in the field of climate change.

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

Chapter 1 now includes a description of the Earth's core in the section on the Earth's interior, which makes that section more complete. Table 1.2 has been updated to reflect changes to the geologic time scale. Discussion of the Keystone Pipeline controversy has been added to box 1.1.

Chapter 2 has been reorganized at the beginning to create a better introduction to the topic. The Web investigation on graphite and diamond has been replaced with a new activity. New photos have been added where needed, including a new figure showing the mineral property streak. Labels have been added to figure 2.23 to make the connection to the text clearer.

Chapter 3 has been reorganized to improve flow and clarity. It opens with the rock cycle and then progresses to the description and identification of igneous rocks, followed by the origin and evolution of magma. The section on intrusive activity now follows the evolution of magma and has been expanded to include laccoliths. The chapter closes with a discussion of igneous activity and plate tectonics. The section on Bowen's reaction series has been expanded. We have added the terms *phaneritic* and *aphanitic* but kept *coarse-grained* and *fine-grained.* Images have been updated, including new photomicrographs of phaneritic and porphyritic textures.

Chapter 4 has been updated with new photos and Web links. A new figure (4.12) showing the generation of explosive eruptions has been added to the section on explosive eruptions to provide a visual aid to students.

Chapter 5 has been reorganized at the beginning to integrate the effects of the atmosphere, hydrosphere, and biosphere into the discussion on weathering, erosion, and transportation, and the rock cycle is now part of the main text.

Chapter 6 has minor rewrites to improve readability. Table 6.2 also includes chert as an inorganic sedimentary rock, and the discussion of breccia was rewritten to more clearly include talus slopes as a depositional environment, which is also now illustrated in figure 6.35. Box 6.2 was updated to include the Mars Science Laboratory and a photo of sedimentary deposits in the Gale Crater.

Chapter 7 has been reorganized to improve its flow and to better emphasize the role of fluids in metamorphism. The hydrothermal processes section has been streamlined and divided into two new sections. The first of these is Hydrothermal Metamorphism, which is now included in the Types of Metamorphism section. The second, Hydrothermal Metamorphism and Plate Tectonics, is included in the section on plate tectonics and metamorphism, which now concludes the chapter. The sections on prograde metamorphism and pressure-temperature paths have been reconfigured into a new section on Metamorphic Grade.

Chapter 8 has been updated to reflect changes to the geologic time scale, with new ages for the boundaries between the Proterozoic and Phanerozoic eons, the Paleozoic and Mesozoic eras, the Mesozoic and Cenozoic eras, and the Paleocene and Eocene epochs. A new Web link has been added to box 8.3.

Chapter 9 has been reorganized so that students first consider the factors controlling mass wasting before learning how to classify different types of mass wasting. The section Common Types of Mass Wasting has been separated into three subsections (Flows, Falls, Slides) to better follow the classification scheme described earlier in the chapter. Box 9.5 has been completely rewritten and now covers the deadly 2014 landslide near Oso, Washington. The box explores the causes of the slide and whether this disaster could have been prevented. Web links within the chapter have been updated to include websites that are more interactive.

Chapter 10 contains new photos and a discussion of the 2013 Colorado flash floods; a new section on reducing flood risk, and box 10.1 has been updated to include new details, references, and photos of the latest controlled floods on the Colorado River. The summary has been expanded to include flooding, recurrence interval, and flood risk. We have tried to shorten the chapter by removing the extensive discussion of historic flooding along the Mississippi River.

Chapter 11 has been reorganized and rewritten to improve the flow of material and to emphasize process over definitions. The chapter begins with the importance of groundwater and follows with a discussion of the water table, porosity and permeability, aquifers, and then the movement of groundwater. We have added a new box, "Fracking for Natural Gas," and the implications for groundwater contamination, and another new box on sinkholes to emphasize the geologic hazard in areas of soluble bedrock. We also expanded the section on karst topography and added a discussion of tower karst and a photo of the Li Valley in southern China.

Chapter 12 now begins with the section "What Is a Glacier?", which defines glaciers and differentiates between valley glaciers and ice sheets and the glaciated terrains they produce. This provides a better introduction to the section on the distribution of glaciers and how they form. Box 12.2 has been updated to reflect the success of the drilling project in reaching Lake Vostok. Box 12.3 has also been updated to reflect the results of recent studies and to reflect North American terminology.

Chapter 13 now includes an expanded discussion of desertification and the severe drought in the midwestern United States, and the probability of future dust storms as climate change occurs (box 13.1). We have labeled the dates on the satellite photos of the shrinking Aral Sea to improve clarity. We have also added a photo and description of the large dust storms that recently blew across Phoenix, Arizona. Box 13.3 now mentions how desert pavement and desert varnish can be used to study desert landforms, climate change, and petroglyphs.

Chapter 14 now begins with a section on shoreline dynamics and includes a photo and discussion of damage from Superstorm Sandy. There has been a major revision of box 14.1, which includes a map showing sea level rise along the U.S. coastline, and a discussion of the consequences of sea level rise. We have also added before and after aerial photos of damage to a barrier island in New Jersey caused by Superstorm Sandy. Box 14.2 has been updated to include Super Typhoon Haiyan, which is the strongest hurricane ever recorded on Earth. We also included a discussion of the record storm surge associated with Superstorm Sandy and the resulting damage.

Chapter 15 has been updated with new photos of geologic structures and updated Web links.

Chapter 16 had been extensively revised in the last edition to include the recent earthquakes in Haiti, New Zealand, Chile, and Japan. In this edition, we have updated Web links and added an updated map of seismic risk in the United States that now also includes risks in Alaska and Hawaii.

Chapter 17 has been edited to improve readability, and several sections have been retitled to make the material more approachable for the reader. Box 17.1 has been replaced with a new box on seismic tomography that includes an exciting new tomographic figure of the entire Earth and a 3-D tomographic diagram of the United States showing the foundering Farallon plate. Box 17.2 now includes updated information and references on new seismic wave analysis that refines the super rotation of the inner core and generation of Earth's magnetic field.

Chapter 18 has been reorganized so the features of the sea floor are more clearly presented, and minor edits improve readability.

Chapter 19 has undergone minor reorganization and rewrites to update material and to improve flow and clarity. Nine figures were revised and/or redrawn, and Web links were updated and now include the EarthScope website and information on the Plate Boundary Observatory. New research that suggests mantle plumes can push a plate and speed up its movement were added to the section "What Causes Plate Motions?"

Chapter 20 has been edited for improved readability and now opens with the section "Mountains and Mountain Building."

Chapter 21 has been updated to reflect the rapid changes in the study of climate change. Figure 21.10 has been redrawn to make it more understandable. Figures 21.14 and 21.16 have been merged into a new figure 21.14 and simplified. New sections on the fate of atmospheric carbon dioxide and the meaning of scientific consensus have been added.

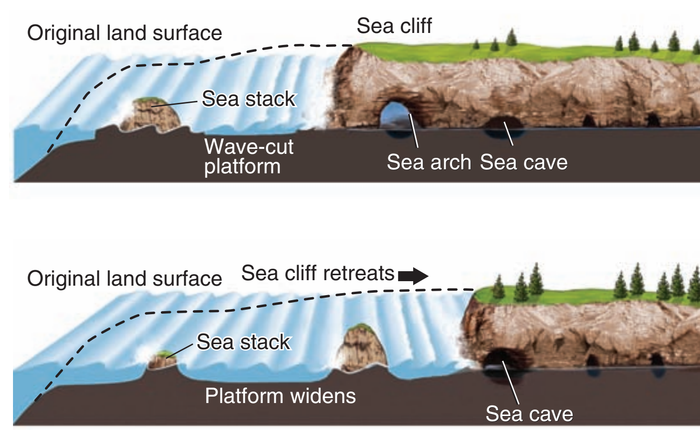
Chapter 22 has been updated to reflect the huge changes in U.S. oil and gas production in recent years due to exploitation of deposits by means of hydraulic fracturing or *fracking*. A new section on fracking has been added.

Chapter 23 has been revised to include a better discussion of the Earth in space and a new section on Enceladus, a moon of Saturn. References to the *Curiosity* mission on Mars and the recent meteorite impact in Chelyabinsk have also been added. 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 a student can 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.



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").

Three-Page Foldout

This foldout, located in the back of the text, is constructed so students can easily leave it folded out and refer to it while reading the text. The front side contains a geographic map of the world so that students can gain a better sense of the location of the places that are mentioned within the text. The North America Tapestry of Time and Terrain map is located on the back of the foldout.

Earth Systems Boxes

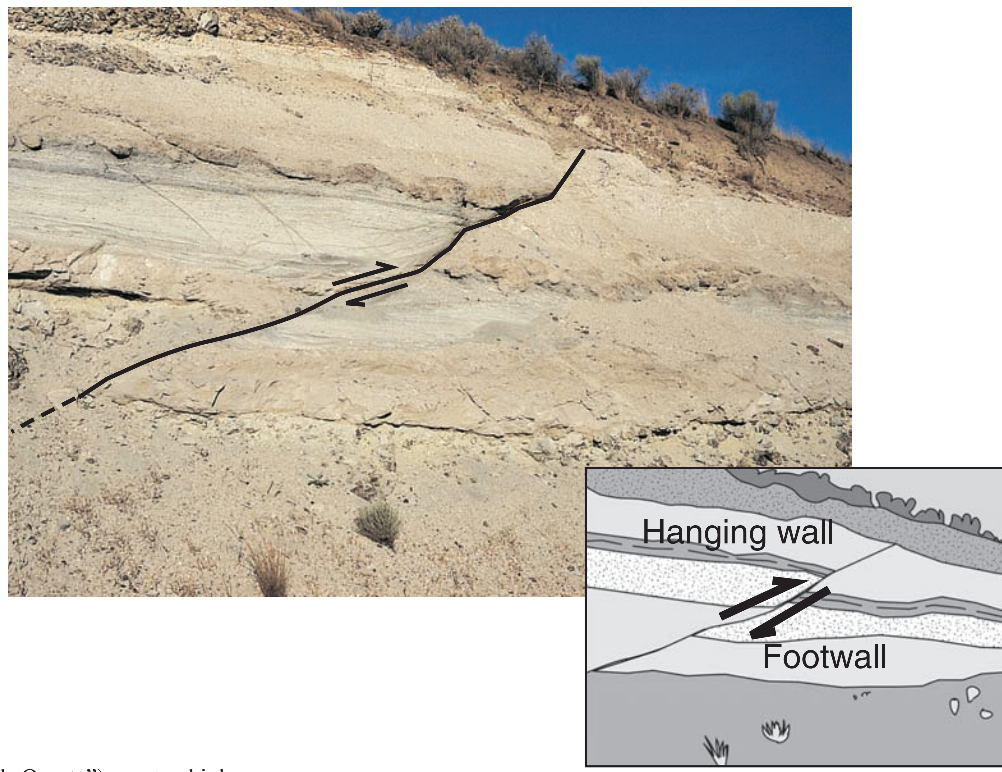
Highlight the interrelationships between the geosphere, the atmosphere, and other Earth systems (e.g., "Oxygen Isotopes and Climate Change").

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.



Web Boxes

Explore topics of interest (e.g., "On Time with Quartz") or at a higher level than is usual for a physical geology course.

WEB BOX 2.7

On Time with Quartz

Ever wonder why your watch has "quartz" printed on it? A small slice of quartz in the watch works to keep incredibly accurate time. This is because a small electric current applied to the quartz causes it to vibrate at a very precise rate (close to 100,000 vibrations per second).

To view an excellent video on how quartz is used to keep time, visit http://www.engineerguy.com/videos/video-quartz-watch.htm.

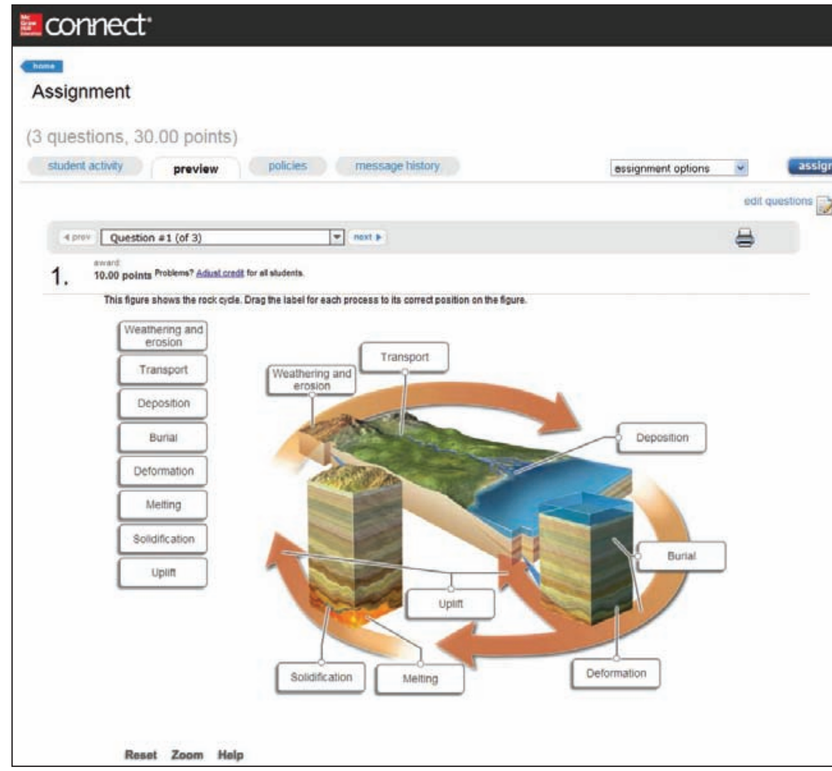
Animations

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 ConnectPlus Geology. A special animation icon has been placed beside each figure in the text that has a corresponding animation.

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 the website.)
- *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.

Mc Graw Hill Education connect plus+ GEOLOGY



McGraw-Hill ConnectPlus® (http://connect.mheducation.com) is a Web-based assignment and assessment platform that gives students the means to better connect with their coursework, with their instructors, and with the important concepts that they will need to know for success now and in the future.

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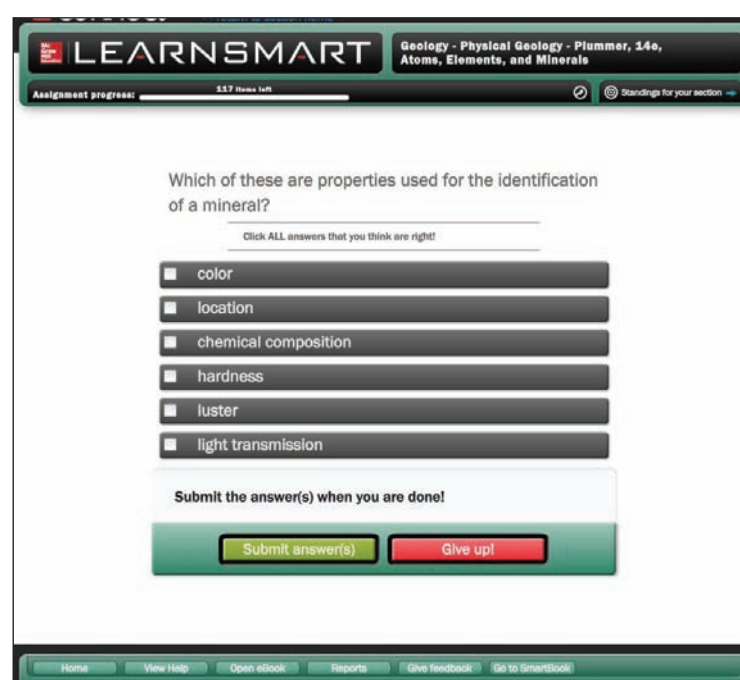
- LearnSmart, an adaptive diagnostic and learning tool
- SmartBook™, an adaptive reading experience
- Powerful reporting against learning outcomes and level of difficulty
- The full textbook as an integrated, dynamic eBook, which you can also assign
- McGraw-Hill Tegrity®, which digitally records and distributes your lectures with a click of a button
- Instructor Resources such as an Instructor's Manual, PowerPoint images, and Test Banks

With ConnectPlus, instructors can deliver assignments, quizzes, and tests online. Instructors can edit existing questions and write entirely new problems; track individual student performance—by question, by assignment, or in relation to the class overall—with detailed grade reports; integrate grade reports easily with learning management systems such as WebCT and Blackboard®; and much more. By choosing Connect®, instructors are providing their students with a powerful tool for improving academic performance and truly mastering course material. Connect allows students to practice important skills at their own pace and on their own schedule. Importantly, students' assessment results and instructors' feedback are all saved online, so students can continually review their progress and plot their course to success.

Mc Graw Hill Education LEARNSMART®



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Visit www.learnsmartadvantage.com to discover for yourself how the LearnSmart diagnostic ensures that students will connect with the content, learn more effectively, and succeed in your course.

SMARTBOOK™

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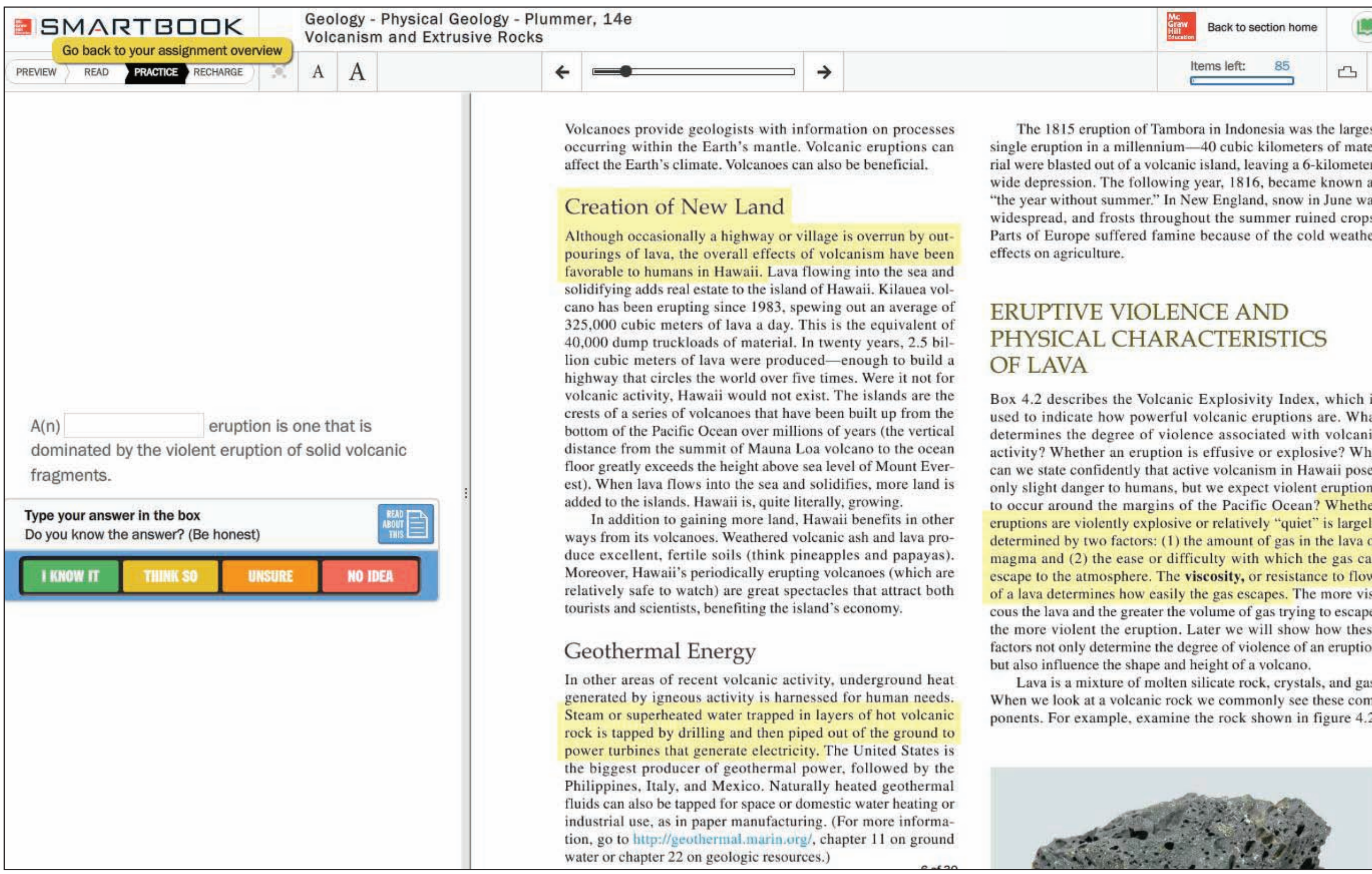

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Instructor Resources

The following resources can be found on ConnectPlus:

- ***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 powered by McGraw-Hill's flexible electronic testing program EZ Test Online. EZ Test Online allows you to create paper and online tests or quizzes in this easy to use program! Imagine being able to create and access your test or quiz anywhere, at any time, without installing the testing software. Now, with EZ Test Online, 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.

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- *Laboratory Manual for Physical Geology,* Eighth Edition, by Jones/Jones ISBN 9780073524139 (MHID 0073524131)

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 this 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.

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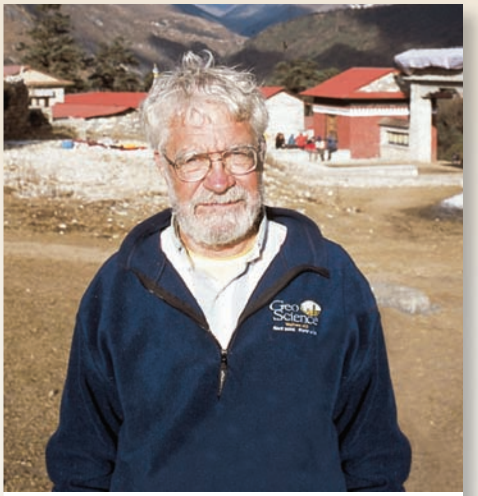
Charles G. Patterson, *Red Rocks Community College*
Christian Poppeliers, *East Carolina University*
Jeffery G. Richardson, *Columbus State Community College*
Adil M. Wadia, *The University of Akron Wayne College*
Stephanie Welch, *Southeastern Louisiana University*

MEET THE AUTHORS



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

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

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 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, 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 BSc. 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 teaches natural disasters, physical geology, geology of Mexico, mineralogy, and metallic ore deposits. Professor Hammersley is an award-winning teacher and a recent recipient of the Outstanding Teacher Award from the CSUS College of Natural Sciences and Mathematics. 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 and the United States and is currently studying areas in northern California and central Mexico. 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. (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. *Photo © 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.

WHO NEEDS GEOLOGY?

Geology benefits you and everyone else on this planet. The clothes you wear, the radio you listen to, the food you eat, and the car you drive 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.

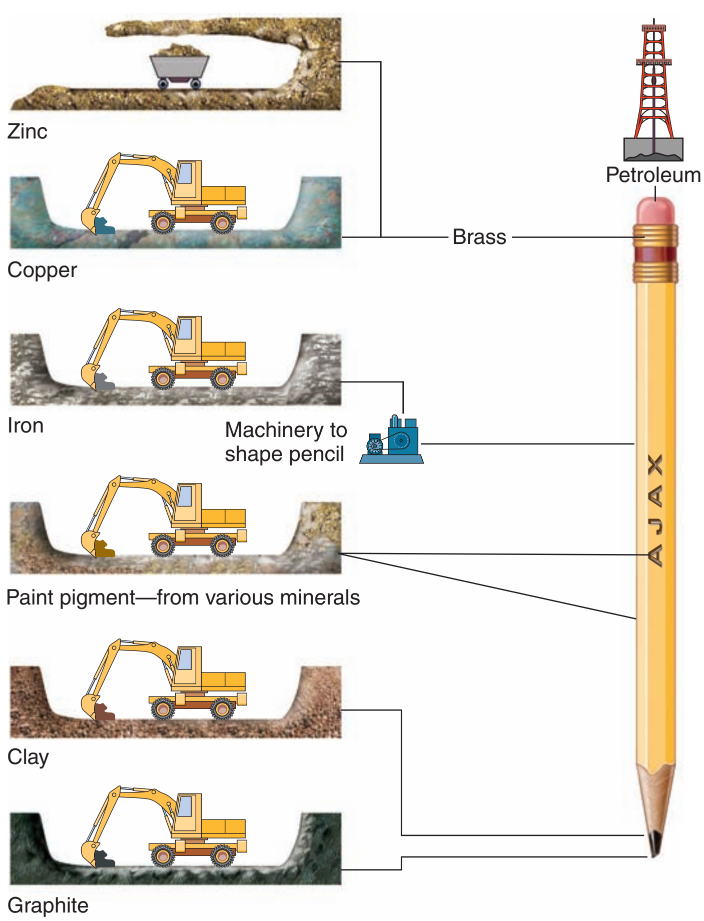


FIGURE 1.1
Earth's resources needed to make a wooden pencil.

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 as a cheap source of energy. During the past few decades, Americans have used up much of their country's known petroleum reserves, which took nature hundreds of millions of years to store in the Earth. The United States, and most other industrialized nations, are now heavily dependent on imported oil. 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.) Finding more of this diminishing resource or developing new extraction technologies 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 for every person living in the United States, approximately 17,333 kilograms (38,212 pounds; for metric conversions, go to appendix E) of resources, including energy resources, are mined annually. The amount of each commodity mined per person per year is 4,083 kilograms stone, 2,835 kilograms sand and gravel, 252 kilograms limestone for cement, 69 kilograms clays, 158 kilograms salt, 221 kilograms other nonmetals, 257 kilograms iron ore, 35 kilograms aluminum ore, 5 kilograms copper, 8 kilograms lead and zinc, 3 kilograms manganese, and 11 kilograms other metals. Americans' yearly per capita consumption of energy resources includes 3,430 liters (906 gallons) of petroleum, 2,570 kilograms of coal, 2,389 cubic meters (84,348 cubic feet) of natural gas, and 0.1 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 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).

ENVIRONMENTAL GEOLOGY 1.1

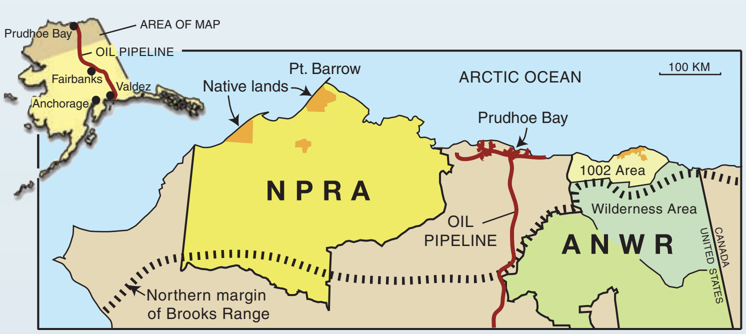
Delivering Alaskan Oil—The Environment versus the Economy

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' largest oil field. Thanks to the Trans-Alaska pipeline, completed in 1977, Alaska has supplied as much as 20% of the United States' domestic oil.

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. The drain on the country's economy and the increasing cost of energy can be major causes of inflation, lower industrial productivity, unemployment, and the erosion of standards of living. At its peak, over 2 million barrels of oil a day flowed from the Arctic oil fields. This means that over $10 billion a year that would have been spent importing foreign oil was kept in the American economy.

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.

Geologists with the U.S. Geological Survey conducted the official environmental impact investigation of the proposed pipeline route in 1972. After an exhaustive study, they recommended against its construction, partly because of the hazards to oil tankers and partly because of the geologic hazards of the pipeline route. Their report was overruled. The Congress and the president of the United States exempted the pipeline from laws that require a favorable environmental impact statement before a major project can begin.



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*

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.

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 2

The Alaska pipeline. *Photo by David Applegate*

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.

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 tsunamis are the most dangerous

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.

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. *Alyeska Pipeline Service Company/U.S. Geologic Survey*

The Trans-Alaska pipeline was designed to last 30 years. Considerable work and money is going into upgrades that will keep it functioning beyond its projected lifetime.

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. The 1972 environmental impact statement had singled out marine oil spills as being the greatest threat to the environment. Based on statistical studies of tanker accidents worldwide, it gave the frequency with which large oil spills could be expected. The *Exxon Valdez* spill should not have been a surprise.

Recently, another large oil pipeline project has been causing much debate. The Keystone Pipeline is expected to deliver oil from Canada and the northern United States to refineries in the Midwest and the Gulf Coast of Texas. Although parts of the pipeline system are already operational, the proposed extension from Nebraska to Texas has faced strong criticism from environmentalists. The potential threat to the environment is certainly of concern. However, the alternative to the pipeline is transporting the 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. A strong political motivation for approving the pipeline is the drive to reduce the United States' dependence on potentially unstable foreign oil sources.

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

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.

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.

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

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 577 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 the poorest country 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 Japanese. 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 tsunamis. In the hamlet of Aneyoshi, one of these stone markers reads, "Remember the calamity of the great tsunamis. 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 tsunamis, are products of Earth's sudden release of energy. Unlike earthquakes and tsunamis, 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.

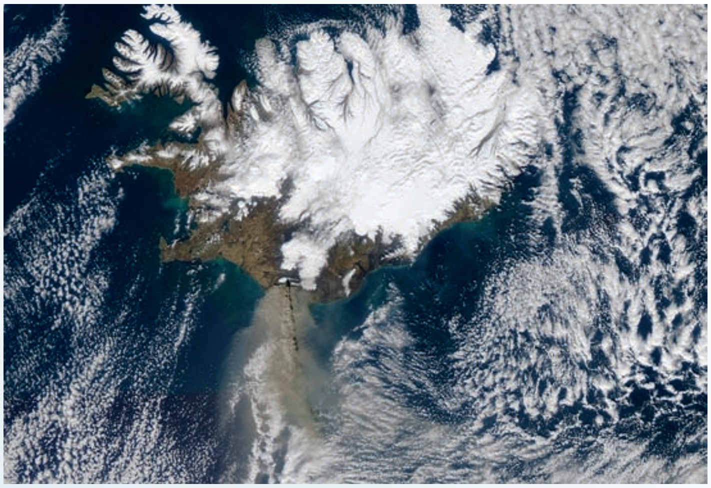
ENVIRONMENTAL GEOLOGY 1.2

A Volcanic Eruption in Iceland Shuts Down European Air Space 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 the 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 Icleand, began erupting lava from fissures on the side of the moutain. 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. *Image by Jeff Schmaltz, MODIS Rapid Response Team, NASA*

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

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 moutain. 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 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, how governments work or do not 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

FIGURE 1.3

The major eruption of Mount Pinatubo on June 15, 1991, as seen from Clark Air Force Base, Philippines. *Photo by 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. *Photo © Jacques Langevin/Corbis*

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.

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. 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. 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.

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. 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 (box figure 1). 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.

Engineering geologists determine whether 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. Demand is increasing for geologists to teach Earth science (which includes meteorology, oceanography, and astronomy as well as geology) in high schools. More and more secondary schools are adding Earth science to their curriculum and need qualified teachers.

BOX 1.3 ■ FIGURE 1
Geologists investigating the Latady Mountains, Antarctica. *Photo by C. C. Plummer*

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

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.