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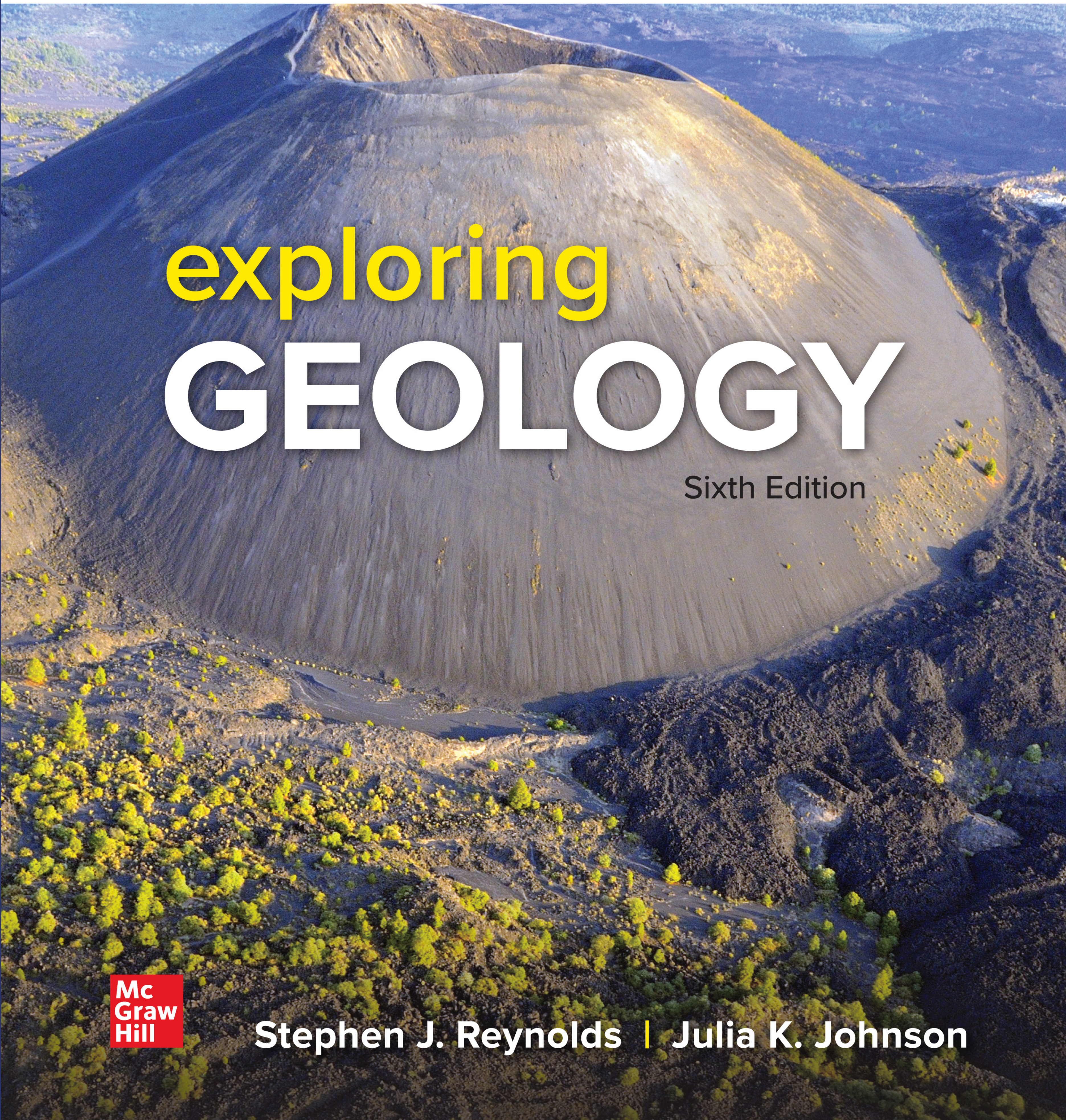


exploring GEOLOGY

Sixth Edition

McGraw Hill

Stephen J. Reynolds | Julia K. Johnson

exploring

GEOLOGY

About the Cover

Parícutin Volcano, located in the Mexican state of Michoacán, stands where a Mexican family once tilled a quiet corn field. For three weeks they had heard what sounded like thunder though no clouds were nearby. Then, on February 20, 1943, an open fissure appeared in the field, and trees began to tremble. The ground hissed and swelled as sulfurous smoke and gray ash rose from the fissure. Volcanic fragments and blobs of magma were thrown skyward, from sand-sized grains carried upward by the winds to large volcanic bombs more than a meter in diameter that crashed around the volcanic vent. By the next day, a volcanic cone 50 m high stood in what had been the corn field the day before.

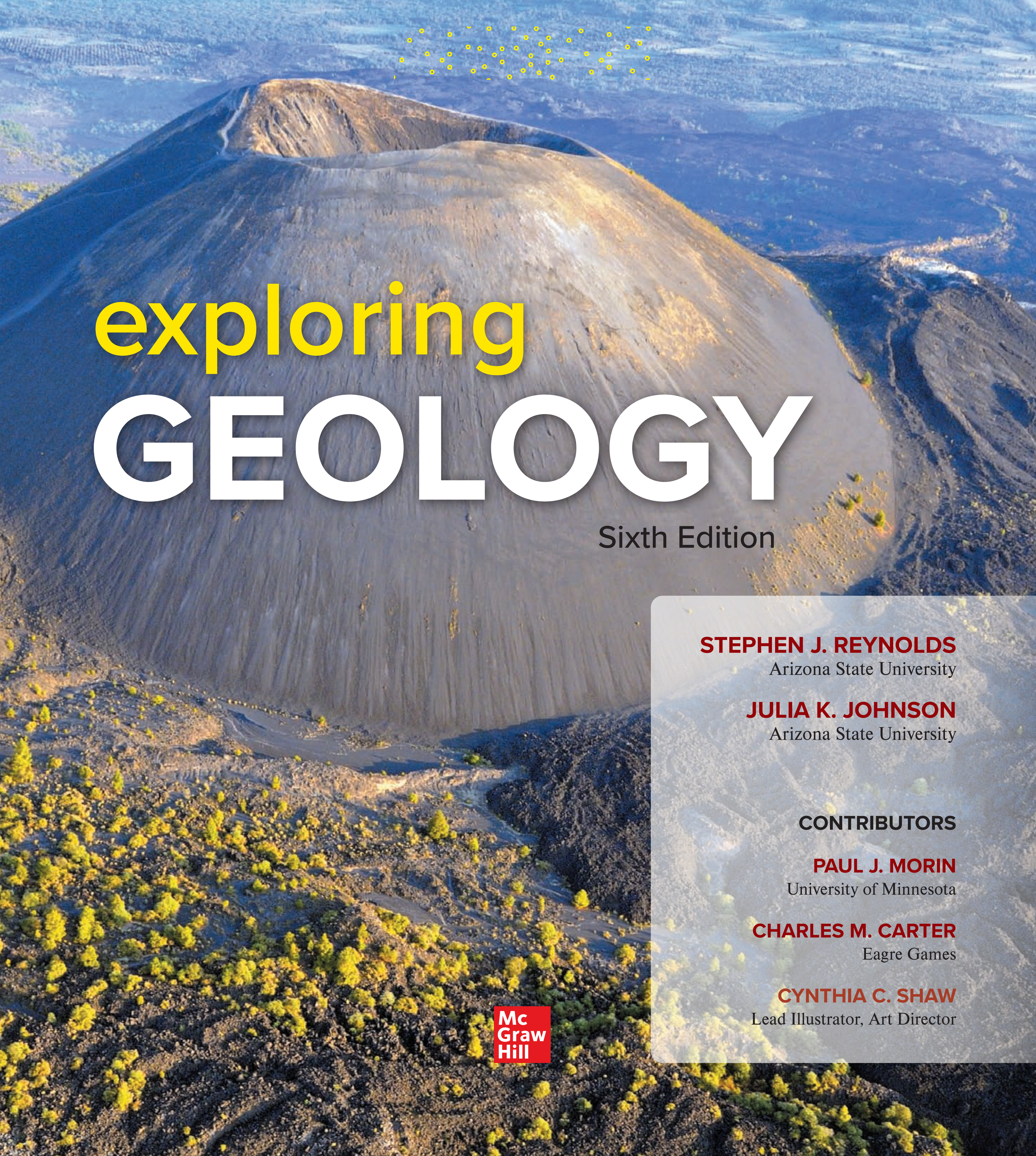
The cone erupted for nine years, giving scientists the unusual opportunity of witnessing the birth, life, and cessation of a volcano. What scientists witnessed was the steady growth of the cinder cone for the first year, with eruptions of lava increasing in frequency with time.

When the volcano became dormant in 1952, the cone had reached a height of 1,391 feet and almost a third of a cubic mile of lava had been erupted onto the surface. The town of San Juan Parangaricutiro was buried; only the steeples of its church remain above the dark, solidified lava flows. Ash had spread over many square miles of the surrounding countryside, blanketing vegetation and forcing local residents to settle elsewhere. The farmer who had first watched the birth of Parícutin planted a sign on his field before leaving: "This volcano is owned and operated by Dionisio Pulido."

Parícutin lies within the broad Trans-Mexican Volcanic Belt, an almost east-west-trending swath of volcanoes that crosses the southern part of Mexico south of Mexico City. The volcanic belt is created as the Rivera and Cocos oceanic plates subduct beneath the southwestern edge of the North American plate.

Cover photograph by Michael Collier

Michael Collier received his BS in geology at Northern Arizona University, MS in structural geology at Stanford, and MD from the University of Arizona. He rowed boats commercially in Grand Canyon in the '70s and '80s, and then practiced family medicine in northern Arizona. Collier has published books about the geology of Grand Canyon, Death Valley, Denali, and Capitol Reef National Park. He has authored books on the Colorado River basin, glaciers of Alaska, and climate change in Alaska, as well as a three-book series on American mountains, rivers, and coastlines. As a special projects writer with the USGS, he produced books about the San Andreas fault, the downstream effects of dams, and climate change. Collier's photography has been recognized with awards from the USGS, the National Park Service, the American Geosciences Institute, and the National Science Teachers Association.



exploring GEOLOGY

Sixth Edition

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EXPLORING GEOLOGY

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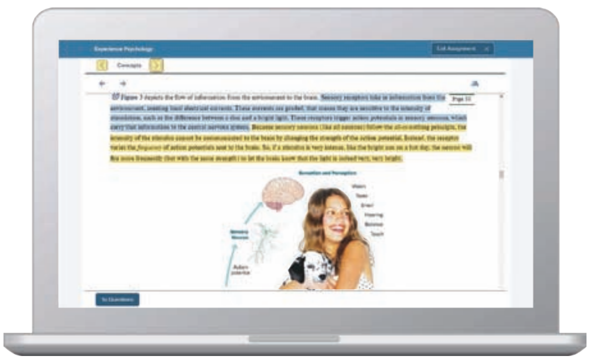

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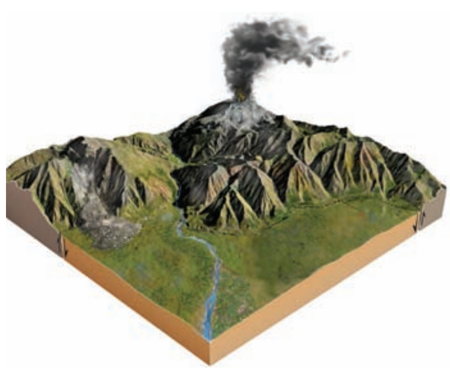

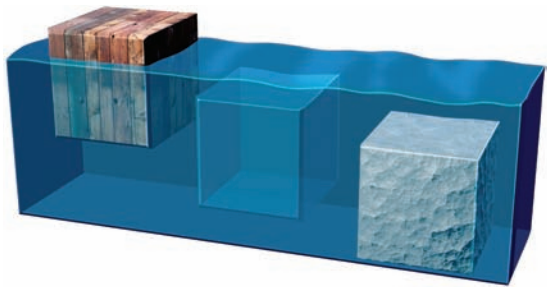

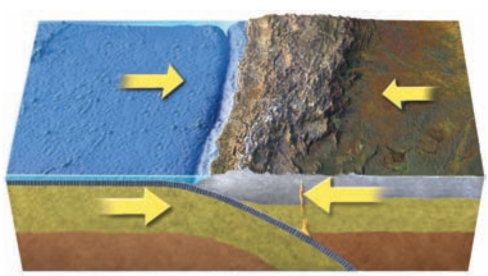

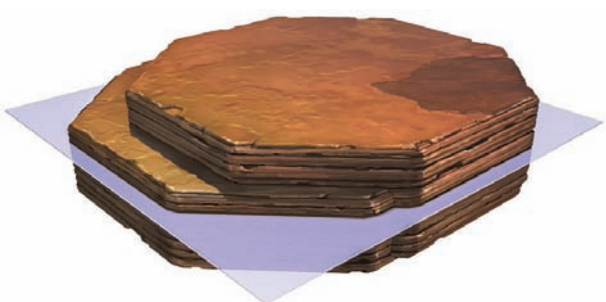

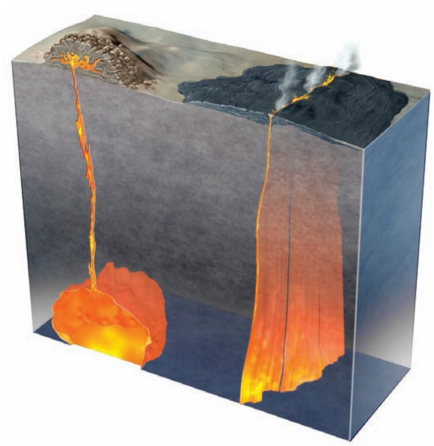

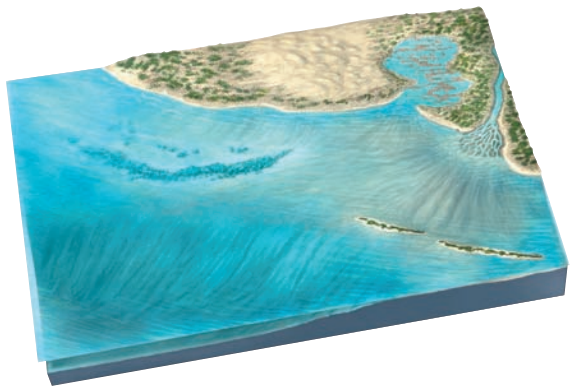

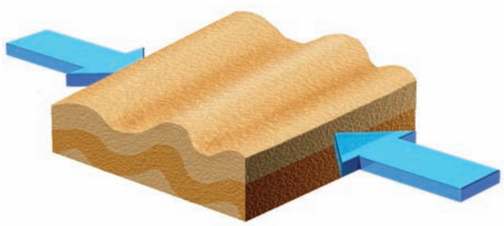

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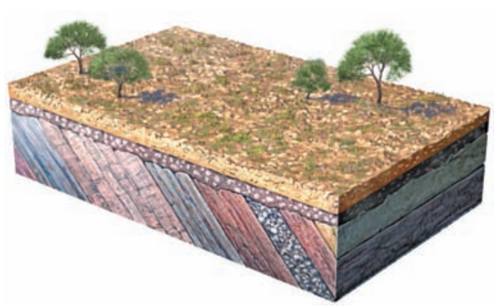

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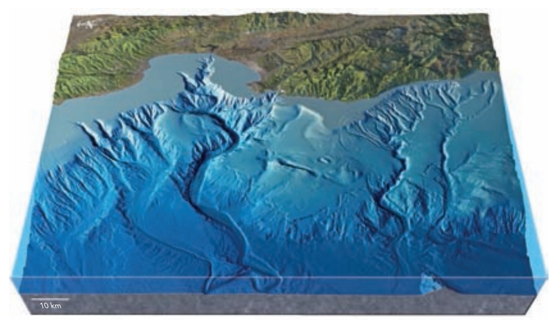

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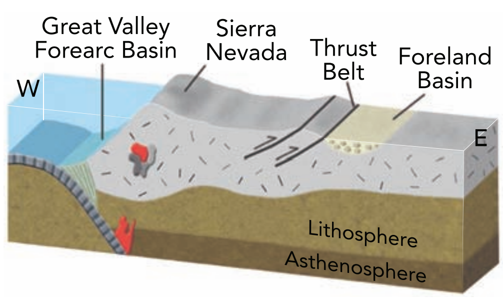

Great Valley
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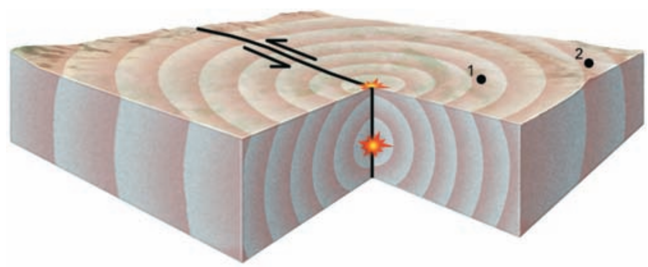

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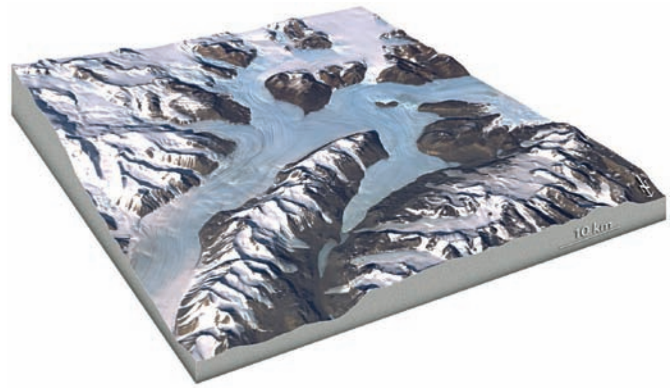

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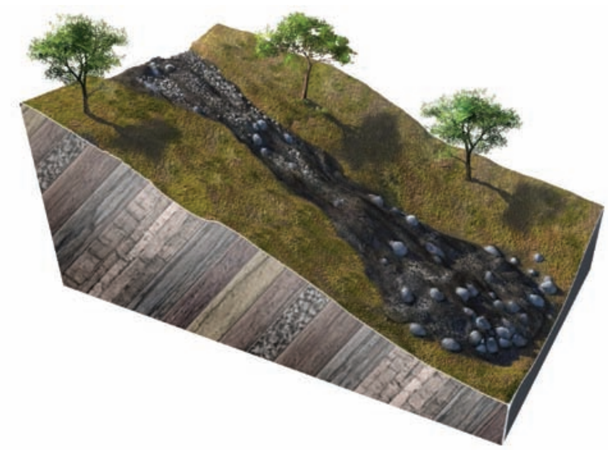

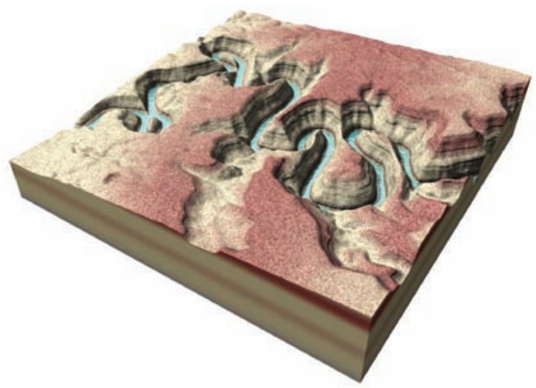

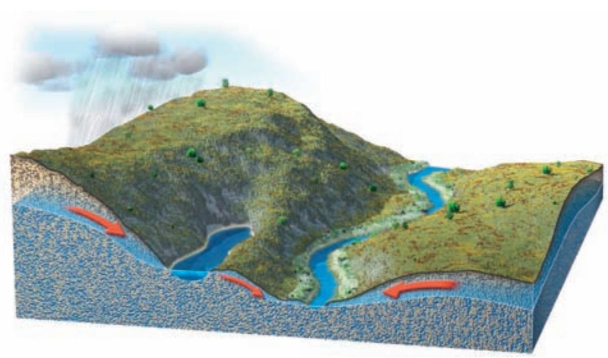

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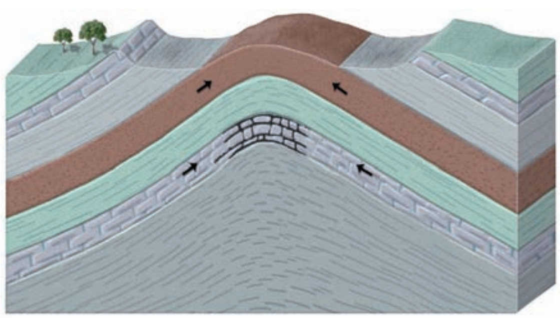

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PREFACE

TELLING THE STORY . . .

WE WROTE *EXPLORING GEOLOGY* SO THAT STUDENTS could learn from the book on their own, freeing up instructors to teach the class in any way they want. I (Steve Reynolds) first identified the need for this book while I was a National Association of Geoscience Teachers' (NAGT) distinguished speaker. As part of my NAGT activities, I traveled around the country conducting workshops on how to infuse active learning and scientific inquiry into introductory college geology courses, including those with upwards of 200 students. In the first part of the workshop, I asked the faculty participants to list the main goals of an introductory geology college course, especially for nonmajors. At every school I visited, the main goals were similar and are consistent with the conclusions of the National Research Council (see box below):

- to engage students in the process of scientific inquiry so that they learn what science is and how it is conducted,
- to teach students how to observe and interpret landscapes and other aspects of their surroundings,
- to enable students to learn and apply important geologic concepts,
- to help students understand the relevance of geology to their lives, and
- to enable students to use their new knowledge, skills, and ways of thinking to become more informed citizens.

I then asked faculty members to rank these goals and estimate how much time they spent on each goal in class. At this point, many instructors recognized that their activities in class were not consistent with their own goals. Most instructors were spending nearly all of class time teaching content. Although this was one of their main goals, it commonly was not their top goal.

Next, I asked instructors to think about why their activities were not consistent with their goals. Inevitably, the answer was that most instructors spend nearly all of class time covering content because (1) textbooks include so much material that students have difficulty distinguishing what is important from what is not; (2) instructors needed to lecture so that students would know what is important; and (3) many students have difficulty learning independently from the textbook.

Like most geologists, author Steve Reynolds prefers teaching students out in the field, where they can directly observe the geology and reconstruct the sequence of geologic events.

In most cases, textbooks drive the curriculum, so the author team decided that we should write a textbook that (1) contains only important material, (2) indicates clearly to the student what is important and what they need to know, and (3) is designed and written in such a way that students can learn from the book on their own. This type of book would give instructors freedom to teach in a way that is more consistent with their goals, including using local examples to illustrate geologic concepts and their relevance. Instructors would also be able to spend more class time teaching students to observe and interpret geology, and to participate in the process of scientific inquiry, which represents the top goal for many instructors.

NRC The National Research Council

NATIONAL COMMITTEE ON SCIENCE EDUCATION STANDARDS AND ASSESSMENT, NATIONAL RESEARCH COUNCIL

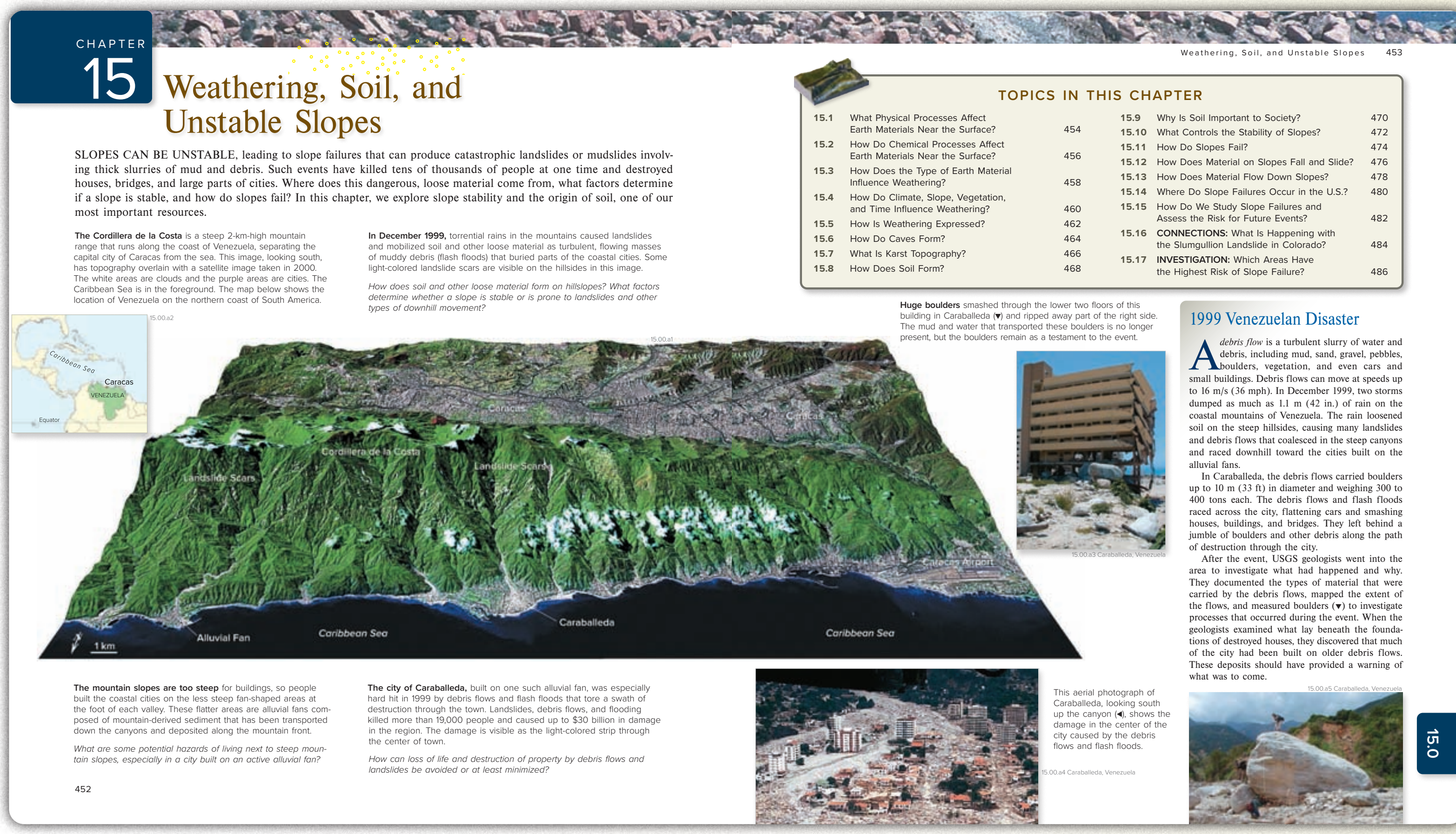
LEARNING SCIENCE IS AN ACTIVE PROCESS.

Learning science is something students do, not something that is done to them. In learning science, students describe objects and events, ask questions, acquire knowledge, construct explanations of natural phenomena, test those explanations in many different ways, and communicate their ideas to others. Science teaching must involve students in inquiry-oriented investigations in which they interact with their teachers and peers.

COGNITIVE AND SCIENCE-EDUCATION RESEARCH

To design a book that supports instructor goals, we immersed ourselves into cognitive and science-education research, especially research on how our brains process different types of information, what obstacles limit student learning from textbooks, and how students use visuals versus text while studying. We also conducted our own research on how students interact with textbooks, what students see when they observe photographs showing geologic features, and how they interpret geologic illustrations, including geologic maps and cross sections. *Exploring Geology* is the result of our literature search and of our own research. As you examine *Exploring Geology*, you will notice that it is stylistically different from most other textbooks, which will likely elicit a few questions.

HOW DOES THIS BOOK SUPPORT STUDENT CURIOSITY AND INQUIRY?



CHAPTER 15

Weathering, Soil, and Unstable Slopes

SLOPES CAN BE UNSTABLE, leading to slope failures that can produce catastrophic landslides or mudslides involving thick slurries of mud and debris. Such events have killed tens of thousands of people at one time and destroyed houses, bridges, and large parts of cities. Where does this dangerous, loose material come from, what factors determine if a slope is stable, and how do slopes fail? In this chapter, we explore slope stability and the origin of soil, one of our most important resources.

The Cordillera de la Costa is a steep 2-km-high mountain range that runs along the coast of Venezuela, separating the capital city of Caracas from the sea. This image, looking south, has topography overlain with a satellite image taken in 2000. The white areas are clouds and the purple areas are cities. The Caribbean Sea is in the foreground. The map below shows the location of Venezuela on the northern coast of South America.

In December 1999, torrential rains in the mountains caused landslides and mobilized soil and other loose material as turbulent, flowing masses of muddy debris (flash floods) that buried parts of the coastal cities. Some light-colored landslide scars are visible on the hillsides in this image.

How does soil and other loose material form on hillslopes? What factors determine whether a slope is stable or is prone to landslides and other types of downhill movement?

15.00.a2

15.00.a1

The mountain slopes are too steep for buildings, so people built the coastal cities on the less steep fan-shaped areas at the foot of each valley. These flatter areas are alluvial fans composed of mountain-derived sediment that has been transported down the canyons and deposited along the mountain front.

What are some potential hazards of living next to steep mountain slopes, especially in a city built on an active alluvial fan?

The city of Caraballeda, built on one such alluvial fan, was especially hard hit in 1999 by debris flows and flash floods that tore a swath of destruction through the town. Landslides, debris flows, and flooding killed more than 19,000 people and caused up to $30 billion in damage in the region. The damage is visible as the light-colored strip through the center of town.

How can loss of life and destruction of property by debris flows and landslides be avoided or at least minimized?

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Weathering, Soil, and Unstable Slopes 453

TOPICS IN THIS CHAPTER

Huge boulders smashed through the lower two floors of this building in Caraballeda (▼) and ripped away part of the right side. The mud and water that transported these boulders is no longer present, but the boulders remain as a testament to the event.

15.00.a3 Caraballeda, Venezuela

This aerial photograph of Caraballeda, looking south up the canyon (◀), shows the damage in the center of the city caused by the debris flows and flash floods.

15.00.a4 Caraballeda, Venezuela

1999 Venezuelan Disaster

A *debris flow* is a turbulent slurry of water and debris, including mud, sand, gravel, pebbles, boulders, vegetation, and even cars and small buildings. Debris flows can move at speeds up to 16 m/s (36 mph). In December 1999, two storms dumped as much as 1.1 m (42 in.) of rain on the coastal mountains of Venezuela. The rain loosened soil on the steep hillsides, causing many landslides and debris flows that coalesced in the steep canyons and raced downhill toward the cities built on the alluvial fans.

In Caraballeda, the debris flows carried boulders up to 10 m (33 ft) in diameter and weighing 300 to 400 tons each. The debris flows and flash floods raced across the city, flattening cars and smashing houses, buildings, and bridges. They left behind a jumble of boulders and other debris along the path of destruction through the city.

After the event, USGS geologists went into the area to investigate what had happened and why. They documented the types of material that were carried by the debris flows, mapped the extent of the flows, and measured boulders (▼) to investigate processes that occurred during the event. When the geologists examined what lay beneath the foundations of destroyed houses, they discovered that much of the city had been built on older debris flows. These deposits should have provided a warning of what was to come.

15.00.a5 Caraballeda, Venezuela

15.0

Exploring Geology promotes inquiry and science as an active process. It encourages student curiosity and aims to activate existing student knowledge by posing the title of every two-page spread and every subsection as a question. In addition, questions are dispersed throughout the book. Integrated into the book are opportunities for students to observe patterns, features, and examples before the underlying concepts are explained. That is, we employ a learning-cycle approach where student exploration precedes the introduction of geologic terms and the application of knowledge to a new situation. For example, chapter 15 on slope stability begins with a three-dimensional image of northern Venezuela, and readers are asked to observe where people are living in this area and what geologic processes might have formed these sites.

Inquire

"*Exploring Geology* is a seminal textbook for the new century, created by a unique team of authors who have synergistically merged their expertise in geology and geoscience teaching, cognitive science, and the graphic arts. The design of the book has been richly informed by current research on how students best learn geoscience, and what topics are essential and relevant. Each chapter is designed as a sequence of two-page inquiry modules; each module focuses on a specific topic, opens with an engaging question, and integrates clear, jargon-free explanations with generous, precisely detailed illustrations. In conventional textbooks, figures are often subordinate to columns and columns of type; in *Exploring Geology*, text and illustrations are mutually embedded in a topical mosaic. At the close of each chapter, a real-world application of the subject matter and an investigative exercise complete the learning cycle. This book is an innovative, accessible resource that fosters understanding through authentic geological inquiry and visualization, rather than dense exposition."

Steven Semken
School of Earth and Space Exploration, Arizona State University
Past President, National Association of Geoscience Teachers

WHY ARE THE PAGES DOMINATED BY ILLUSTRATIONS?

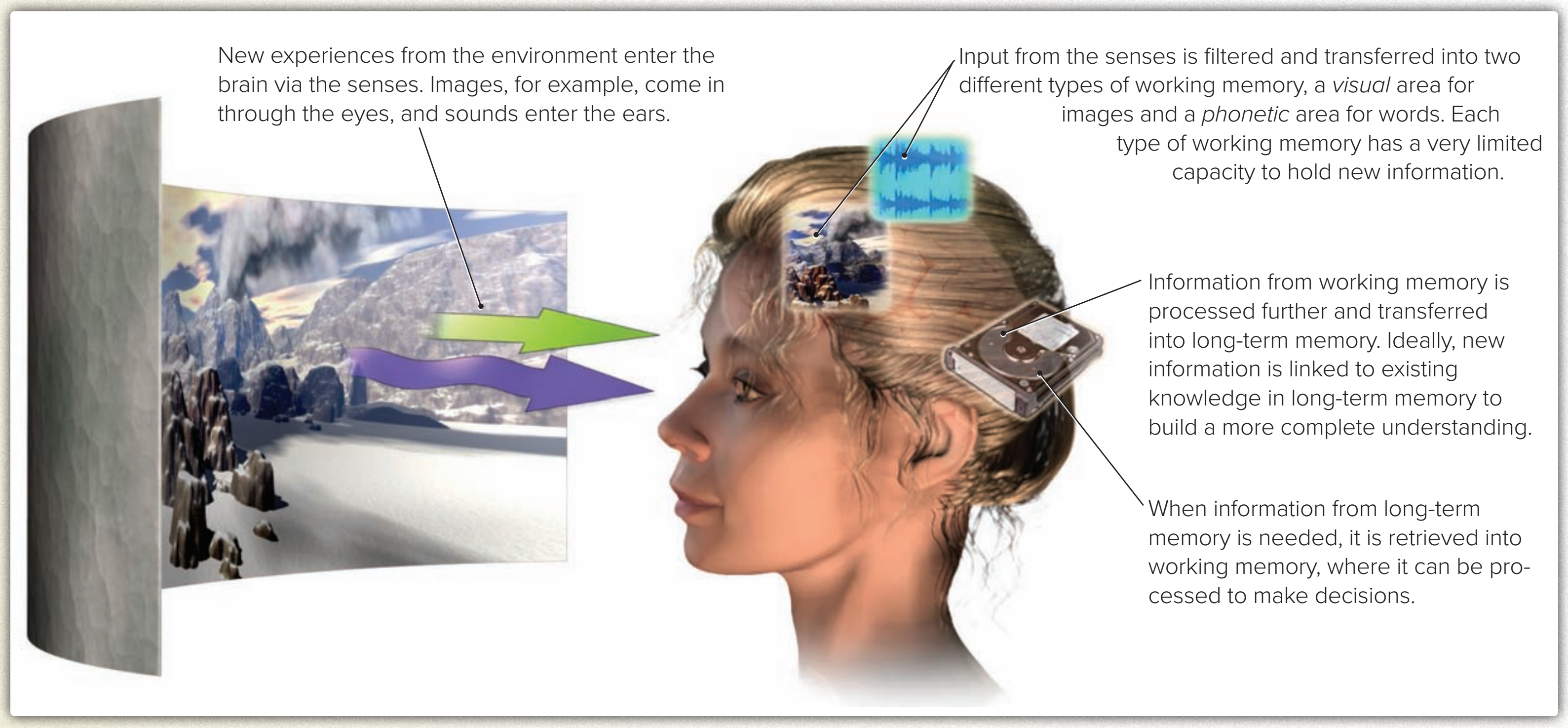
Geology is an extremely visual science. Typically, geology textbooks contain a variety of photographs, maps, cross sections, block diagrams, and other types of illustrations. These diagrams help portray the distribution and geometry of geologic units on the surface and in the subsurface in a way words could never do. In geology, a picture really is worth a thousand words or more.

Innovate

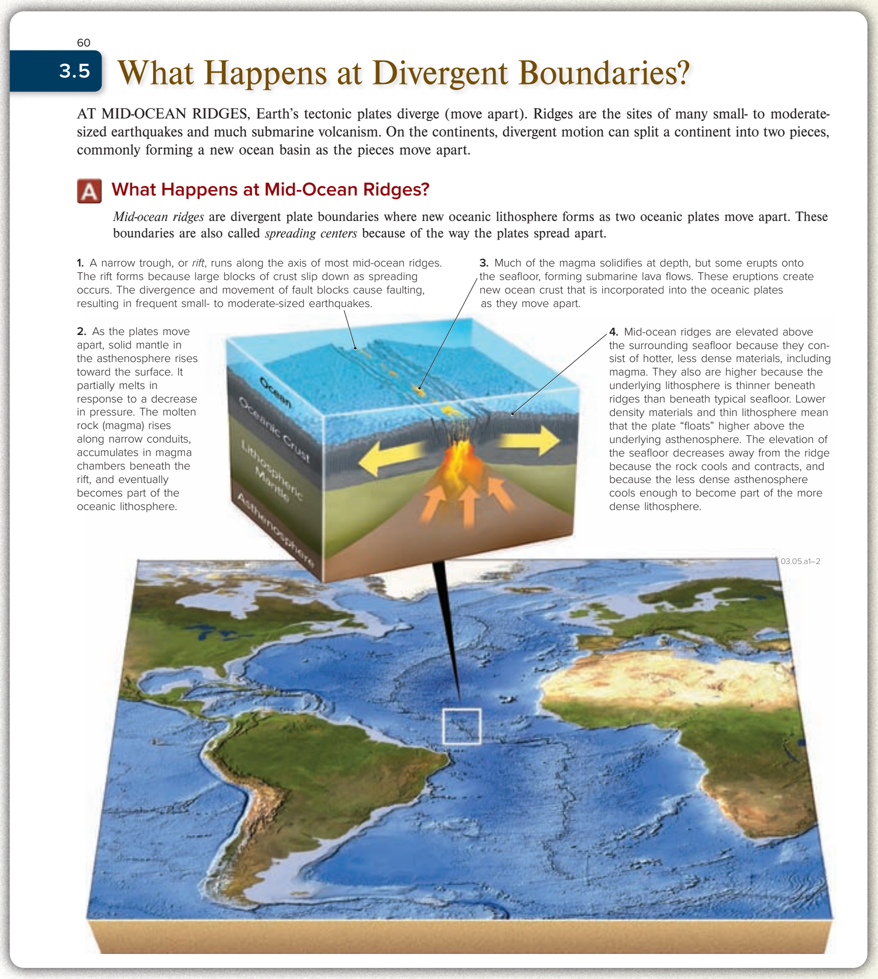
In June 2008, The McGraw-Hill Companies announced that *Exploring Geology*, just released in its First Edition, had received the distinguished Corporate Achievement Award for Innovation. Each year, McGraw-Hill Higher Education publishes 200 to 300 titles in science, economics, marketing, humanities, and career education. *Exploring Geology* was recognized for its pioneering design and innovative pedagogical approach that is based on cognitive and science-education research. This unique text features over 2,600 extraordinary line-art drawings and photographs that support clearly articulated learning outcomes, authentic inquiry, and models of how geoscientists approach geologic problems. It represents a dramatically different approach, a new type of textbook, designed for today's students.

Exploring Geology contains a wealth of figures to take advantage of the visual nature of geology and the efficiency of figures in conveying geologic information. This book contains few large blocks of text, and most text is in smaller blocks that are specifically linked with illustrations. An example of our integrated figure-text approach is shown on the previous page and on the next page. In this approach, each short block of text is one or more complete sentences that succinctly describe a geologic feature, geologic process, or both of these. Most of these text blocks are connected to their illustrations with leader lines so that readers know exactly which feature or part of the diagram is being referenced by the text block. A reader does not have to search for the part of the figure that corresponds to a text passage, as occurs when a student reads a traditional textbook with large blocks of text referencing a figure that may appear on a different page.

The approach in *Exploring Geology* is consistent with the findings of cognitive scientists, who conclude that our minds have two different processing systems, one for processing pictorial information (images) and one for processing verbal information (speech and written words), as illustrated below. Images enter our consciousness through our eyes, and text can enter either through our eyes, such as when we read, or through our ears, as occurs during a lecture. Research into learning and cognition shows that having text enter via our ears, while our eyes examine an image, is among the best ways to learn.



Cognitive scientists also speak about two types of memory: *working memory* holds information and actively processes it, whereas *long-term memory* stores information until we need it. Both the verbal and pictorial processing systems have a limited amount of working memory, and our minds have to use much of our mental processing space to reconcile the two types of information in working memory. For information that has both pictorial and verbal components, as most geoscience information does, the amount of knowledge we retain depends on reconciling these two types of information, on transferring information from working memory to long-term memory, and on linking the new information with our existing mental framework. For this reason, this book integrates text and figures, as in the example shown here. For more information on cognitive load, see Jaeger, A. J., Shipley, T. F., and Reynolds, S. J., 2017, The roles of working memory and cognitive load in geoscience learning: *Journal of Geoscience Education*, v. 65, no. 4, p. 506–518.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3.5 What Happens at Divergent Boundaries?

AT MID-OCEAN RIDGES, Earth's tectonic plates diverge (move apart). Ridges are the sites of many small- to moderate-sized earthquakes and much submarine volcanism. On the continents, divergent motion can split a continent into two pieces, commonly forming a new ocean basin as the pieces move apart.

A What Happens at Mid-Ocean Ridges?

Mid-ocean ridges are divergent plate boundaries where new oceanic lithosphere forms as two oceanic plates move apart. These boundaries are also called *spreading centers* because of the way the plates spread apart.

1. A narrow trough, or *rift*, runs along the axis of most mid-ocean ridges. The rift forms because large blocks of crust slip down as spreading occurs. The divergence and movement of fault blocks cause faulting, resulting in frequent small- to moderate-sized earthquakes.

2. As the plates move apart, solid mantle in the asthenosphere rises toward the surface. It partially melts in response to a decrease in pressure. The molten rock (magma) rises along narrow conduits, accumulates in magma chambers beneath the rift, and eventually becomes part of the oceanic lithosphere.

3. Much of the magma solidifies at depth, but some erupts onto the seafloor, forming submarine lava flows. These eruptions create new ocean crust that is incorporated into the oceanic plates as they move apart.

4. Mid-ocean ridges are elevated above the surrounding seafloor because they consist of hotter, less dense materials, including magma. They also are higher because the underlying lithosphere is thinner beneath ridges than beneath typical seafloor. Lower density materials and thin lithosphere mean that the plate "floats" higher above the underlying asthenosphere. The elevation of the seafloor decreases away from the ridge because the rock cools and contracts, and because the less dense asthenosphere cools enough to become part of the more dense lithosphere.

WHY ARE THERE SO MANY FIGURES?

This textbook contains more than 2,600 figures, which is two to three times the number in most introductory geology textbooks. One reason for this is that the book is designed to provide a concrete example of each rock type, environment, or geologic feature being illustrated. Research shows that many college students require concrete examples before they can begin to build abstract concepts. Also, many students have limited travel experience, so photographs and other figures allow them to observe places, environments, and processes they have not been able to observe firsthand. The inclusion of an illustration for each text block reinforces the notion that the point being discussed is important. In many cases, as in the example in this Preface,

Visualize

"This is it! This is a book that my students can use to *learn*, not just 'do the reading.' The focus on questions on every page draws students in, and the immediacy of the illustration and text focused on each question makes it almost impossible for students not to want to plunge in to find out how each question is answered. And the centrality of high-quality illustrations, rather than exhaustive text, is a key component for helping students learn once they are engaged. Geoscience is a visual science, and this approach helps students visualize geologic processes in the real world, truly learning rather than simply preparing to parrot back definitions. Do I worry that this book isn't packed with text? Not in the slightest! With examples, real-world data, and research results easily accessible on the Internet, I don't want or need an introductory textbook that tries to be encyclopedic. I want a book that engages students, captures their imaginations, and helps them learn. This is the book!"

Barbara J. Tewksbury
Hamilton College
Past President, American Geological Institute
Past President, National Association of Geoscience Teachers

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7.2 What Sedimentary Environments Are Near Shorelines and in Oceans?

Sedimentary Environments and Rocks 179

OCEANS AND THEIR SHORELINES are dynamic environments with wind, waves, and ocean currents transporting sediment eroded from the coastline or brought in from elsewhere. The characteristics of each environment, especially the types of sediment, depend mostly on the proximity to shore, the availability of sediment, and the depth, temperature, and clarity of the water. Examine the large figure below and try to envision what you would expect in each setting, including the type of sediment that would occur there.

07.02.a2 Carmel, CA

1. *Beaches* are stretches of coastline along which sediment has accumulated (◀). Most beaches consist of sand, pieces of shells, and rounded gravel, cobbles, or boulders. The setting determines which of these components is most abundant. Some shorelines have bedrock all the way to the ocean and so they have little or no beach. Wide, sandy beaches are more inviting as places to relax and play.

07.02.a3 Akumal, Mexico

2. The water near the shoreline may be sheltered by offshore reefs or islands. The sheltered water, called a *lagoon* (◀), is commonly shallow, calm, and perhaps warm. The nearshore parts of lagoons contain sand, mud, and stones derived from land, whereas the outer parts may have sand and pieces of coral eroded from a reef.

07.02.a4 Raja Ampat, Indonesia

3. Where ocean water is shallow, warm, and clear, coral and other marine creatures construct *reefs* (◀), which can parallel the coast, encircle islands, or form irregular mounds and platforms. Reefs typically protect the shoreline from the energetic, big waves of the deeper ocean.

4. Away from the shoreline, many landmasses are flanked by continental shelves and slopes consisting of layers of mud, sand, and carbonate minerals. Material from these sites can move down the slope in landslides or in turbulent, flowing masses of sand, mud, and water called *turbidity currents*. The slopes of some continents are incised by branching *submarine canyons* (not shown here) that funnel sediment toward deeper waters.

07.02.a1

5. The deep part of the seafloor is a dark, cold environment that is commonly several kilometers beneath the surface. It generally receives less sediment than areas closer to land, and its sediment is dominated by fine, windblown dust and by remains of mostly single-celled marine organisms.

07.02.a5 Namibia

6. Sandy dunes that are inland from beaches are called *coastal dunes* (◀). These dunes commonly form where sand and finer sediment from the beach are blown or washed inland and then reshaped by the wind. When strong winds blow onto land, sand can move from the beach to the dunes, and sand can move back toward the beach when winds blow toward the sea or lake.

07.02.a6 Olympic Peninsula, WA

7. Some shorelines include low areas, called *tidal flats* (▶), that are flooded by the seas during high tide but exposed to the air during low tide. Most tidal flats are covered by mud and sand or are rocky. Some low parts of the land adjacent to tidal flats can accumulate salt and other *evaporite minerals* as seawater and terrestrial (on-land) waters evaporate under hot, arid (dry) conditions.

07.02.a7 Mississippi Delta, LA

8. In addition to the parts of deltas overlapping the shore, *submarine deltas* extend in some places for tens of kilometers offshore (▲). The muddy or sandy front of the delta may be unstable, and material can slide or tumble down the slope, sending sediment into deeper water.

9. Other accumulations of sand rise above the shallow coastal waters as long, narrow islands, called *barrier islands*. Most barrier islands, such as the one below (▼), are only hundreds of meters wide. The areas between barrier islands and the shoreline are commonly shallow lagoons or saltwater marshes.

07.02.a8 Santa Rosa Island, FL

Before You Leave This Page

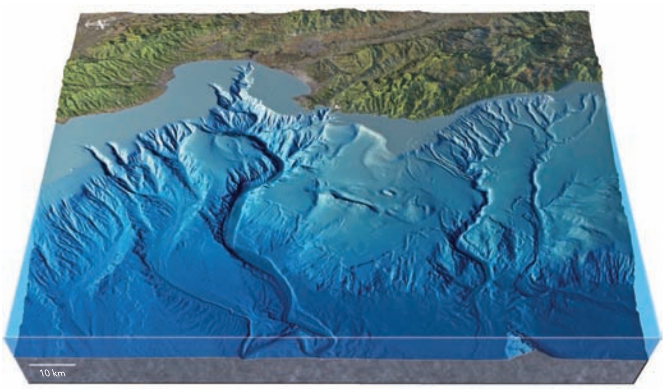
✓ Sketch and describe the main sedimentary environments in oceanic and nearshore environments.

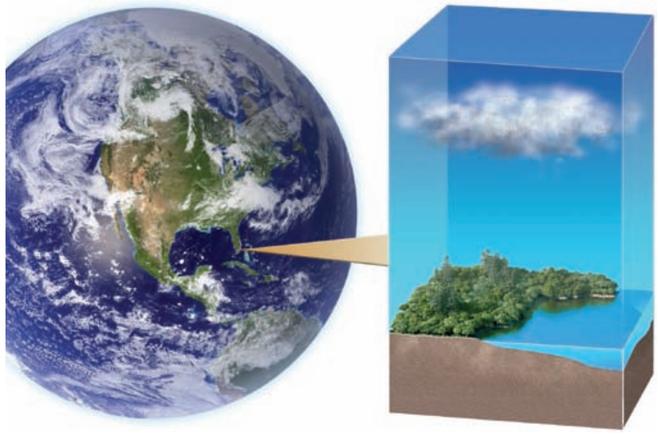
7.2

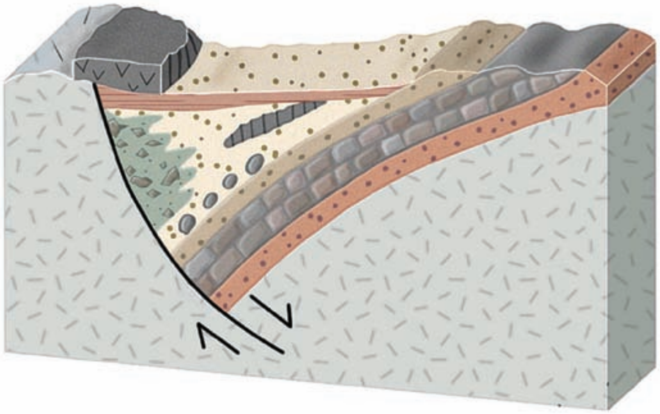
conceptualized figures are integrated with photographs and text so that students can build a more coherent view of the environment or process.

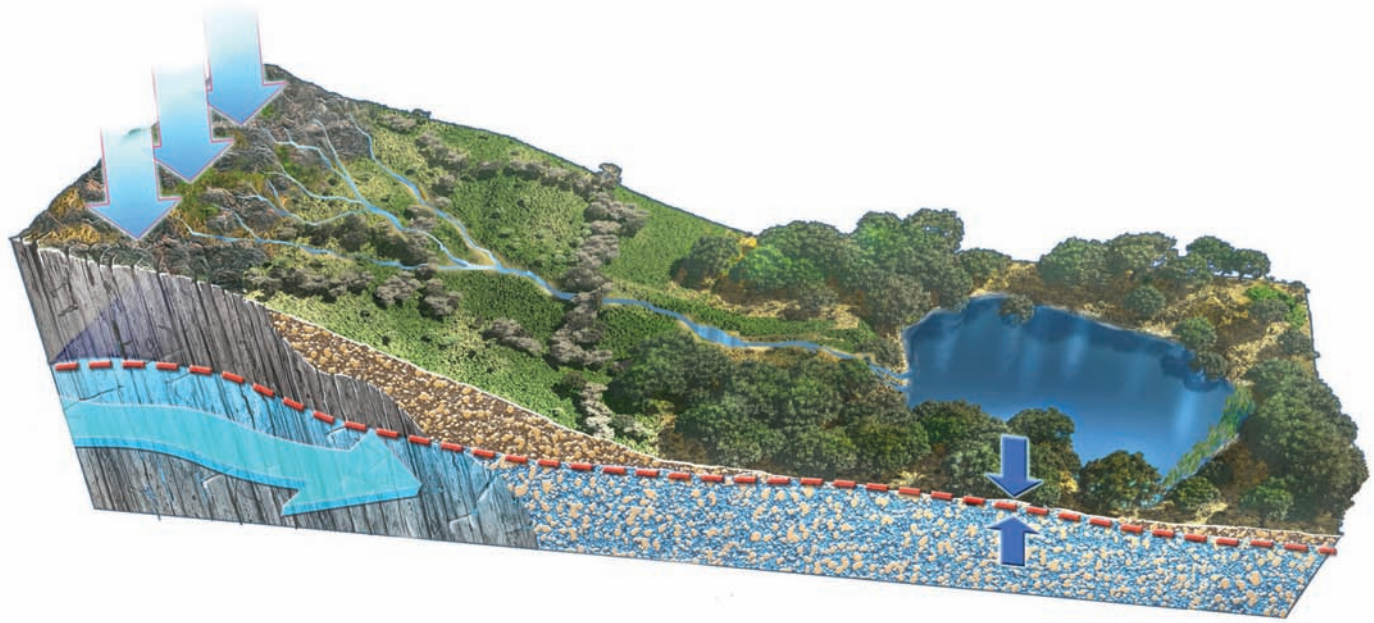
Exploring Geology focuses on the most important geologic concepts and makes a deliberate attempt to eliminate text that is not essential for student learning of these concepts. Inclusion of information that is not essential tends to distract and confuse students rather than illuminate the concept; thus you will see fewer words. Cognitive and science-education research has identified a redundancy effect, where information that restates and expands upon a more succinct description actually results in a decrease in student learning. Specifically, students learn less if a long figure caption restates information contained elsewhere on the page, such as in a long block of text that is detached from the figure. We avoid the redundancy effect by including only text that is integrated with the figure.

The style of illustrations in *Exploring Geology* was designed to be more inviting to today's visually oriented students who are used to photo-realistic, computer-rendered images in movies, videos, and computer games. For this reason, many of the figures were created by world-class artists who have worked on Hollywood movies, on television shows, for *National Geographic,* and in the computer-graphics industry. In most cases, the figures incorporate real data, such as satellite images and aerial photographs. Our own research shows that many students do not understand geologic cross sections and other subsurface diagrams, so nearly every cross section in this book has a three-dimensional aspect, and many maps are presented in a perspective view with topography. Research findings by us and others indicate that including people and human-related items on photographs and figures attracts undue attention, thereby distracting students from the geologic features being illustrated. As a result, our photographs have nondistracting indicators of scale, like dull coins and plain marking pens. Figures and photographs do not include people or human-related items unless (1) we are trying to illustrate how geoscientists study geologic processes and features, (2) illustrate the relevance of the processes on humans, or (3) help students appreciate that geoscience can be done by diverse types of people, potentially including them, as depicted in our photographs.









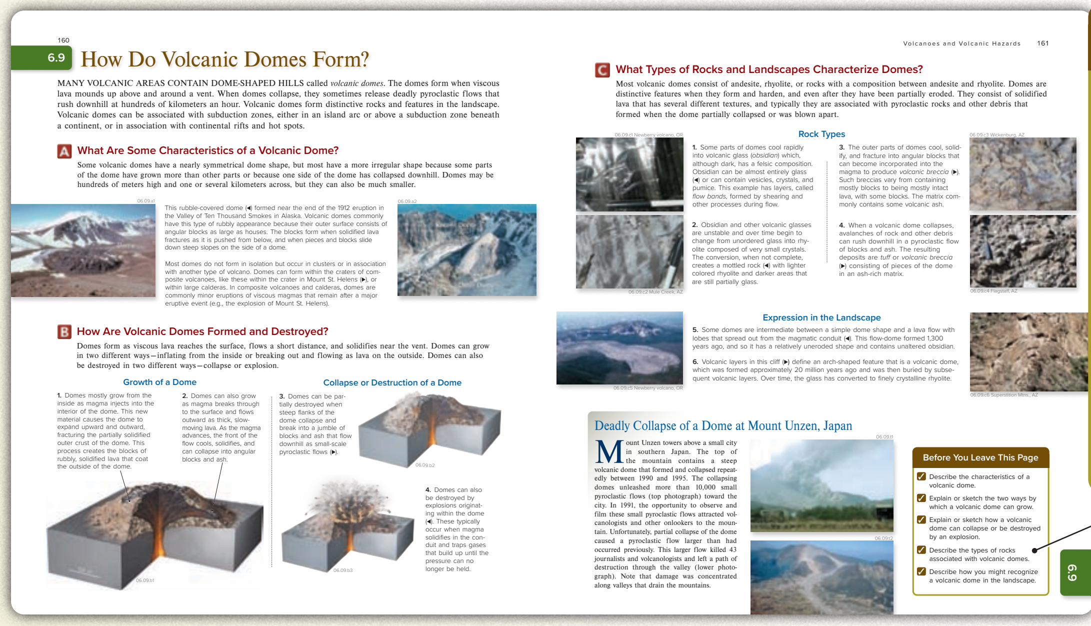
HOW ARE GEOLOGIC TERMS INTRODUCED IN THIS BOOK?

Wherever possible, we introduce terms after students have an opportunity to observe the feature or concept that is being named. This approach is consistent with several educational philosophies, including a learning cycle and just-in-time teaching. Research on learning cycles shows that students are more likely to retain a term if they already have a mental image of the thing being named. For example, this book presents students with the collection of igneous rocks shown to the right and asks them to think about how they would classify the rocks. Only then does the textbook present a classification of igneous rocks.

Also, the figure-based approach allows terms to be introduced in their context rather than as a definition that is detached from a visual representation of the term. In this book, we introduce new terms in italics rather than in boldface because boldfaced terms on a textbook page cause students to immediately focus mostly on the terms rather than build an understanding of the concepts. The book includes a glossary for those students who wish to look up the definition of a term to refresh their memory. To expand comprehension of the definition, each entry in the glossary references the page where the term is defined in the context of a figure.

WHY DOES THE BOOK CONSIST OF TWO-PAGE SPREADS?

This book consists of two-page spreads, most of which are further subdivided into sections. Research has shown that because of our limited amount of working memory, much new information is lost if it is not incorporated into long-term memory. Many students keep reading and highlighting their way through a textbook without stopping to integrate the new information into their mental framework. New information simply displaces existing information in working memory before it is learned and retained. This concept of cognitive load has profound implications for student learning during lectures and while reading textbooks. Two-page spreads and subsections help prevent cognitive overload by providing natural breaks that allow students to stop and consolidate the new information before moving on.


160

6.9 How Do Volcanic Domes Form?

Volcanoes and Volcanic Hazards 161

A What Are Some Characteristics of a Volcanic Dome?

B How Are Volcanic Domes Formed and Destroyed?

Growth of a Dome

Collapse or Destruction of a Dome

C What Types of Rocks and Landscapes Characterize Domes?

Rock Types

Expression in the Landscape

Deadly Collapse of a Dome at Mount Unzen, Japan

Before You Leave This Page

Before You Leave This Page

- ✓ Describe the characteristics of a volcanic dome.
- ✓ Explain or sketch the two ways by which a volcanic dome can grow.
- ✓ Explain or sketch how a volcanic dome can collapse or be destroyed by an explosion.
- ✓ Describe the types of rocks associated with volcanic domes.
- ✓ Describe how you might recognize a volcanic dome in the landscape.

Each spread has a unique number, such as 6.9 for the 9th topical two-page spread in chapter 6 (see previous page). These numbers help instructors and students keep track of where they are and what is being covered. Each two-page spread, except for those that begin and end a chapter, contains a *Before You Leave This Page* checklist that indicates what is important and what is expected of students before they move on. This list contains learning objectives for the spread and provides a clear way for the instructor to indicate to the student what is important. The items on these lists are compiled into a master *What-to-Know* list.

SIGNIFICANT ADVANTAGES OFFERED BY *EXPLORING GEOLOGY*

Two-page spreads and integrated *Before You Leave This Page* lists offer the following advantages to the student:

- Information is presented in relatively small and coherent chunks that allow a student to focus on one important aspect or geologic system at a time.
- Students know when they are done with this particular topic and can self-assess their understanding with the *Before You Leave This Page* list.
- Two-page spreads allow busy students to read or study a complete topic in a short interval of study time, like during breaks between classes.
- All test questions and assessment materials are tightly articulated with the *Before You Leave This Page* lists so that exams and quizzes cover precisely the same material that was assigned to students via the *What-to-Know* list.

The two-page spread approach also has huge advantages for the instructor. Before writing this book, the authors wrote the items for the *Before You Leave This Page* lists. We then used this list to decide what figures were needed, what topics would be discussed, and in what order. In other words, *the textbook was written from the learning objectives*. The *Before You Leave This Page* lists provide a straightforward way for an instructor to tell students what information is important. Because we provide the instructor with a master *What-to-Know* list, an instructor can selectively assign or eliminate content by providing students with an edited *What-to-Know* list. Alternatively, an instructor can give students a list of assigned two-page spreads or sections within two-page spreads. In this way, the instructor can identify content for which students are responsible, even if the material is not covered in class.

HOW IS THIS BOOK ORGANIZED?

Two-page spreads are organized into 19 chapters that are arranged into five major groups: (1) introduction to Earth and the science of geology, (2) earth materials and the processes that form them, (3) geologic time and tectonic systems, (4) climate and surface processes, and (5) capstone chapters on resources and planetary geology. The first three chapters provide an overview of geology, the scientific approach to geology, and plate tectonics—a unifying theme interwoven throughout the rest of the book. The next five chapters cover earth materials, including minerals (chapter 4), different families of rocks and structures (chapters 5–8), and the processes that form or modify rocks. Unlike many geology books, *Exploring Geology* begins the discussion of earth materials with an examination of landscapes—something students can relate to—as a lead-in to rocks, then to minerals, and finally to atoms, the most abstract topic in geology books. The sedimentary environments chapter includes a brief introduction to weathering, setting the stage for the discussion of clastic sediments but saving a more detailed discussion of weathering and soils for the part of the book that deals with surficial processes. Also, this book integrates the closely related topics of metamorphism and deformation into a single chapter.

After earth materials, we cover the principles of geologic time, emphasizing how geologists reconstruct Earth's history (chapter 9). We then move on to ocean basins, mountains and basins, and earthquakes (chapters 10–12), all of which integrate and apply information about rocks, structures, geologic time, and plate tectonics. These chapters provide important details about aspects of plate tectonics after students have gained an understanding of rocks, structures, and geologic time from earlier chapters. We have also incorporated a small component of historical geology, including evolution of the continents and ocean basins.

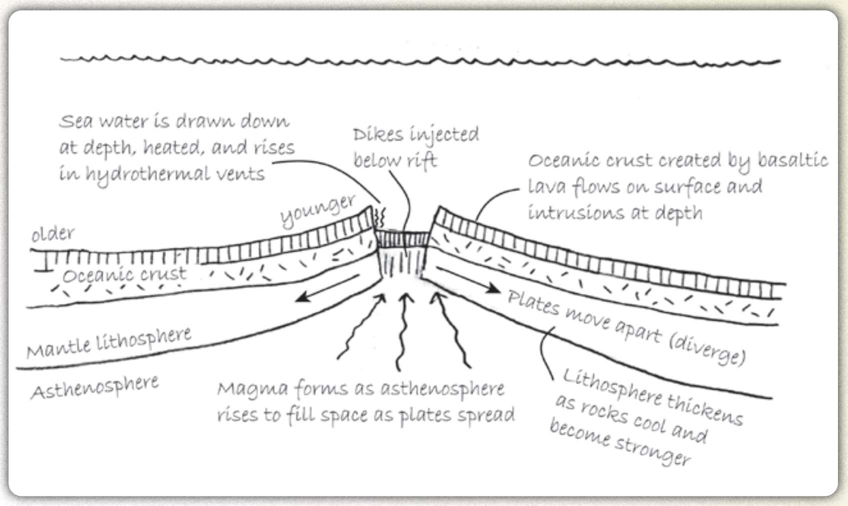
Next, we briefly discuss weather and climate (chapter 13) to provide a backdrop for subsequent chapters on surface processes and to introduce timely topics, such as hurricanes and climate change. This chapter also discusses deserts, drought, and rain forests. Glaciers, coasts, and sea-level changes are integrated into a single chapter (chapter 14) to present a system approach to earth processes and to emphasize the interplay between glaciations, sea level, and the character of the shoreline. Chapter 15 focuses on weathering, soils, and slope stability; chapter 16 presents streams and flooding; and chapter 17 covers surface-water and groundwater resources and groundwater-related problems.

We consider the last two chapters to be capstones, integrating and applying previous topics to enable students to understand energy and mineral resources (chapter 18) and planetary geology (chapter 19). These two chapters give students and instructors an opportunity to see how an understanding of rock types, rock-forming processes, geologic structures, geologic time, and the flow of water and other fluids can help us understand important resources and the surfaces of other planetary bodies. The late placement of both chapters allows a more comprehensive treatment of these topics than would be possible if they were incorporated into earlier chapters.

SPECIAL TEXT FEATURES

Concept Sketches

Most items on the *Before You Leave This Page* list are by design suitable for student construction of concept sketches. Concept sketches are sketches that are annotated with complete sentences that identify geologic features, describe how the features form, characterize the main geologic processes, and summarize geologic histories (▶).

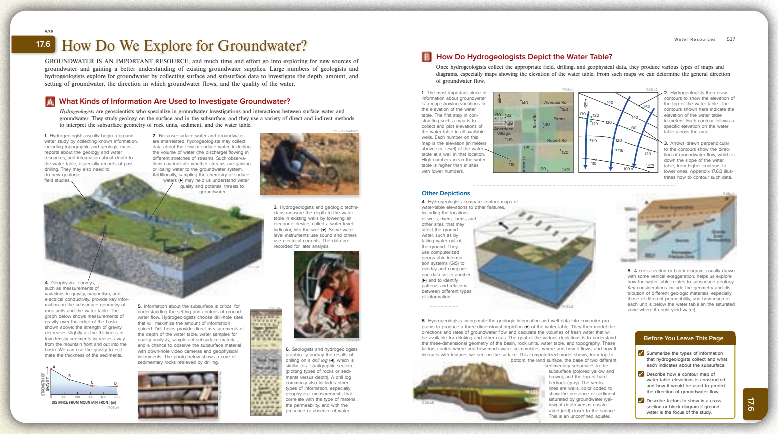


Concept sketches are an excellent way to actively engage students in class and to assess their understanding of geologic features, processes, and history. Concept sketches are well suited to the visual nature of geology, especially cross sections, maps, and block diagrams. Geologists are natural sketchers using field notebooks, blackboards, publications, and even napkins, because sketches are an important way to record observations and thoughts, organize knowledge, and try to visualize geometries of rock bodies and sequences of events. The step-by-step process of creating a concept sketch is explored further in Chapter 1. An instructor does not need to use concept sketches with this book (it works well with and is accompanied by more traditional types of assessment, such as test banks), but students can use concept sketches to build deeper understanding of key topics. We provide a list of concept-sketch questions to instructors, but it is easy for instructors to create their own, such as for topics not in the textbook.

For more information, see Johnson, J. K., and Reynolds, S. J., 2005. Concept sketches–Using student- and instructor-generated annotated sketches for learning, teaching, and assessment in geology courses. *Journal of Geoscience Education*, v. 53, pp. 85–95.

TWO-PAGE SPREADS

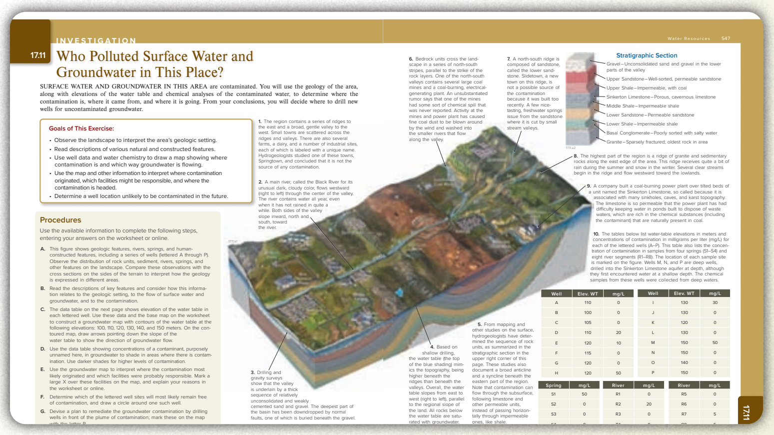
Most of the book consists of *two-page spreads*, each of which is about one or more closely related topics. Topical spreads convey the geologic content and help organize knowledge.



Each chapter has at least one two-page spread illustrating how geology impacts society and another two-page spread that specifically describes how geoscientists study typical problems.

The penultimate two-page spread in each chapter is a *Connections* spread, which is designed to help students connect and integrate the various concepts from the chapter and to show how these concepts can be applied to an actual location. *Connections* are about real places that illustrate the geologic concepts and features covered in the chapter and explicitly illustrate how a geologic problem is investigated and how geologic problems have relevance to society. The *Connections* spread also prepares the student for a following *Investigation* two-page spread.

Each chapter ends with an *Investigation* spread that is an exercise in which students apply the knowledge, skills, and approaches learned in the chapter. These exercises mostly involve virtual places that students explore and investigate to make observations and interpretations and to answer a series of geologic questions.



Investigations are modeled after the types of problems geologists investigate, and they use the same kinds of data and illustrations encountered in the chapter. The Investigation includes a list of goals for the exercises and step-by-step instructions, including calculations and methods for constructing maps, graphs, and other figures. These investigations can be completed by students in class, as worksheet-based homework, or as online activities.

NEW IN THE SIXTH EDITION

The sixth edition of *Exploring Geology* includes numerous significant revisions, with every chapter receiving additions and improvements. This edition also features a new Appendix. The style, approach, and sequence of chapters is unchanged, but every chapter received new photographs, new or revised figures, major to minor editing of text blocks and, in some cases, reorganization. We revised many text blocks to improve clarity and conciseness, or to present recent discoveries and events. Most chapters contain the same number and order of two-page spreads, but four chapters each gained a new two-page spread, and other chapters had sections that were completely revised. Many changes were made in response to comments by reviewers and students. The book contains many edits as a result of careful re-reading of the entire book. The most important revisions are listed below:

- The most obvious change is the addition of an Appendix, which focuses on helping students improve their quantitative and spatial skills, such as how to convert from one unit to another and how to contour data. The Appendix consists of one-page and two-page sections, each related to and referenced from a specific two-page spread in the body of the book. There is coverage of general scientific literacy topics, such as scientific notation, how to read and plot graphs, the fundamental gas laws, and units of matter, energy, and motion. There are also geoscience-specific topics, including calculating rates of seafloor spreading, how to read a weather map, how to construct a hydrograph, and estimating the frequency of flooding.
- This edition contains nearly 150 new photographs, with a deliberate intention to represent a wider geographic diversity, to provide clearer examples, to expand the discussion of specific topics, and to provide more information about a geologic process, material, or feature. In addition, we reprocessed a small number of existing photographs to improve their fidelity.
- This edition contains nearly 110 new or replaced illustrations. Many illustrations from the previous edition were replaced with new versions to update information so that it is more current, to improve student understanding of certain complex topics, and for improved appearance. Some of these revisions consisted only of adding labels and shading.
- This edition contains two-page spreads that are entirely new. In chapter 1, we added a two-page spread on how to learn using concept sketches, which are simple sketches annotated with labels and complete sentences to explain features, processes, and interrelationships. Concept sketches were, and still are, mentioned in the Preface, but the new two-page spread provides a step-by-step approach for constructing a concept sketch by way of an example. We created a new gemstones two-page spread for the chapter on minerals (chapter 4). Chapter 13 gained a two-page spread as a consequence of expansion of the discussion of wind-related processes and features, especially types of sand dunes. A new two-page spread in chapter 16 explores the characteristics and formation of natural bridges and arches.
- Another major change occurred in chapter 2, which explores strategies and examples for how to understand and study earth features and processes. We completely revised two two-page spreads about the scientific method. We explain inductive versus deductive versus abductive reasoning, and we further explore observations versus interpretations, as well as the distinction between science done by hypothesis testing and scientific discoveries that arose from exploration.
- A number of two-page spreads have been extensively revised with improved layout, illustrations, and text. In addition to the new or revised illustrations, we updated text to reflect new ideas or new data. For example, we updated figures for increases in global temperatures, sea-surface temperatures, and CO_2 content of the atmosphere.
- Throughout the book, most text boxes are now numbered sequentially within a section. This will help direct students to read the text boxes in a specific order and helps with the sequence of presentation on phones and other small devices. It also allows an instructor to reference text in a more specific way.
- This edition features a different serif font from the previous edition. This font is highly readable on portable electronic devices while retaining fidelity to a quality printed book. This font replacement resulted in small changes in layout of individual text blocks on almost every page.

CHAPTER 1 received a major revision, with an aim toward guiding students to begin observing and interpreting landscapes earlier than in previous editions. Accordingly, we moved an observing landscapes two-page spread from chapter 2 to early in chapter 1, and we followed it with the new two-page spread on concept sketches, a spread also focused on landscapes. Our thinking was that most instructors, including us, begin showing photographs of landscapes on the first day of class, so students should have an early introduction about how to observe different features in a landscape. The chapter includes eight new photographs and five new or revised illustrations. As in all chapters, we wrote new text or often significantly edited text and layouts when we replaced a photograph. The chapter has a reference to the first entry in the Quantitative and Spatial Skills Appendix, which summarizes the units we use to describe matter, energy and motion. All other entries in the Appendix are referenced in the appropriate chapter, although not all Appendix references are listed below.

CHAPTER 2 focuses on teaching students scientific problem solving and was heavily revised. The chapter lost the aforementioned observing landscape two-page spread (to chapter 1), and now the first topical two-page spread (after the opener) immediately helps students starting to think about how to use modern environments to interpret the origin of rocks and other past deposits. In addition, the four pages specifically on the process of science are almost all new material, including coverage of different types of reasoning. The chapter has 11 new photographs compared to the previous edition and two revised illustrations. In addition to the two-page spread that was moved to chapter 1, this chapter lost two figures, one photograph, and one table compared to the previous edition.

CHAPTER 3 received a major revision, revolving around four flat maps that were each replaced by three globes. The globes provide a more distortion-free depiction of the distribution of earthquakes, volcanoes, global relief, and different types of plate boundaries. Each globe figure shows a different part of the planet, with the three partly overlapping hemispheric views providing coverage of every location on Earth, except the tip of the poles. We have concluded that globe depictions help students focus on one part of the planet at a time and in the process gain a greater understanding of the whole. The pages featuring the globes are much more visual and inviting than they were with the flat maps. As we do for every global data set in the textbook, we have generated spinning-globe movies of each of these data sets, so that instructors can use these in class for a more interactive experience, and students can use the movies to explore distributions of geologic phenomena. In addition to the 12 new globes, we revised two other illustrations. The text accompanying the new globes was edited and expanded, owing to new space opened up by replacing rectangular maps with circular globes.

CHAPTER 4 contains a new two-page spread on gemstones, a topic of interest to many students. In addition, we wrote two new sections about other topics. Largely due to this new material, the chapter has 19 new photographs. Chemical reactions are presented in a different format than other types of equations.

CHAPTER 5 is mostly unchanged, except for minor edits. It contains two new photographs and a reference to a section in the Appendix on how to plot and read graphs to explore scientific questions.

CHAPTER 6 has eight new photographs, each of which is accompanied by edited or completely rewritten text. It also features three new globes that replaced a flat map, presented in the context of assessing risk for volcanic eruptions in different regions of the planet. Text associated with the globes was extensively edited and revised in layout.

CHAPTER 7 includes nine new photographs of sedimentary environment and rocks, accompanied by revised text. The photographs include new ones from the Outer Banks of North Carolina and the Republic of Palau. Several sections were reorganized to take advantage of the new and improved photographs. In this chapter, as throughout the book, figures created by Professor Ronald Blakey were updated to his most recent and higher resolution versions. This chapter has three such figures.

CHAPTER 8 contains four new photographs of structures, and we edited text associated with the new photographs. We significantly revised the layout and text about strike-slip zones. Four illustrations received labels or were otherwise lightly revised.

CHAPTER 9 has three new photographs and four revised figures. We edited or rewrote the text accompanying each new photograph. We completely redid the layout for a section on how understanding earth history helps us study geologic hazards. We expanded our discussion on concretions as something that might look like a fossil but generally is not, and added a new photograph showing concretions.

CHAPTER 10 received 15 new globe figures, replacing five flat maps. The first set of nine globes shows sediment thickness, depth of the seafloor, and age of the seafloor. Six other new globes portray the distribution of hot spots and island arcs. For each globe, the associated text was expanded, edited, and rearranged in layout. Six figures provided by Ronald Blakey were updated to his new versions and relabeled. In total, the chapter has 21 new or replaced illustrations.

CHAPTER 11 features 21 new Ronald Blakey figures. Eleven globes depict the geologic evolution of continents and oceans on the planet, and 10 maps portray the history of North America. Section lines on the maps were adjusted to better match the accompanying geologic cross sections. We modified two other illustrations, including the terrane map of California and Nevada.

CHAPTER 12 received only minor revision. It has two new photographs and four revised illustrations, as well as minor text edits. It references a section in the Appendix on the Mercalli Intensity Scale.

CHAPTER 13 is much changed. It gained one two-page spread as a result of us expanding and revising the coverage of sand dunes and other wind-related features. Partly as a result of these changes, the chapter contains 23 new photographs. There are nine new or revised figures, including one on types of dunes and one on desert pavement. All graphs were revised to reflect updated global temperatures and CO_2 values.

CHAPTER 14 received 14 new photographs from diverse locations. It also has five revised or new illustrations, including a new figure on the equilibrium line in glaciers.

CHAPTER 15 was lightly revised and has eight new photographs. It contains a new photograph and brief discussion of the Oso landslide.

CHAPTER 16 received a new two-page spread on natural bridges and arches, which has six new photographs and seven new figures. The chapter has six other new photographs and one revised figure. The chapter contains references to three sections in the Appendix—ones on constructing a hydrograph, calculating stream gradients, and estimating the frequency of flooding using actual data .

CHAPTER 17 had minor revisions but ten new photographs and one revised figure. We deleted a section on drinking-water standards to allow additional space for our coverage of describing volumes of water.

CHAPTER 18 contains 12 new or reprocessed photographs. We updated a figure for consumption of materials and revised the coverage of solar energy. We also added a photograph and brief description of dimension stone and added information about weathering of copper deposits, built around two new spectacular photographs taken within an open pit. We added a photograph and expanded our discussion of the Sudbury impact and related mineral deposits.

CHAPTER 19 had minor revisions, with the addition of four new images, three taken by rovers currently on Mars. We also replaced one photograph of a lunar breccia.

FRONT AND BACK MATTER, including the *Preface*, *Glossary*, and *Index,* were revised and updated to reflect the revised table of contents and changes in page numbers due to reorganizations.

ACKNOWLEDGMENTS

Writing a totally new type of introductory geology textbook would not be possible without the suggestions and encouragement we received from instructors who reviewed various drafts of this book. We are especially grateful to people who contributed days reviewing the book or attending symposia to openly discuss the vision. Many colleagues enthusiastically encouraged us onward, including Bruce Herbert, Dexter Perkins, Steve Semken, Diane Clemens-Knott, Jeff Knott, Barbara Tewksbury, and Cathy Manduca. Previous editions received special attention, including full-book reviews, from reviewers Dexter Perkins, Grenville Draper, Scott Linneman, Richard Sedlock, and Bill Dupré. David Williams always provides thoughtful guidance about revising the planetary geology chapter. Mike Kelly coauthored the first two editions, expertly researching, illustrating, and writing about especially challenging topics, such as earthquake mechanics, stream dynamics, and climate. Many of his illustrations and words grace the pages of this edition, including some of our favorite passages. For this edition, we incorporated some material from our *Exploring Physical Geography* and *Exploring Earth Science* textbooks, including figures and text contributed by our coauthors Robert V. Rohli, Peter R. Waylen, and Mark A. Francek. In particular, nearly half of the sections in our new Quantitative and Spatial Skills Appendix were developed in conjunction with our geography coauthors and were based on those originally included in *Exploring Physical Geography*. For all this help and support, we are very grateful.

This book contains over 2,600 figures, two to three times more than a typical introductory geoscience textbook. This massive art program required great effort and artistic abilities from the artists who turned our vision and sketches into what truly are pieces of art. The art program was shaped by Chuck Carter and Paul Morin, who were coauthors in previous editions of this book and who contributed many illustrations to the book. We greatly appreciate the dedication and artistic touches of illustrators Susie Gillatt, Daniel Miller, and David Fierstein. We also benefited from interactions with designers David Hash and Chris Willis, who helped translate our ideas about pedagogy into a workable and aesthetically sound design. Cindy Shaw deserves special praise for handling most revisions to illustrations, going the extra step of researching the geology of places to decide how to best show the geologic features. She acted as Art Director and Lead Illustrator from the second edition onward, greatly improving the book by standardizing illustrations, nudging and redoing troublesome parts of the layout, and adding arrows and other special touches. Susie Gillatt expertly improved all new photographs and delivered finished files in an astonishingly prompt manner. Terra Chroma, Inc. supported many aspects in the development of this book. Numerous people went out of their way to provide us with photographs, illustrations, and advice—in some cases going out into the field to take the photographs we needed. These helpful people included Vince Matthews, Ron Blakey, Michael Collier, Cindy Shaw, Bill Dupré, Tom Sharp, Allen Glazner, Ramón Arrowsmith, Garry Hayes, Daniel Griffin, Martin Munro, Ariel Anbar, Jessica Barone, Doug Bartlett, Don Burt, Phil Christensen, Ed Garnero, Jeff Knott, Matthew Larsen, Spencer Lucas, Henrik Thorburn, Dan Trimble, Bixler McClure, Vladamir Romanovsky, Scott Johnson, Chris Marone, Tom McGuire, Michael Ort, Peg Owens, Jack Ridge, Nancy Riggs, Steve Semken, James Speer, Barbara Tewksbury, Manfred Plaschke, and David Walsh. For logistical reasons, we did not use all the photographs offered to us, but we greatly appreciated receiving them. Many instructors, including Dexter Perkins, Liz Balbord, Callan Bentley, Steve Boss, Bruce Bartleson, Reed Burgett, George Davis, Grenville Draper, Jack Farmer, Jeff Lee, David Lemone, Steve Marshak, Gretchen Miller, Jennifer Rahn, Gina Szeblewski and Adolph Yonkee took us out in the field or guided us to interesting geologic sites in different regions in order to help us diversify our collection of photographs.

We used a number of data sources to create many illustrations. Reto Stöckli of the Department of Environmental Sciences at ETH Zürich and NASA-Goddard produced the Blue Marble and Blue Marble Next Generation global satellite composites. We used data from the ZULU server at the NASA Earth Science Enterprise Scientific Data Purchase Program for hundreds of figures in this book. Brian Davis of the USGS EROS Data Center was quick to find elusive data, and Collin Bode of the National Center for Earth-surface Dynamics was indispensable in helping us process GIS data. Debbie Leedy, Melanie Coyan, and Joshua Coyan provided various types of 3D files.

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Finally, a project like this is truly life consuming, especially when the author team is doing the writing, illustrating, photography, final page layout, media development, and development of assessments, teaching ancillaries, and the instructor's website. We are extremely appreciative of the support, patience, and friendship we received from family members, friends, colleagues, and students who shared our sacrifices and successes during the creation of this new vision of a textbook. We thank Susie Gillatt; John and Kay Reynolds; and our always helpful, book-writing companions Widget, Jasper, and Ziggy Reynolds, Hermosa Gillatt, and Annabelle Louise and Hazel Johnson. We thank and appreciate all of you so much!

REVIEWERS

Special thanks and appreciation go out to all reviewers. This book was improved by many beneficial suggestions, new ideas, and invaluable advice provided by these reviewers. We appreciate all the time they devoted to reviewing manuscript chapters, attending focus groups, surveying students, and promoting this text to their colleagues:

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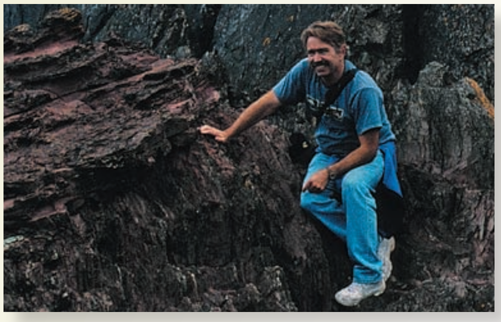


Stephen J. Reynolds received an undergraduate geology degree from the University of Texas at El Paso, and M.S. and Ph.D. degrees in structure/tectonics and regional geology from the University of Arizona. He then spent 10 years directing the geologic framework and mapping program of the Arizona Geological Survey, where he completed the 1988 *Geologic Map of Arizona*. Steve is a President's Professor in the School of Earth and Space Exploration at Arizona State University. He has taught Physical Geology, Structural Geology, Advanced Field Geology, Orogenic Systems, Cordilleran Regional Geology, Teaching Methods in the Geosciences, and others. He helped establish the ASU Center for Research on Education in Science, Mathematics, Engineering, and Technology (CRESMET), and was President of the Arizona Geological Society. He has authored or edited over 200 geologic maps, articles, and reports, including the 866-page *Geologic Evolution of Arizona*. He also coauthored *Structural Geology of Rocks and Regions,* a widely used structural geology textbook, and *Observing and Interpreting Geology*, *a Laboratory Manual for Physical Geology*. He and Julia Johnson authored *Exploring Earth Science* and, working with a team of geographers, authored *Exploring Physical Geography.* Both books follow the style and approach of the award-winning *Exploring Geology* textbook. His current geologic research focuses on structure, tectonics, and mineral deposits of the Southwest, including northern Mexico. For over 20 years, he has done science-education research on student learning in college geology courses, especially the role of visualization. He was the first geologist with his own eye-tracking laboratory, where he and his students researched student learning, demonstrating that students learn more when using the unique design, layout, and approach of this textbook, compared to using materials in a traditional textbook layout. Steve is known for innovative teaching methods, has received numerous teaching awards, and has an award-winning website. He was a National Association of Geoscience Teachers (NAGT) distinguished speaker, and he travels across the country presenting talks and workshops on how to infuse active learning and inquiry into large introductory geoscience classes. He is commonly an invited speaker to national workshops and symposia on active learning, visualization, and teaching methods in college geoscience courses. He has been a long-time industry consultant in mineral, energy, and water resources and environmental issues, and has received outstanding alumni awards from UTEP and the University of Arizona. At ASU, he recently was designated as a President's Professor, ASU's highest honor recognizing inspired, innovative teaching and scholarship of learning.

JULIA K. JOHNSON

Julia K. Johnson is a full-time faculty member in the School of Earth and Space Exploration at Arizona State University. Her research involves structural geology, regional geology, and geoscience education. The main focus of her geoscience education research is on student- and instructor-generated sketches (concept sketches) for learning, teaching, and assessment in college geology classes. Prior to coming to ASU, she did groundwater studies of copper deposits and taught full-time in the Maricopa County Community College District, teaching Physical Geology, Environmental Geology, and their labs. At ASU, she teaches Introduction to Geology to more than 2,000 students per year in in-person and online classes. She has taught more than 20,000 students! Julia supervises the associated introductory geology labs and coordinates the introductory geology teaching efforts of the School of Earth and Space Exploration, helping other instructors incorporate active learning and inquiry into large lecture classes. At ASU, Julia coordinated an innovative project focused on redesigning introductory geology classes so that they incorporated more online content and asynchronous learning. This project was very successful in improving student performance, mostly due to the widespread implementation of concept sketches and partly due to Julia's approach of decoupling multiple-choice questions and concept-sketch questions during exams and other assessments. As a result of the innovation and documented results, Julia's redesign project was identified as exemplary by the National Center for Academic Transformation (NCAT). She gives talks and webinars to faculty members across the country about how to redesign their own classes to improve efficiency and student performance at the same time. Julia is recognized as one of the best science teachers at ASU, and has received student-nominated teaching awards and very high teaching evaluations in spite of her challenging classes. In recognition of her teaching, she was a Featured Faculty of the Month on ASU's website in 2005. She has authored publications on geology and science-education research, including an article in the *Journal of Geoscience Education* on concept sketches. Her geologic map of the Phoenix Mountains is among the most downloaded publications at the Arizona Geologic Survey, with over 20,000 downloads and counting. She coauthored *Observing and Interpreting Geology*, *a Laboratory Manual for Physical Geology, Exploring Earth Science,* and *Exploring Physical Geography*. She developed a number of websites used by many geology students, including the *Visualizing Topography* website, *Biosphere 3D* website, and a website, components of which are used by online physical geology labs around the country.

PAUL MORIN

Paul J. Morin is Director of the Polar Geospatial Center at the University of Minnesota. He is responsible for supporting National Science Foundation scientific and research operations through remote sensing and other geospatial data, focused on the Antarctic and Artic regions. He also has strong interests in the effects of artistic technique and technology on the efficacy of visualizations in the hands of students. For several years, he was an NAGT distinguished speaker visiting universities and colleges to present talks on the role of visualization in geology courses. Paul is a co-investigator and co-developer of earth science museum exhibits that travel the world, being featured at the American Museum of Natural History, the Field Museum, and many others. His visualizations have been published in *Wired*, *National Geographic*, and *Nature.* Paul help coauthor *Exploring Geology*, and his data-based art work is featured throughout this textbook.

CHARLES M. CARTER

Chuck has been working in the science and entertainment industries for more than 35 years. He worked on the groundbreaking video game *Myst* and on more than two dozen other video games in a variety of art, animation, and management roles, including computer graphics supervisor and art director. His illustration and animation work has been used extensively by *National Geographic*, and his illustrations and layouts are featured in books published by *National Geographic* to feature the best of its artwork. In 1994, he was instrumental in helping launch *National Geographic Online*. His illustrations and animations have also appeared in *Scientific American*, *Wired*, the BBC, and NASA, among others. Chuck designed digital matte paintings and animations for TV shows, as well as animation and digital environments for motion rides. He founded Eagre Games, Maine, designing fully immersive adventures Chuck coauthored and was art director of early editions of this textbook.

CINDY SHAW

Cynthia Shaw has been illustrating science for most of her life, beginning with an eighth-grade poster on Yellowstone geysers that sparked her interest in science. She started producing art for academic publications while in college, and later became involved with science curriculum development. Cindy holds a B.A. in zoology from the University of Hawaii-Manoa as well as a master's in education from Washington State University, where she researched the use of science illustration as a teaching and learning tool for the science classroom. Now focusing on earth science, mapping, and coral reef ecology, she writes and illustrates for textbooks, museums, and children's books, and develops ancillary science educational materials through her business, *Aurelia Press*. Her children's novel, *Grouper Moon*, is used in many U.S. and Caribbean classrooms, and is making a positive impact on fostering children's appreciation for coral reef and fisheries conservation. She is currently landlocked in Richland, Washington.

SUSIE GILLATT

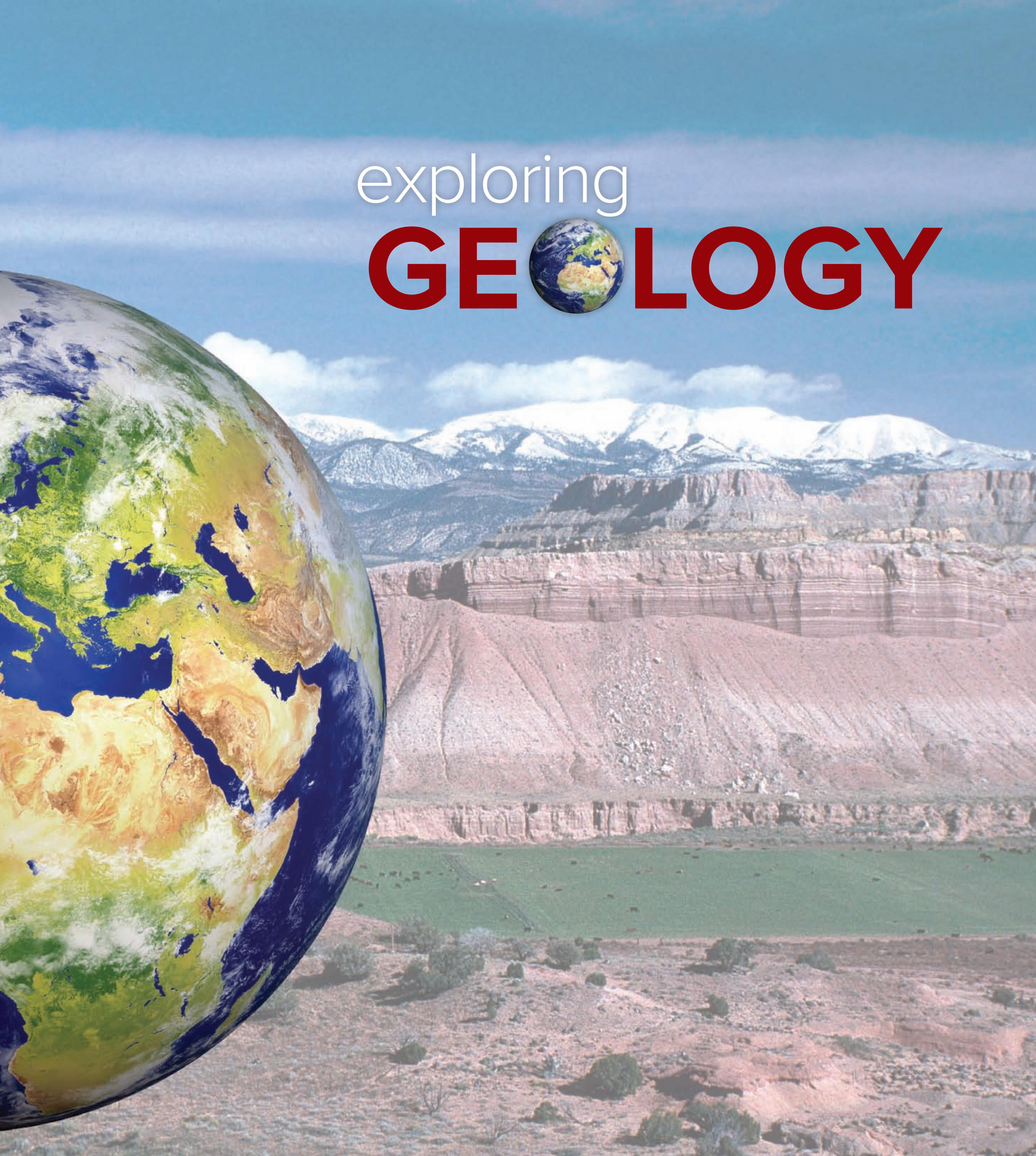
Susie Gillatt grew up in Tucson, Arizona, where she received a bachelor of arts degree from the University of Arizona. She has worked as a photographer and in the field of video production. She is president of Terra Chroma, Inc., which publishes a physical geology lab manual, among other activities. Susie focuses on scientific illustration and photo preparation for academic books and journals. Many of the photographs in this book were contributed by Susie from her travels to experience different landscapes, ecosystems, and cultures around the world. For her own art, she especially enjoys combining photography with digital painting, watercolor, and other artistic mediums. Inspired by nature, she likes discovering and capturing the abstract designs found in natural patterns. Her award-winning art has been displayed in galleries in Arizona, Colorado, and Texas. She lives in the desert environments of Tucson and in the alpine scenery of the San Juan Mountains of southwestern Colorado.

DANIEL MILLER

Born in North Carolina, Daniel has been a self-taught artist from the start. He drew and painted in grade school. After high school, he began his professional career as a silversmith, then goldsmith, painter and sculptor, designer, and art director. Attaining his goal of working in the film industry, he created notable sculptural elements for many major films, soon moving on to Los Angeles. His film credits include *Stargate* and *The Chronicles of Riddick*, to name a few. He completed other large-scale sculptural installments, including *Fountains of the Gods* at Caesars Palace in Las Vegas. Daniel taught himself computer 2D and 3D skills, including animation, leading to contributions as a concept artist and matte painter for films and the video game industry. Daniel lives on the Olympic Peninsula of Washington, where he is a sculptor and painter.

DAVID FIERSTEIN

David Fierstein attended the University of California at Santa Cruz, where he received a bachelors degree in Chemistry and completed the graduate certificate program in Science Illustration. David utilizes 3D digital modeling and painting to depict engineering and scientific concepts in the context of natural landforms and processes. His work has been used by *Scientific American*, *National Geographic,* and the Monterey Bay Aquarium Research Institute. His artwork has also appeared in college textbooks, including *Exploring Geology*, *Exploring Earth Science*, and *Exploring Physical Geography*. Currently, David combines programming and art to create science-based games for touch-screen devices and virtual reality that immerse the player in the life cycle of an animal.


exploring
GEOLOGY

CHAPTER

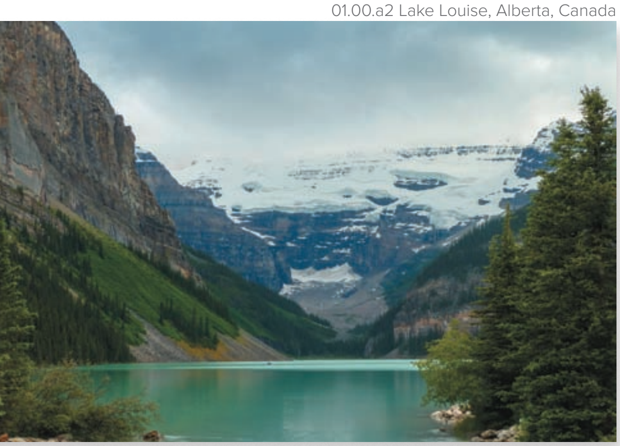
1

The Nature of Geology

GEOLOGY HAS MANY EXPRESSIONS in our world. Geologic processes reshape Earth's interior and sculpt its surface. They determine the distribution of metals and petroleum, and they control which places are most susceptible to volcanoes, floods, and other natural disasters. Geology is the study of ancient seas, rivers, and other environments, the organisms that inhabited such environments, and the formation and destruction of mountain ranges and other landforms. Geology encompasses factors such as climate and the availability of water that are critical to ecosystems. In this book we explore geology, *the science of Earth,* and examine why an understanding of geology is important in our modern world.

North America and the surrounding ocean floor have a wealth of interesting features. The large image below (▼) is computer-generated and combines different types of data to show features on the land and seafloor. The shading and colors on land are from space-based satellite images, whereas the colors and shading on the seafloor indicate depths below the surface of the sea. Find the region where you live. What types of features are there?

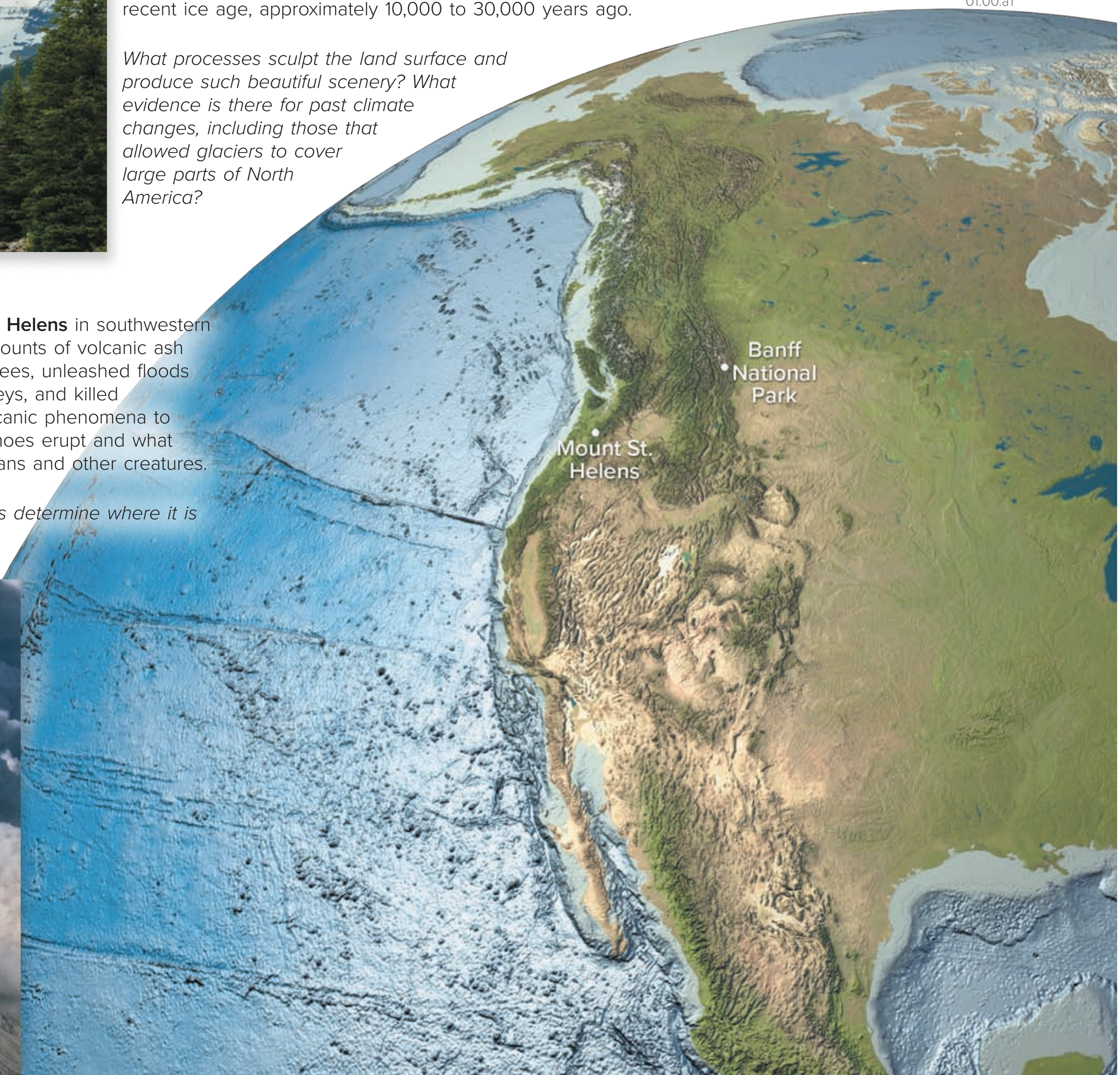
01.00.a2 Lake Louise, Alberta, Canada



The dramatic scenery of Banff National Park of Alberta, Canada, features beautiful mountains, valleys, lakes, and glaciers (◀). The peaks and valleys preserve evidence of being carved by glaciers that once were much more extensive, such as during the most recent ice age, approximately 10,000 to 30,000 years ago.

What processes sculpt the land surface and produce such beautiful scenery? What evidence is there for past climate changes, including those that allowed glaciers to cover large parts of North America?

01.00.a1



The 1980 eruption of Mount St. Helens in southwestern Washington (▼) ejected huge amounts of volcanic ash into the air, toppled millions of trees, unleashed floods and mudflows down nearby valleys, and killed 57 people. Geologists study volcanic phenomena to determine how and when volcanoes erupt and what hazards volcanoes pose to humans and other creatures.

How do geologic studies help us determine where it is safe to live?

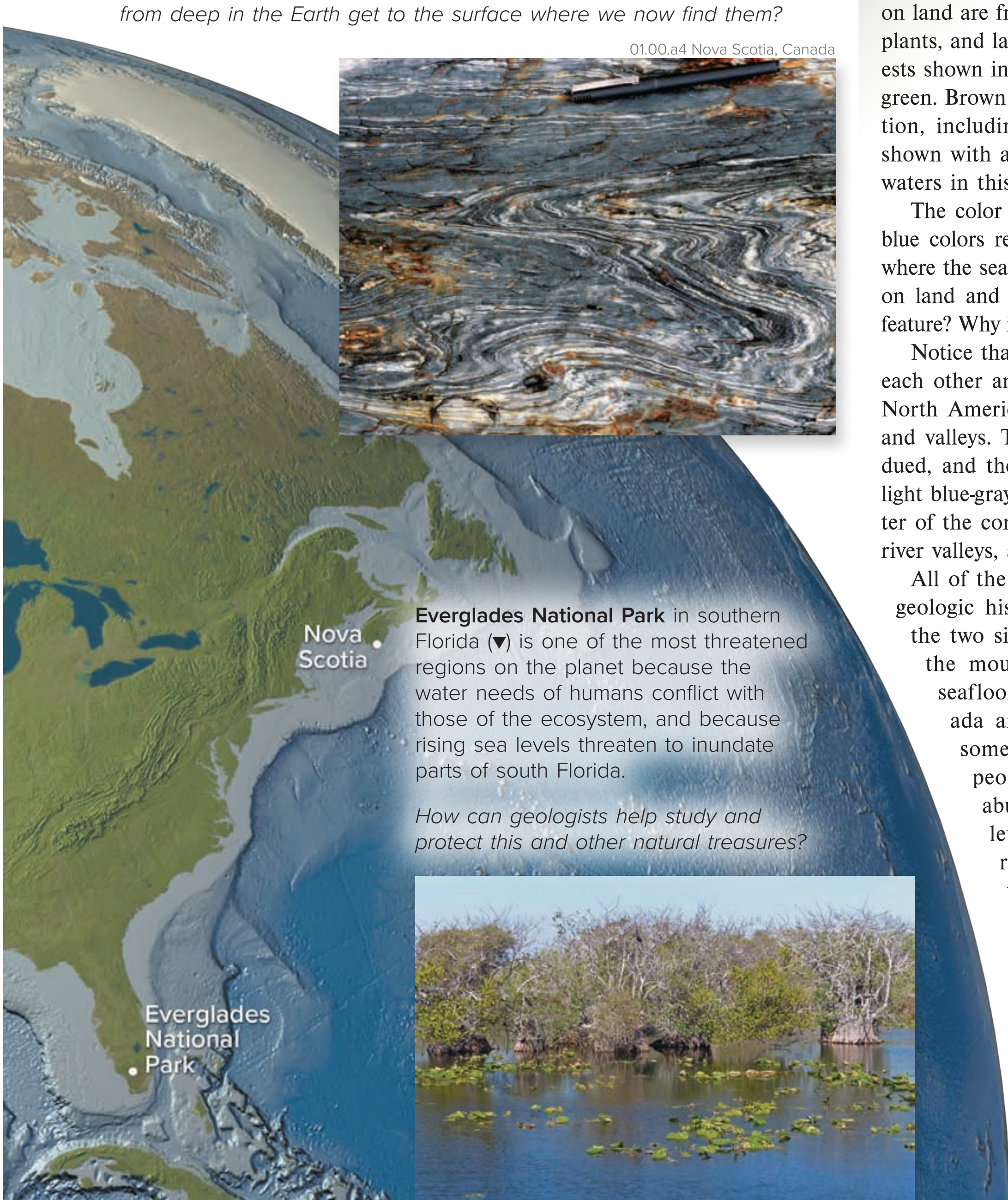
01.00.a3 Mount St. Helens, WA

TOPICS IN THIS CHAPTER

Rocks of New England and easternmost Canada record a fascinating history, which includes an ancient ocean that was destroyed by the collision of two landmasses. Many of these rocks, such as those in Nova Scotia, have contorted layers (▼), and some rocks provide evidence of having been formed at a depth of 30 km below the surface.

How do layers in rocks get squeezed and deformed, and how do rocks from deep in the Earth get to the surface where we now find them?

01.00.a4 Nova Scotia, Canada



Everglades National Park in southern Florida (▼) is one of the most threatened regions on the planet because the water needs of humans conflict with those of the ecosystem, and because rising sea levels threaten to inundate parts of south Florida.

How can geologists help study and protect this and other natural treasures?

01.00.a5 Everglades NP, FL

A View of North America

North America is a diverse continent, ranging from the low, tropical rain forests of Mexico to the high Rocky Mountains of western Canada. In this large image of North America, the colors on land are from satellite images that show the distribution of rock, soil, plants, and lakes. Green colors represent dense vegetation, including forests shown in darker green and fields and grassy plains shown in lighter green. Brown colors represent deserts and regions that have less vegetation, including regions where rock and sand are present. Lakes are shown with a solid blue color. Note that there are no clouds or ocean waters in this artificial picture.

The color of the ocean floor varies with depth below sea level. Light blue colors represent shallow areas, whereas dark blue represents places where the seafloor is deep. Observe the larger features in this image, both on land and at sea. Ask yourself the following questions: What is this feature? Why is it located here? How did it form? In short, what is its story?

Notice that the two sides of North America look very different from each other and from the middle of the continent. The western part of North America appears more complex because it has many mountains and valleys. The mountains in the eastern United States are more subdued, and the East Coast is surrounded by a broad shelf (shown in a light blue-gray) that continues out beneath the Atlantic Ocean. The center of the continent has no large mountains but has broad plains, hills, river valleys, and large lakes.

All of the features on this image of Earth are part of geology. The geologic history of North America explains why the mountains on the two sides of the continent are so different and when and how the mountains formed. Geology explains how features on the seafloor came to be, and why the central United States and Canada are the agricultural heartland of the continent, whereas some other areas are deserts. The high standard of living of people in the United States and Canada is largely due to an abundance of natural resources, especially water, coal, petroleum, minerals, and fertile soils. Such resources are the result of Earth's geologic history. In short, geology controls the height and shape of the land and seafloor, the types of materials that are present, and the processes that affect the land, sea, and us. As shown throughout this book, geology affects many aspects of society.

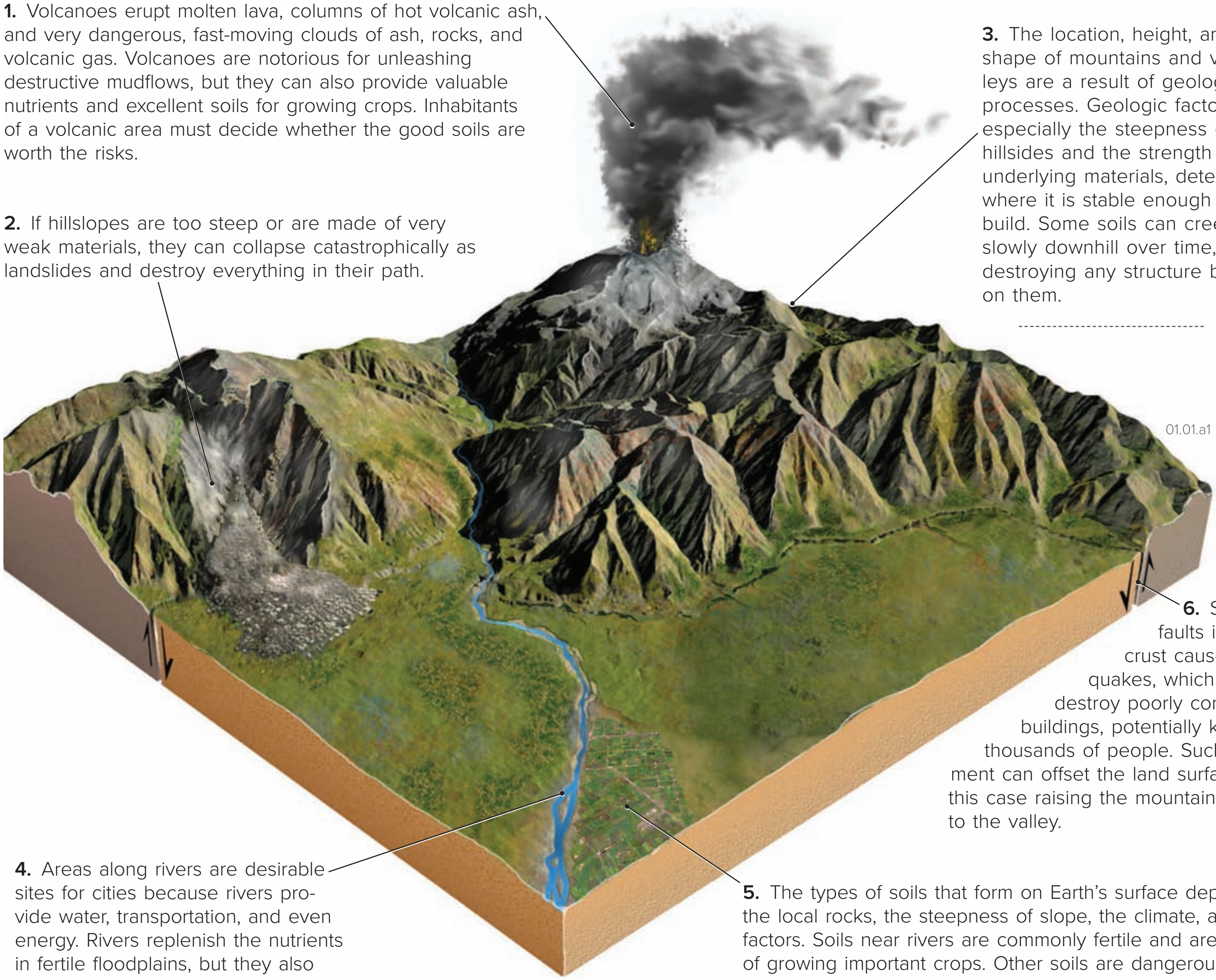
1.0

1.1 How Does Geology Influence Where and How We Live?

GEOLOGY INFLUENCES OUR LIVES IN MANY WAYS. Geologic features and processes constrain where people can live because they determine whether a site is safe from landslides, floods, or other natural hazards. Some areas are suitable building sites, but other areas are underlain by unstable geologic materials that could cause damage to any structure that might be built. Geology also controls the distribution of energy resources and the materials required to build houses, cars, and factories. Finally, geologic processes shape the surface of the planet and produce a wonderful diversity of landscapes, including beautiful scenery.

A Where Is It Safe to Live?

The landscape around us contains many clues about whether a place is relatively safe or whether it is a natural disaster waiting to happen. What important clues should guide our choice of a safe place to live?



B How Does Geology Influence Our Lives?

To explore how geology affects our lives, observe this photograph, which shows a number of different features, including clouds, snowy mountains, slopes, and a grassy field with horses and cows (the small, dark spots). For each feature you recognize, think about what is there and what processes might be occurring. Then, think about how geology influences the lives of the animals and how it would influence your life if this was your home. Think about this before reading on.

1. In the distance are snow-covered mountains partially covered with clouds. Snow and clouds both indicate the presence of water, an essential ingredient for life. The mountains have a major influence on water in this scene. As the snow melts, water flows downhill toward the lowlands to the horses and cows.

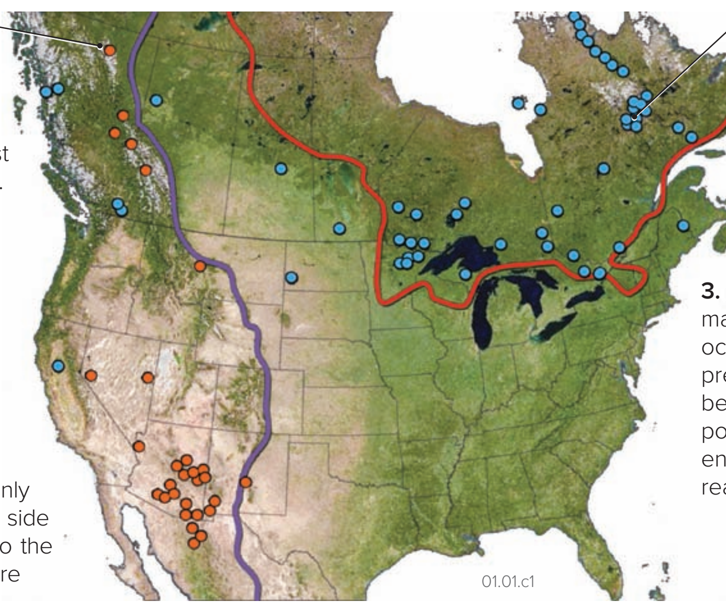
2. The horses and cows roam on a flat, grassy pasture and avoid slopes that are steep or barren of vegetation. The steepness of slopes reflects the strength of the rocks and soils, and the flat pasture resulted from loose sand and other materials that were laid down during flooding along a desert stream. Where is the likely source of the water needed to grow grass in the pasture?

01.01.b1 Henry Mtns., UT

C What Controls the Distribution of Natural Resources?

This map of North America shows the locations of large currently or recently active copper mines (orange dots) and iron mines (blue dots). What do you notice about the distribution of each type of mine?

1. Large *copper* mines are restricted to the mountainous western part of the continent (west of the purple line). *Magma* (molten rock) invaded this part of the continent between 160 and 35 million years ago and formed the copper deposits. As described later in this book, these magmas formed only along the western side of the continent, so the copper deposits are here, too.



01.01.c1

2. Large *iron* mines are common in the Great Lakes region and in eastern Canada, within an area called the *Canadian Shield* (inside the red line). Most rocks in this region are older than one billion years, and the iron-rich rocks formed at a time in Earth's history when oxygen became more abundant in the atmosphere, causing iron dissolved in the seas to precipitate into vast iron-rich layers. Rocks of this early age are less common in the west, so this type of iron deposit is less common, too.

3. The age of rocks and how the rocks formed are two of many geologic factors that control where mineral resources occur. Resources are often not located where humans would prefer them to be for logistical, political, or environmental reasons.

Before You Leave This Page

- ✓ Sketch or list some ways that geology controls where it is safe to live.
- ✓ Explain how geology influences the distribution of natural resources.

1.2 How Does Geology Help Explain Our World?

THE WORLD HAS INTERESTING FEATURES at all scales. Views from space show oceans, continents, and mountain belts. Traveling through the countryside, we notice smaller things—a beautiful rock formation or soft, green hills. Upon closer inspection, the rocks may include fossils that provide evidence of ancient life and past climates. Here, we give examples of how geology explains big and small features of our world.

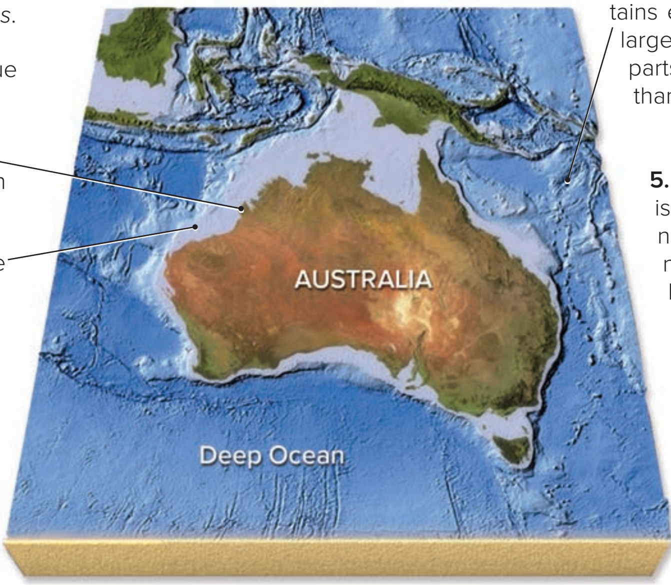
A How Do Continents Differ from Ocean Basins?

Examine this computer-generated view (▼) of the continent of Australia and the surrounding ocean basins. Colors on land show vegetation, rocks, soil, and sand, whereas colors in the oceans indicate depth, with darker blue being the deepest seafloor. Note the main features, especially those on the seafloor.

1. This map illustrates one of the most important distinctions on Earth — our planet is divided into *continents* and *oceans*.

2. The boundary between the blue colors of the oceans and the greens and browns of the land is the shoreline, which outlines the familiar shape of Australia as seen on world maps.

3. Surrounding the land is a fringe of seafloor that is not very deep, represented on this map by light blue colors. This fringe of shallow seafloor, called the *continental shelf*, is wider on the north side of the continent than on the other three sides. Geologists consider the continent to continue past the shoreline and to the outer edge of the continental shelf.



01.02.a1

4. The seafloor beneath deep parts of the ocean is locally complex, containing chains of submarine mountains east of Australia and long features that look like large scratch marks south of the continent. The deep parts of the seafloor in this region are much rougher than the smooth-appearing continental shelf.

5. The distinction between continents and oceans is a reflection of differences in their geology. Continents and oceans differ in the types and thicknesses of the rocks they contain and, as we will learn later, form in very different ways. Within the oceans are major variations in the depth and character of the seafloor from place to place. The land also varies in elevation and character, such as higher, more vegetation-covered mountains in eastern Australia than in the rest of the continent. Each region, whether on land or beneath the ocean, has its own geologic history, and the landscape and rocks contain clues as to the geologic events that affected each place.

B What Stories Do Landscapes Tell?

Observe this photograph of a canyon wall and think of at least two questions about what you see. Go ahead, try it!

1. The landscape has cliffs and slopes composed of rock units that are shades of tan, brown, and yellow.

2. In the bottom half of the image, some large, angular blocks of brownish rock are perched near the edge of a lower cliff.

01.02.b1 Superstition Mtns., AZ

3. Several questions about the landscape come to mind. What types of rocks are exposed here? How did the large, brownish blocks get to their present position? How long will it take for the blocks to fall or slide off the lower cliff?

4. The answer to each question helps explain part of the scene. The first question is about the *present*, the second is about the *past*, and the third is about the *future*. The easiest questions to answer are usually about the present, and the hardest ones are about the past or the future.

5. All of the rocks in this view are volcanic rocks, typical of those formed during a very explosive type of volcanic eruption.

6. The large blocks are composed of the same material as the upper brown cliff and were part of that cliff before falling or sliding downhill onto the slope below.

7. It is difficult to predict when the blocks will fall off the lower cliff. Some blocks near the edge could fall in the next rainstorm, but others will probably be there for millions of years.

C How Has the Global Climate Changed Since the Ice Ages?

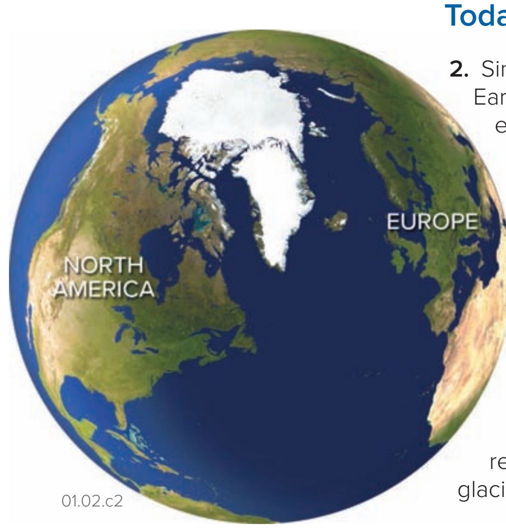
These computer-generated images show where glaciers and large ice sheets were during the last ice age and where they are today. Note how the extent of these features changed in this relatively short period of time. What caused this change, and what might happen in the future because of global warming or cooling?

28,000 Years Ago

1. Twenty-eight thousand years ago, Earth's climate was slightly cooler than it is today. Cool climates permitted continental ice sheets to extend across most of Canada and into the upper Midwest of the United States. Ice sheets also covered parts of northern Asia and Europe.

01.02.c1

Today



01.02.c2

2. Since 20,000 years ago, Earth's climate warmed enough to melt back the ice sheets to where they are today. Our knowledge of the past extent of ice sheets comes from geologists who examine the landscape for appropriate clues, including glacial features and deposits that remained after the glaciers retreated.

D What Is the Evidence That Life in the Past Was Different from Life Today?

Museums and action movies contain scenes, like the one below, of dinosaurs lumbering or scampering across a land covered by exotic plants. Where does the evidence for these strange creatures come from?

1. This mural (▶), painted by artist Karen Carr, is two stories tall and shows what types of life are interpreted to have been on Earth during the Jurassic Period, approximately 160 million years ago. Dinosaurs roamed the landscape, while the ancestors of birds began to take flight. Flowering plants were not yet abundant and grasses had not yet appeared, so non-flowering trees, bushes, and ground cover dominated the landscape.

01.02.d1

01.02.d2 Dinosaur NP, UT

2. Fossil bones of Jurassic dinosaurs (◀) are common in Dinosaur National Park, Utah. From such bones and other information, geologists infer how long ago these creatures roamed the planet, what the creatures looked like, how big they were, how they lived, and why they died. Studying the rocks that enclose the bones provides clues to the local and global environments at the time of the dinosaurs. Rocks and fossils are the record of past geologic events, environments, and prehistoric creatures.

Before You Leave This Page

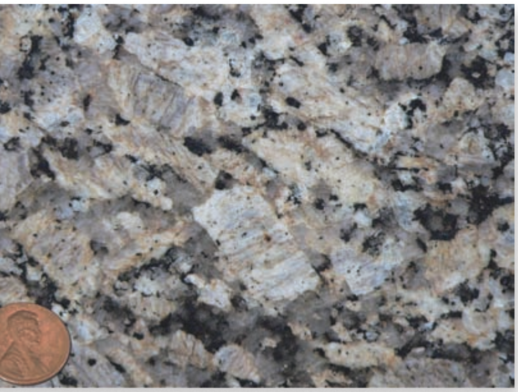
- ✓ Explain the difference in appearance between continents and oceans.
- ✓ Describe some things we can learn about Earth's past by observing its landscapes, rocks, and fossils.

1.3 What Is Inside Earth?

HAVE YOU EVER WONDERED WHAT IS INSIDE EARTH? We can directly observe the uppermost parts of Earth, but what else is down there? Earth consists of concentric layers that have different compositions. The outermost layer is the *crust*, which includes *continental crust* and *oceanic crust*. Beneath the crust is the *mantle*, Earth's most voluminous layer. The molten *outer core* and the solid *inner core* are at Earth's center.

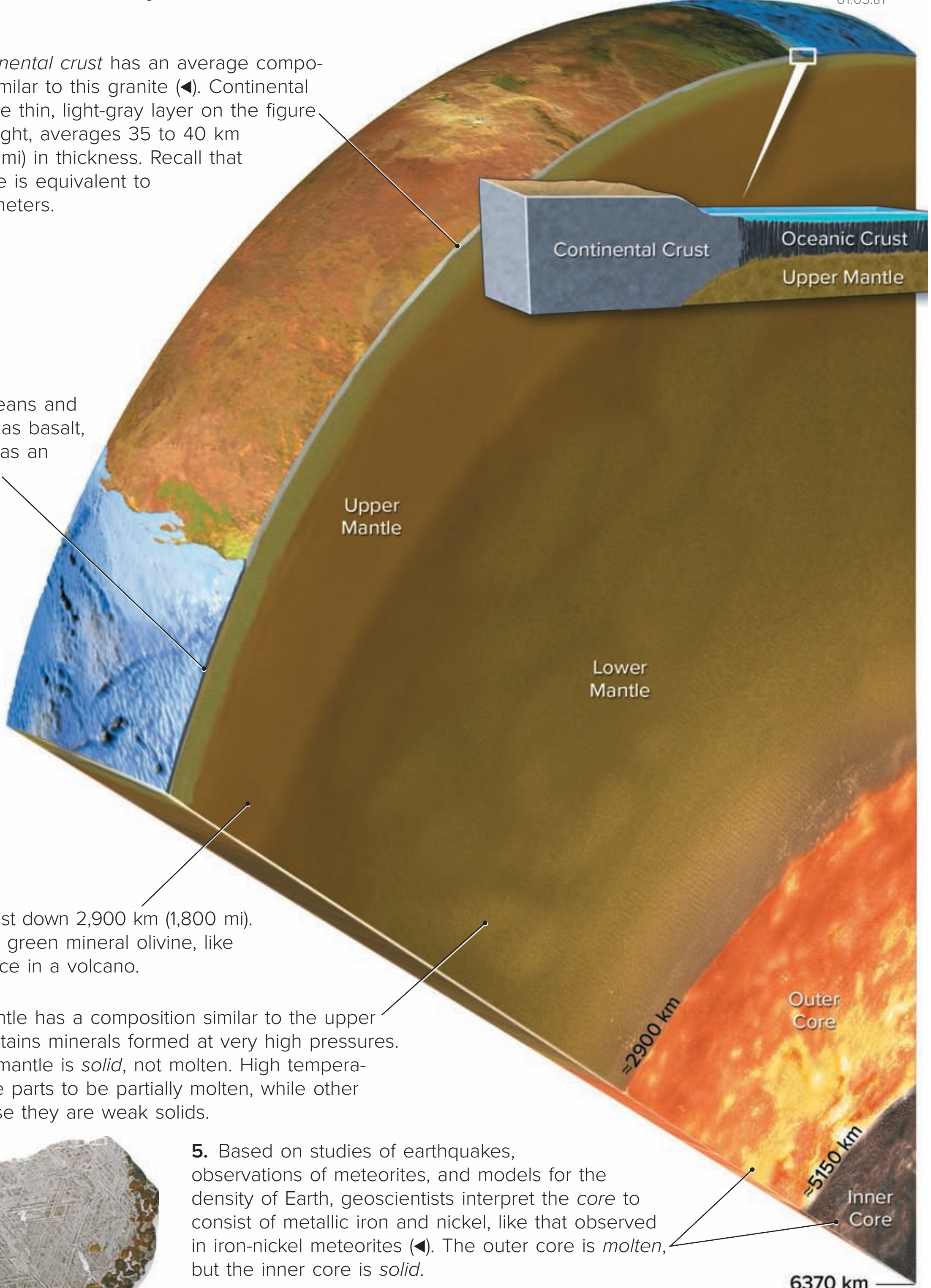
A How Does Earth Change with Depth?

01.03.a2 Polished slab



1. *Continental crust* has an average composition similar to this granite (◀). Continental crust, the thin, light-gray layer on the figure to the right, averages 35 to 40 km (20–25 mi) in thickness. Recall that one mile is equivalent to 1.6 kilometers.

01.03.a1

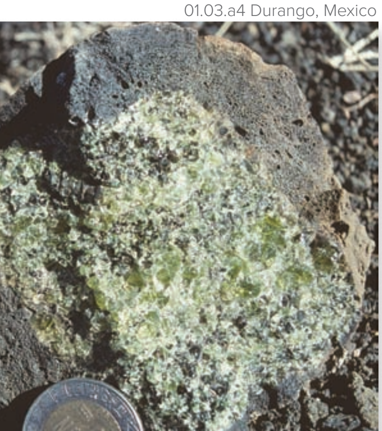


2. *Oceanic crust* exists beneath the deep oceans and has an average composition that is the same as basalt, a common dark lava rock (▼). Oceanic crust has an average thickness of about 7 km (4 mi), which is much thinner than can be shown here (the barely visible dark-gray layer).

01.03.a3 Carrizozo, NM

3. The *mantle* extends from the base of the crust down 2,900 km (1,800 mi). Much of the upper mantle is composed of the green mineral olivine, like the center (▼) of this rock brought to the surface in a volcano.

01.03.a4 Durango, Mexico



4. The lower mantle has a composition similar to the upper mantle, but it contains minerals formed at very high pressures. Nearly all of the mantle is *solid*, not molten. High temperatures cause some parts to be partially molten, while other parts flow because they are weak solids.

01.03.a5

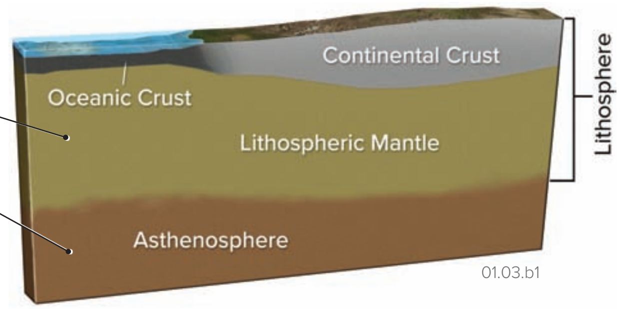
5. Based on studies of earthquakes, observations of meteorites, and models for the density of Earth, geoscientists interpret the *core* to consist of metallic iron and nickel, like that observed in iron-nickel meteorites (◀). The outer core is *molten*, but the inner core is *solid*.

B Are Some Layers Stronger Than Others?

In addition to layers with different compositions, Earth has layers that are defined by strength and by how easily the material in the layers fractures or flows when subjected to forces.

1. The uppermost part of the mantle is relatively strong and solidly attached to the overlying crust. The crust and uppermost mantle together form an upper, rigid layer called the *lithosphere* (*lithos* means *"stone"* in Greek). The part of the uppermost mantle that is in the lithosphere is the *lithospheric mantle*.

2. The mantle directly beneath the lithosphere is mostly solid, but it is hotter than the rock above and can flow under pressure. This part of the mantle, called the *asthenosphere*, functions as a soft, weak zone over which the lithosphere may move. The word *asthenosphere* is from a Greek term for "*not strong.*" The asthenosphere is approximately 80 to 150 km thick, so its base can be as deep as about 250 km.

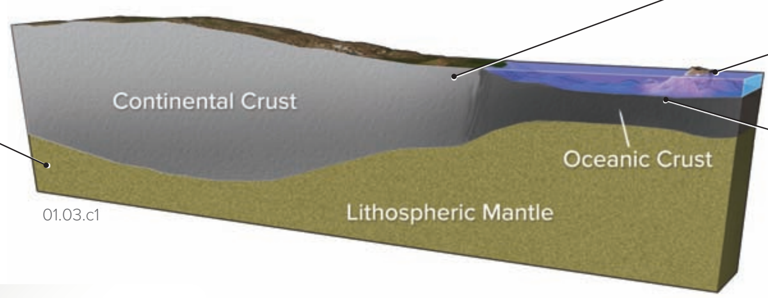


C Why Do Some Regions Have High Elevations?

Why is the Gulf Coast of Texas near sea level, while the Colorado mountains are 3 to 5 km (2 to 3 mi) above sea level? Why are the continents mostly above sea level, but the ocean floor is below sea level? The primary factor controlling the elevation of a region is the thickness of the underlying crust.

1. The granitic crust is less dense than the underlying mantle, so it rests, or floats, on top of the mantle. The underlying lithospheric mantle is mostly solid, not liquid.

2. The thickness of continental crust ranges from less than 25 km (16 mi) to more than 60 km (37 mi). Regions that have high elevation generally have thick crust. The crust beneath the Rocky Mountains of Colorado is commonly more than 45 km (28 mi) thick.



3. The crust beneath low-elevation regions like Texas is thinner. If the crust is thinner than 30 to 35 km (18 to 20 mi), the area will probably be below sea level, but it can still be part of the continent, like on a continental shelf.

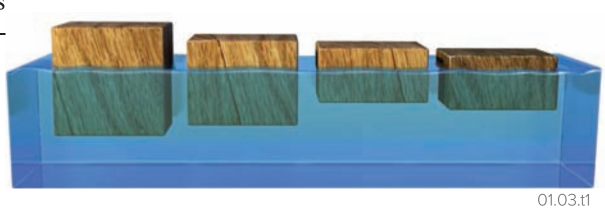
4. Most islands are volcanic mountains built on oceanic crust, but some are small pieces of continental crust.

5. Oceanic crust is thinner than continental crust and consists of denser rock than continental crust. As a result, regions underlain only by oceanic crust are well below sea level.

Density and Isostasy

The relationship between regional elevation and crustal thickness is similar to that of wooden blocks of different thicknesses floating in water (▼). Wood floats on water because it is less dense than water. Ice floats on water because it is less dense than water, although ice and water have the same composition. Thicker blocks of wood, like thicker parts of the crust, rise to higher elevations than do thinner blocks of wood.

For Earth, we envision the crust being supported by mantle that is solid, unlike the liquid water used in this wooden-block example. This concept of different thicknesses of crust riding on the mantle is called *isostasy.* Isostasy explains most of the variations in elevation from one region to another, and it is commonly paraphrased by saying *mountain belts have thick crustal roots*. As in the case of the floating wooden blocks, most of the change in crustal thickness occurs at depth and less occurs near the surface. Smaller, individual mountains do not necessarily have thick crustal roots. They can be supported by the strength of the crust, like a small lump of clay riding on one of the wooden blocks.



The *density* of the rocks also influences regional elevations. The fourth block shown here has the same thickness as the third block, but it consists of a denser type of wood. It therefore floats lower in the water. Likewise, a region of Earth underlain by especially dense crust or mantle is lower in elevation than a region with less dense crust or mantle, even if the two regions have similar thicknesses of crust. Temperature also controls the thickness of the lithosphere, which also affects a region's elevation. If the lithosphere in some region is heated, it expands, becoming less dense, and so the region rises in elevation. Thinner lithosphere also yields higher elevations.

Before You Leave This Page

- ✓ Sketch the major layers of Earth.
- ✓ Sketch and describe differences in thickness and composition between continental crust and oceanic crust, and contrast lithosphere and asthenosphere.
- ✓ Sketch and discuss how the principle of isostasy can explain differences in regional elevation.