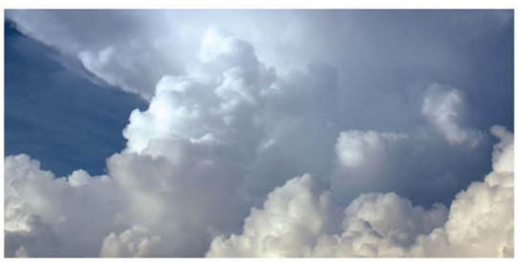
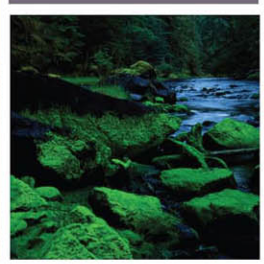
VISUALIZING Geology

BARBARA W. MURCK • BRIAN J. SKINNER

FOURTH EDITION





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WILEY

VISUALIZING
GEOLOGY

FOURTH EDITION

DEDICATION

This book is dedicated to Cathy Skinner.

My friend, role model, and inspiration – BWM

My colleague, partner, and soulmate – BJS

REMEMBRANCE

As this book was going to press we learned of the death of Clifford Mills, long-time editor, mentor, and friend.

Thanks and farewell, Cliff. Your skills and judgement live on in this and many other Wiley books.

VISUALIZING GEOLOGY

FOURTH EDITION

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WILEY

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Preface

HOW IS WILEY VISUALIZING DIFFERENT?

Wiley Visualizing is based on decades of research on the use of visuals in learning (Mayer, 2005).[1] The visuals teach key concepts and are pedagogically designed to **explain, present,** and **organize** new information. The figures are tightly integrated with accompanying text; the visuals are conceived with the text in ways that clarify and reinforce major concepts while allowing students to understand the details. This commitment to distinctive and consistent visual pedagogy sets Wiley Visualizing apart from other textbooks.

The texts offer an array of remarkable photographs, maps, and media from photo collections around the world. Wiley Visualizing's images are not decorative; such images can be distracting to students. Instead, they are purposeful and the primary driver of the content. These authentic materials immerse the student in real-life issues and experiences and support thinking, comprehension, and application.

Together these elements deliver a level of rigor in ways that maximize student learning and involvement. Wiley Visualizing has been proven to increase student learning through its unique combination of text, photographs, and illustrations, with online animations, simulations, and assessments.

1. **Visual Pedagogy.** Using the Cognitive Theory of Multimedia Learning, which is backed up by hundreds of empirical research studies, Wiley's authors create visualizations for their texts that specifically support students' thinking and learning—for example, the selection of relevant materials, the organization of the new information, or the integration of the new knowledge with prior knowledge.

2. **Authentic Situations and Problems.** *Visualizing Geology 4e* benefits from an array of remarkable photographs, maps, and media; these authentic materials immerse the student in real-life issues in geology, thereby enhancing motivation, learning, and retention (Donovan & Bransford, 2005).[2]

3. **Designed with Interactive Multimedia.** *Visualizing Geology 4e* is tightly integrated with *WileyPLUS*, our online learning environment that provides interactive multimedia activities in which learners can actively engage with the materials. The combination of textbook and *WileyPLUS* provides learners with multiple entry points to the content, giving them greater opportunity to explore concepts and assess their understanding as they progress through the course. *WileyPLUS* is a key component of the Wiley Visualizing learning and problem-solving experience, setting it apart from other textbooks whose online component is mere drill-and-practice.

Wiley Visualizing and the *WileyPLUS* Learning Environment a natural extension of how we learn

To understand why the Visualizing approach is effective, it is first helpful to understand how we learn.

1. Our brain processes information using two main channels: visual and verbal. Our *working memory* holds information that our minds process as we learn. This "mental workbench" helps us with decisions, problem-solving, and making sense of words and pictures by building verbal and visual models of the information.

2. When the verbal and visual models of corresponding information are integrated in working memory, we form more comprehensive and lasting mental models.

3. When we link these integrated mental models to our prior knowledge, stored in our *long-term memory,* we build even stronger mental models. When an integrated (visual plus verbal) mental model is formed and stored in long-term memory, real learning begins.

The effort our brains put forth to make sense of instructional information is called *cognitive load*. There are two kinds of cognitive load: productive cognitive load, such as when we're engaged in learning or exert positive effort to create mental models; and unproductive cognitive load, which occurs when the brain is trying to make sense of needlessly complex content or when information is not presented well. The learning process can be impaired when the information to be processed exceeds the capacity of working memory. Well-designed visuals and text with effective pedagogical guidance can reduce the unproductive cognitive load in our working memory.

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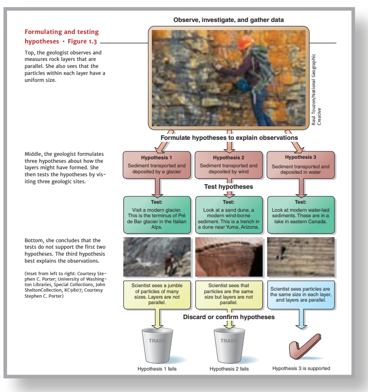
[1] Mayer, R.E. (Ed.) (2005). *The Cambridge Handbook of Multimedia Learning*. Cambridge University Press.
[2] Donovan, M.S., & Bransford, J. (Eds.) (2005). *How Students Learn: Science in the Classroom*. The National Academy Press. Available online at http://www.nap.edu/openbook.php?record_id=11102&page=1.

Wiley Visualizing is designed for engaging and effective learning

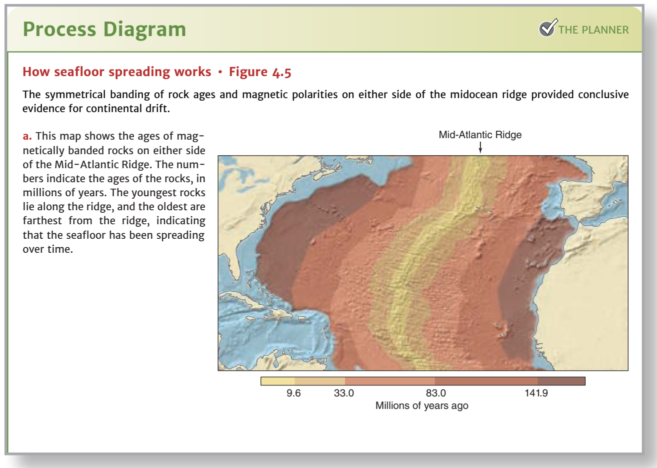
The visuals and text in *Visualizing Geology 4e* are specially integrated to present complex processes in clear steps and with clear representations, organize related pieces of information, and integrate related information. This approach, along with the use of interactive multimedia, minimizes unproductive cognitive load and helps students engage with the content. When students are engaged, they're reading and learning, which can lead to greater knowledge and academic success.

Research shows that well-designed visuals, integrated with comprehensive text, can improve the efficiency with which a learner processes information. In this regard, SEG Research, an independent research firm, conducted a national, multisite study evaluating the effectiveness of Wiley Visualizing. Its findings indicate that students using Wiley Visualizing products (both print and multimedia) were more engaged in the course, exhibited greater retention throughout the course, and made significantly greater gains in content area knowledge and skills, as compared to students in similar classes that did not use Wiley Visualizing.[3]

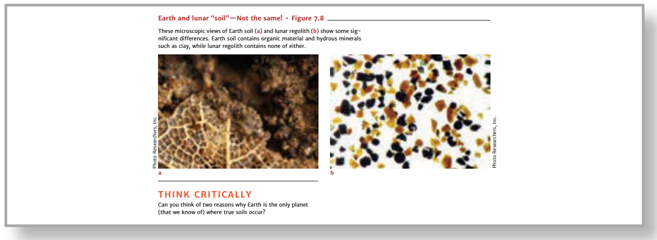
The use of *WileyPLUS* can also increase learning. According to a white paper titled "Leveraging Blended Learning for More Effective Course Management and Enhanced Student Outcomes" by Peggy Wyllie of Evince Market Research & Communications, studies show that effective use of online resources can increase learning outcomes. Pairing supportive online resources with face-to-face instruction can help students to learn and reflect on material, and deploying multimodal learning methods can help students to engage with the material and retain their acquired knowledge.



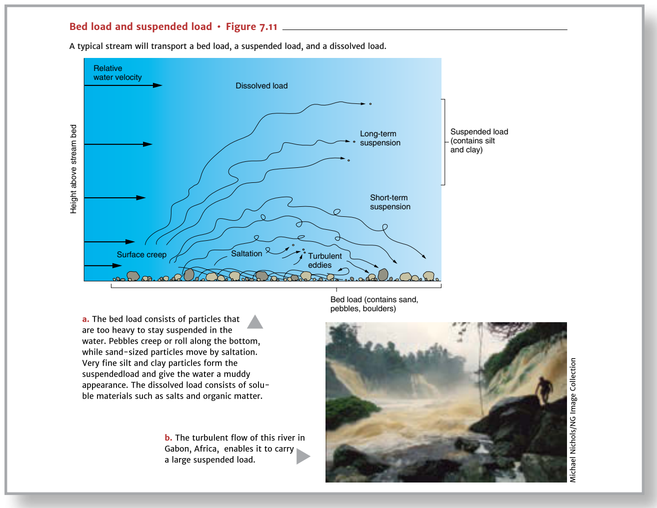
Using the scientific method (Figure 1.3) This matrix visually organizes abstract information to reduce cognitive load.



Seafloor spreading (Figure 4.5) Through a logical progression of graphics, this illustration directs learners' attention to the underlying concept. Textual and visual elements are physically integrated. This eliminates split attention—when too many sources of information divide attention.



Earth and lunar "soil"—Not the same! (Figure 7.8) Photos are paired so that students can compare and contrast them, thereby grasping the underlying concept. Adjacent caption eliminates split attention.



Bed load and suspended load (Figure 7.11) From abstraction to reality: Linking the graph to a photo illustrates how data on the graph relates to an actual river.

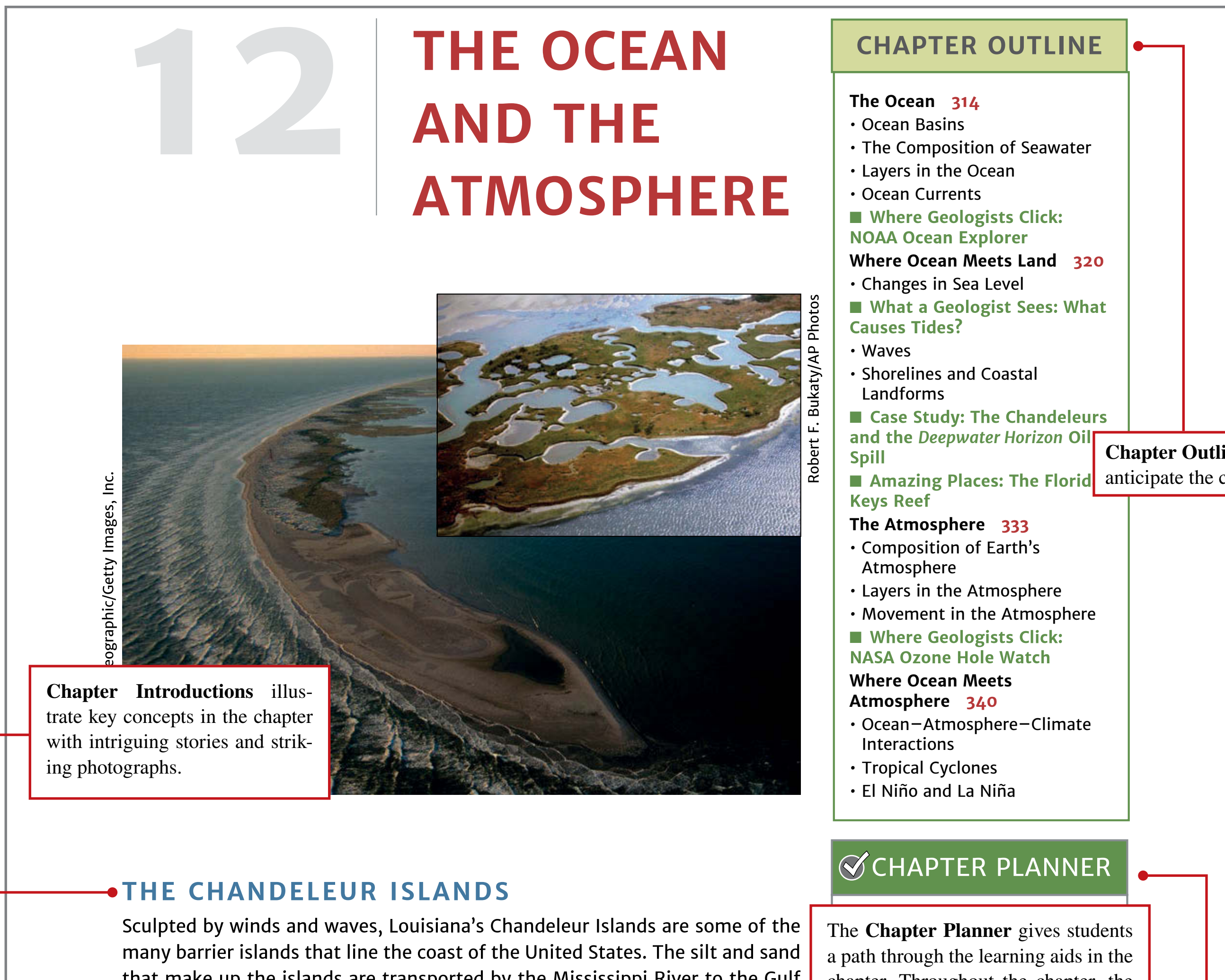
[3] SEG Research (2009). Improving Student-Learning with Graphically Enhanced Textbooks: A Study of the Effectiveness of the Wiley Visualizing Series.

HOW ARE THE WILEY VISUALIZING CHAPTERS ORGANIZED?

Student engagement is more than just exciting videos or interesting animations—engagement means keeping students motivated to keep going. It is easy to get bored or lose focus when presented with large amounts of information, and it is easy to lose motivation when the relevance of the information is unclear. The design of *WileyPLUS* is based on cognitive science, instructional design, and extensive research into user experience. It transforms learning into an interactive, engaging, and outcomes-oriented experience for students.

Each Wiley Visualizing chapter engages students from the start

Chapter opening text and visuals introduce the subject and connect the student with the material that follows.



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THE OCEAN AND THE ATMOSPHERE

Robert F. Bukaty/AP Photos

eographic/Getty Images, Inc.

CHAPTER OUTLINE

The Ocean 314
- Ocean Basins
- The Composition of Seawater
- Layers in the Ocean
- Ocean Currents
- **Where Geologists Click: NOAA Ocean Explorer**

Where Ocean Meets Land 320
- Changes in Sea Level
- **What a Geologist Sees: What Causes Tides?**
- Waves
- Shorelines and Coastal Landforms
- **Case Study: The Chandeleurs and the *Deepwater Horizon* Oil Spill**
- **Amazing Places: The Florida Keys Reef**

The Atmosphere 333
- Composition of Earth's Atmosphere
- Layers in the Atmosphere
- Movement in the Atmosphere
- **Where Geologists Click: NASA Ozone Hole Watch**

Where Ocean Meets Atmosphere 340
- Ocean–Atmosphere–Climate Interactions
- Tropical Cyclones
- El Niño and La Niña

Chapter Outlines anticipate the content.

Chapter Introductions illustrate key concepts in the chapter with intriguing stories and striking photographs.

THE CHANDELEUR ISLANDS

Sculpted by winds and waves, Louisiana's Chandeleur Islands are some of the many barrier islands that line the coast of the United States. The silt and sand that make up the islands are transported by the Mississippi River to the Gulf

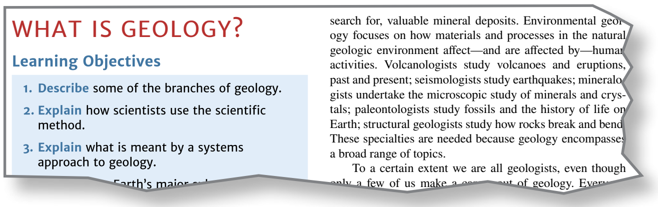
CHAPTER PLANNER

The **Chapter Planner** gives students a path through the learning aids in the chapter. Throughout the chapter, the Planner icon prompts students to use the learning aids and to set priorities as they study.

Wiley Visualizing guides students through the chapter

The content of Wiley Visualizing gives students a variety of approaches—visuals, words, interactions, video, and assessments—that work together to provide a guided path through the content.

Learning Objectives at the start of each section indicate in behavioral terms the concepts that students are expected to master while reading the section.



WHAT IS GEOLOGY?

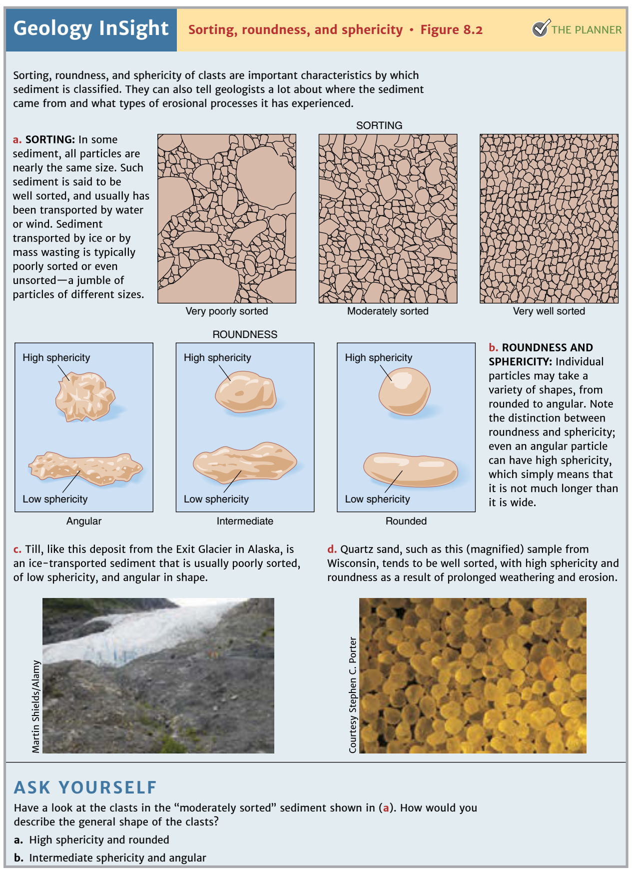
Learning Objectives

1. Describe some of the branches of geology.
2. Explain how scientists use the scientific method.
3. Explain what is meant by a systems approach to geology.

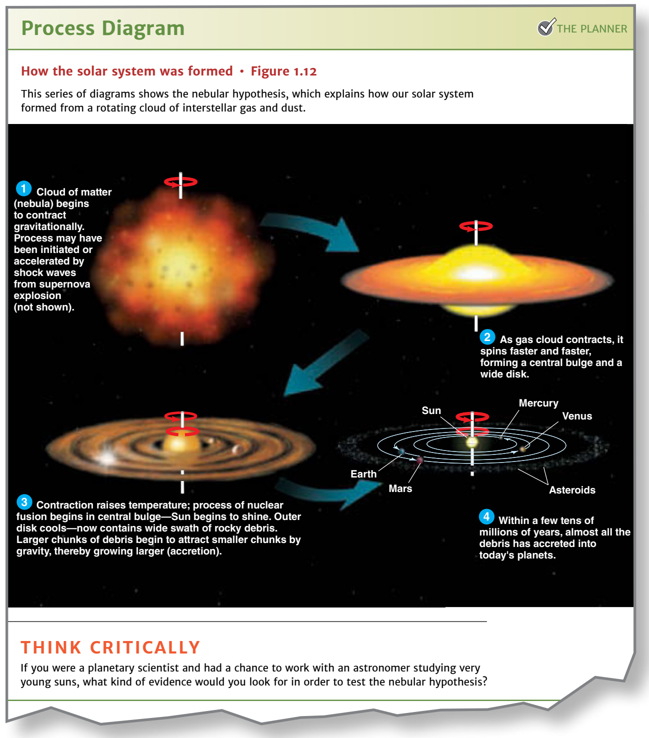
search for, valuable mineral deposits. Environmental geol ogy focuses on how materials and processes in the natural geologic environment affect—and are affected by—human activities. Volcanologists study volcanoes and eruptions, past and present; seismologists study earthquakes; mineralogists undertake the microscopic study of minerals and crystals; paleontologists study fossils and the history of life on Earth; structural geologists study how rocks break and bend. These specialties are needed because geology encompasses a broad range of topics.

To a certain extent we are all geologists, even though

Geology InSight features are multipart visual sections that focus on a key concept or topic in the chapter, exploring it in detail or in broader context using a combination of photos, diagrams, maps, and data.



Process Diagrams provide in-depth coverage of processes correlated with clear, step-by-step narrative, enabling students to grasp important topics with less effort.



Case Studies are in-depth examinations of fascinating and important issues in geology.

CASE Study

THE PLANNER

The "Little Grand Canyon"

Providence Canyon in Georgia is a gorgeous example of a canyon carved into deeply weathered soil, but it is also a dreadful example of poor soil management. In Figure a, in the canyon wall you can readily spot the dark brown A horizon, the bright red B horizon that is full of clay, and the paler E horizon. This is a good, productive soil, but unfortunately much of it has been washed away.

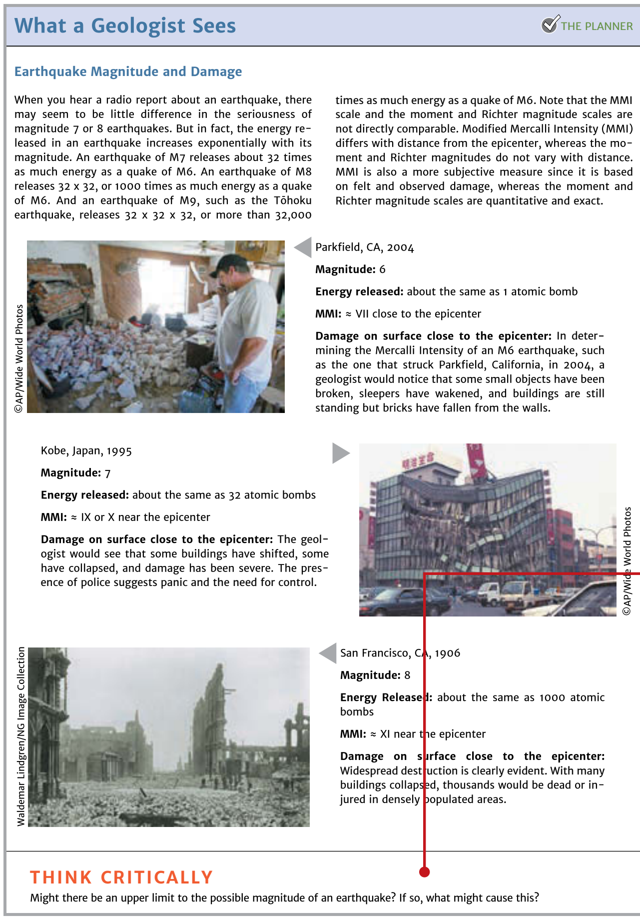
Some people call Providence Canyon the "Little Grand Canyon" because of its layered appearance, but in reality they are very different. The Grand Canyon was carved into sedimentary rock strata millions of years ago, by natural erosional processes. Providence Canyon is less than 200 years old; it, too, was formed by erosion but greatly accelerated by human activity.

There was no canyon here when settlers from Europe began farming in the early 1800s. The farmers plowed straight up and down the hills, and the furrows rapidly developed into gullies. By 1850, the gullies were 1 to 2 meters deep. The farmers had to abandon their fields, but by then, erosion in the gullies was running amok. The canyon is now more than 50 meters deep. Unfortunately, there are many such locations in North America.

In the early 20th century, scientists involved with erosion studies pointed out that water flowing in plowed land needed to be controlled. To fight erosion, farmers now use contour plowing (Figure b). Instead of going in straight lines downhill, the furrows follow the contour of the land. This slows runoff and inhibits the formation of gullies, helping to retain the topsoil on the field.

a. Providence Canyon resulted from intense erosion of poorly managed agricultural fields.

Kevin Horan/Stone/Getty Images, Inc.



What a Geologist Sees

THE PLANNER

Earthquake Magnitude and Damage

When you hear a radio report about an earthquake, there may seem to be little difference in the seriousness of magnitude 7 or 8 earthquakes. But in fact, the energy released in an earthquake increases exponentially with its magnitude. An earthquake of M7 releases about 32 times as much energy as a quake of M6. An earthquake of M8 releases 32 x 32, or 1000 times as much energy as a quake of M6. And an earthquake of M9, such as the Tōhoku earthquake, releases 32 x 32 x 32, or more than 32,000 times as much energy as a quake of M6. Note that the MMI scale and the moment and Richter magnitude scales are not directly comparable. Modified Mercalli Intensity (MMI) differs with distance from the epicenter, whereas the moment and Richter magnitudes do not vary with distance. MMI is also a more subjective measure since it is based on felt and observed damage, whereas the moment and Richter magnitude scales are quantitative and exact.

©AP/Wide World Photos

Parkfield, CA, 2004

Magnitude: 6

Energy released: about the same as 1 atomic bomb

MMI: ≈ VII close to the epicenter

Damage on surface close to the epicenter: In determining the Mercalli Intensity of an M6 earthquake, such as the one that struck Parkfield, California, in 2004, a geologist would notice that some small objects have been broken, sleepers have wakened, and buildings are still standing but bricks have fallen from the walls.

Kobe, Japan, 1995

Magnitude: 7

Energy released: about the same as 32 atomic bombs

MMI: ≈ IX or X near the epicenter

Damage on surface close to the epicenter: The geologist would see that some buildings have shifted, some have collapsed, and damage has been severe. The presence of police suggests panic and the need for control.

©AP/Wide World Photos

Waldemar Lindgren/NG Image Collection

San Francisco, CA, 1906

Magnitude: 8

Energy Released: about the same as 1000 atomic bombs

MMI: ≈ XI near the epicenter

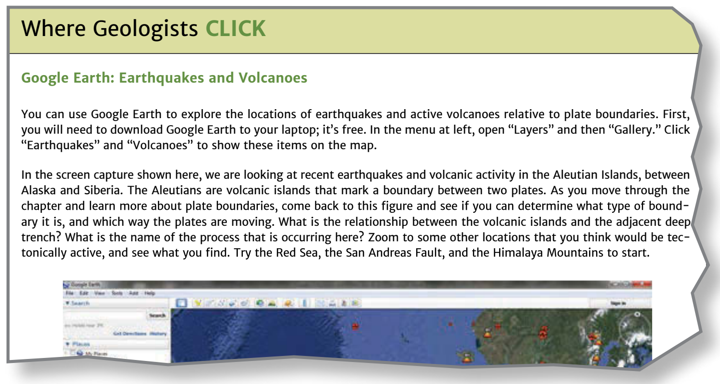
Damage on surface close to the epicenter: Widespread destruction is clearly evident. With many buildings collapsed, thousands would be dead or injured in densely populated areas.

THINK CRITICALLY

Might there be an upper limit to the possible magnitude of an earthquake? If so, what might cause this?

What a Geologist Sees highlights a concept or phenomenon that would stand out to a geologist. Photos and figures are used to improve students' understanding of the usefulness of a geology perspective and to develop their observational skills.

Think Critically questions let students analyze the material and develop insights into essential concepts.



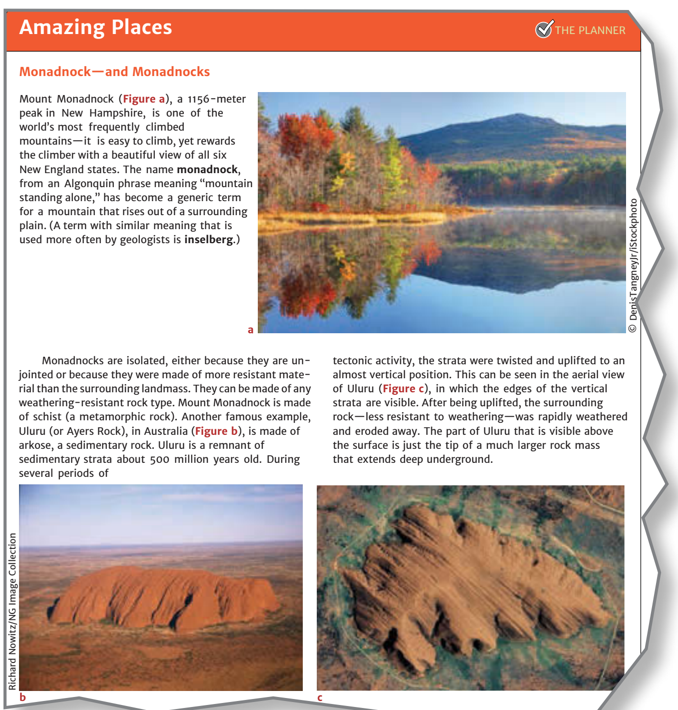
Where Geologists CLICK

Google Earth: Earthquakes and Volcanoes

You can use Google Earth to explore the locations of earthquakes and active volcanoes relative to plate boundaries. First, you will need to download Google Earth to your laptop; it's free. In the menu at left, open "Layers" and then "Gallery." Click "Earthquakes" and "Volcanoes" to show these items on the map.

In the screen capture shown here, we are looking at recent earthquakes and volcanic activity in the Aleutian Islands, between Alaska and Siberia. The Aleutians are volcanic islands that mark a boundary between two plates. As you move through the chapter and learn more about plate boundaries, come back to this figure and see if you can determine what type of boundary it is, and which way the plates are moving. What is the relationship between the volcanic islands and the adjacent deep trench? What is the name of the process that is occurring here? Zoom to some other locations that you think would be tectonically active, and see what you find. Try the Red Sea, the San Andreas Fault, and the Himalaya Mountains to start.

Where Geologists Click showcases a website that professionals use and encourages students to try out its tools.



Amazing Places

THE PLANNER

Monadnock—and Monadnocks

Mount Monadnock (Figure a), a 1156-meter peak in New Hampshire, is one of the world's most frequently climbed mountains—it is easy to climb, yet rewards the climber with a beautiful view of all six New England states. The name **monadnock**, from an Algonquin phrase meaning "mountain standing alone," has become a generic term for a mountain that rises out of a surrounding plain. (A term with similar meaning that is used more often by geologists is **inselberg**.)

a

© DenisTangneyJr/iStockphoto

Monadnocks are isolated, either because they are unjointed or because they were made of more resistant material than the surrounding landmass. They can be made of any weathering-resistant rock type. Mount Monadnock is made of schist (a metamorphic rock). Another famous example, Uluru (or Ayers Rock), in Australia (Figure b), is made of arkose, a sedimentary rock. Uluru is a remnant of sedimentary strata about 500 million years old. During several periods of tectonic activity, the strata were twisted and uplifted to an almost vertical position. This can be seen in the aerial view of Uluru (Figure c), in which the edges of the vertical strata are visible. After being uplifted, the surrounding rock—less resistant to weathering—was rapidly weathered and eroded away. The part of Uluru that is visible above the surface is just the tip of a much larger rock mass that extends deep underground.

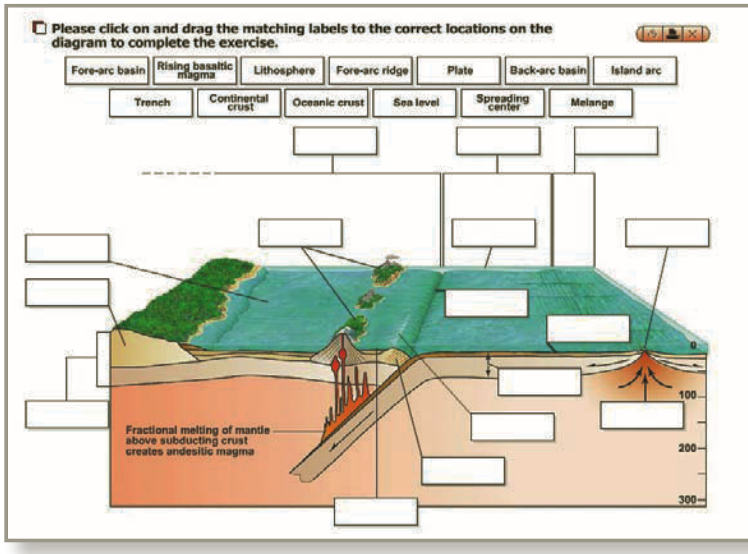
Richard Nowitz/NG Image Collection

b

c

The **Amazing Places** sections take the student to a unique place that provides a vivid illustration of a concept in the chapter. Students could easily visit most of the Amazing Places someday and so continue their geologic education.

GeoDiscoveries Media Library is an interactive media source of animations, simulations, and interactivities allowing instructors to visually demonstrate key concepts in greater depth.



CONCEPT CHECK STOP

1. What physical and chemical changes happen in rock undergoing metamorphism?
2. What distinguishes burial metamorphism from regional metamorphism?
3. How does regional metamorphism in a subduction zone differ from regional metamorphism in a collision zone?
4. What process changes the chemical composition of a rock, rather than just its texture or mineral assemblage?

Coordinated with the section-opening **Learning Objectives**, at the end of each section **Concept Check** questions allow students to test their comprehension of the learning objectives.

Student understanding is assessed at different levels

Wiley Visualizing with *WileyPLUS* offers students lots of practice material for assessing their understanding of each study objective. Students know exactly what they are getting out of each study session through immediate feedback and coaching.

The **Summary** revisits each major section, with informative images taken from the chapter. These visuals reinforce important concepts.

SUMMARY

THE PLANNER

1 Earthquakes and Earthquake Hazards 107

- **Seismology** relates earthquakes to the processes of plate tectonics. Although the motion of tectonic plates is very gradual, friction causes the rocks in the crust to jam together for long periods and then to break suddenly and lurch forward, causing an earthquake to occur. Earthquakes can cause large vertical or horizontal displacements of the ground, but much of the damage they cause results from the violent shaking that accompanies the displacement.
- The shaking motion experienced during an earthquake can be explained by the **elastic rebound model**, which says that the energy stored in bent and deformed rocks is released as **seismic waves**. After an earthquake, the rocks return to their undeformed state.
- In many cases the destructiveness of earthquakes is magnified by secondary hazards, such as fires, landslides, liquefaction (see the photo), and tsunamis. Proper building design and earthquake preparedness can greatly reduce the loss of life from earthquakes and secondary hazards.

Secondary hazards: Ground liquefaction • Figure 5.4

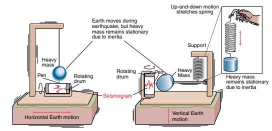
Courtesy NOAA/NGDC

- Short-term forecasting of earthquakes is still very unreliable. Scientists have concentrated their efforts on finding precursor phenomena, such as foreshocks, but with limited success. However, long-term forecasting can provide a good idea of which regions are at risk. One of the main tools of long-term forecasting is **paleoseismology**, which reveals when past earthquakes occurred in a given region, as well as the periodicity and magnitudes of past earthquakes.

2 The Science of Seismology 115

- **Seismographs** produce recordings of seismic waves that are called **seismograms.** In a basic seismograph (see the diagram), a pen is attached to a heavy suspended mass. Seismic waves cause the paper to shake while the pen stays still and traces a wavy line on the vibrating paper.

Seismograph • Figure 5.7



- Earthquakes produce three main types of seismic waves: **compressional waves**, or P waves (primary waves); **shear waves**, or S waves (secondary waves); and a variety of **surface waves**. Compressional and shear waves are called **body waves** because they travel through Earth's interior.
- Compressional waves travel faster than shear waves and hence arrive at seismographs first. The difference in arrival times between the P and S waves allows seismologists to compute the distance, but not the direction, to the **focus** of an earthquake. To determine the precise location of the **epicenter**, seismologists need measurements from three separate seismic stations. They can then determine the location by triangulation.
- The Richter and moment **magnitude** scales are measures of earthquake intensity that can be determined regardless of the distance to the earthquake or the amount of damage done. Both are logarithmic scales, in which each unit of magnitude corresponds roughly to a 10-fold increase in the amplitudes of seismic waves, but a 32-fold increase in the amount of energy released by the earthquake. The Modified Mercalli Intensity scale is a descriptive scale based on the extent of earthquake damage. On the MMI scale, the intensity is highest near the epicenter.

CRITICAL AND CREATIVE THINKING QUESTIONS

1. How did sea-surface temperatures at the peak of the last glaciation differ from those of the present? Why do you think some regions of the ocean have shown more change than others? What influence would these changes have had on atmospheric circulation and weather?
2. How can isotopic analyses of deep-sea sediment reveal changes in global ice volumes?
3. At the height of the most recent ice age, vegetation in North America south of the ice front must have been very different from the vegetation today. Do some research and find out what is known of vegetation changes in your area over the past 20,000 years.

6. Consider the maps in Figure 14.18 a and b. On the left is RCP 2.6, the "peak and decline" scenario for CO_2 emissions; on the right is RCP 8.5, the "continued high emissions" scenario. Locate your home region on the maps. What do the projections hold for RCP 2.6 in this location? Wetter? Warmer? Cooler? Drier? By how much? How different is the RCP 8.5 projection for this location?

Projected effects of increases in atmospheric CO_2 • Figure 14.18

RCP 2.6 RCP 8.5
Change in average surface temperature (1986–2005 to 2081–2100)

Critical and Creative Thinking Questions challenge students to think more broadly about chapter concepts. The level of these questions ranges from simple to advanced; they encourage students to think critically and develop an analytical understanding of the ideas discussed in the chapter.

What is happening in this picture? presents a photograph that is relevant to a chapter topic and illustrates a situation students are not likely to have encountered previously.

WHAT IS HAPPENING IN THIS PICTURE?

From September 14 to October 4, 2005, a series of earthquakes and eruptions in the Afar Desert in Ethiopia opened up the rift seen in this photograph, which is 60 meters wide at its widest point. The rift is part of a much more extensive depression where two plates, the African and the Somalian plates, are spreading apart. (Older rifts can also be seen in the background.) Compare this photo to the map and satellite image in this chapter's *What a Geologist Sees*.

THINK CRITICALLY

What will happen to Ethiopia if the spreading continues?

Think Critically questions ask students to apply what they have learned in order to interpret and explain what they observe in the image.

SELF-TEST

(Check your answers in Appendix D.)

1. The work of geologists over the years has supported Wegener's contention that the current continental masses were assembled into a single supercontinent, which Wegener called _______.
   a. Pangaea
   b. Transantarctica
   c. Gondwana
   d. Tethys
   e. Laurasia
2. Which of the following lines of evidence supporting continental drift did Wegener not use when he first proposed his hypothesis?
   a. the apparent fit of the continental margins of Africa and South America
   b. ancient glacial deposits of the southern hemisphere
   c. the apparent polar wandering of the magnetic north pole
   d. the close match of ancient geology between West Africa and Brazil
   e. the close match of ancient fossils on continents separated by ocean basins
3. Analysis of apparent polar wandering paths led geophysicists to conclude _______.
   a. that Earth's magnetic poles have wandered all over the globe in the past several hundred million years
   b. that the continents had moved because it is known that the magnetic poles themselves are essentially fixed
   c. that the apparent wandering path of a continent provides a historical record of the position of that continent over time
   d. Both b and c are correct.
4. _______ is the process through which oceanic crust splits and moves apart along a midocean ridge and new oceanic crust forms.
   a. Continental drift
   b. Paleomagnetism
   c. Seafloor spreading
   d. Continental rifting
5. This map shows the age of the seafloor, across the northern extent of the Atlantic Ocean. The Mid-Atlantic Ridge can be seen stretching roughly north–south (in the yellow band) down the middle of the map. Yellow through red colors show rocks of similar age. Number them on the map from 1 (oldest) through 5 (youngest).

Visual end-of-chapter **Self-Tests** pose review questions that ask students to demonstrate their understanding of key concepts.

WHY *VISUALIZING GEOLOGY 4E*?

The goal of *Visualizing Geology 4e* is to introduce students to geology and Earth system science through the distinctive mode of visual learning that is the hallmark of the Wiley Visualizing series. Students will learn that the geologic features we see and experience result from interactions among three grand cycles, which extend from Earth's core to the fringes of our atmosphere: the tectonic cycle, the rock cycle, and the water cycle. We place special emphasis on plate tectonics because it is an organizing principle and a framework that unifies our understanding of geologic activity on our planet.

Case studies throughout the book bring the science of geology into focus in students' everyday lives. We fit current events into a larger picture that explains how Earth works and why such events happen. Students will also learn about how human actions affect Earth systems and vice versa. The unique format of Wiley Visualizing allows us to reinforce the textual content with arresting images that are, in many cases, the next best thing to being there. Geology invites us to travel outside our familiar environment to distant parts of the world. As in previous editions of *Visualizing Geology*, we have had access to some of the best photos, photographers, and photo researchers in the industry. With such a terrific photography and art program, and with features such as *Amazing Places* and *What A Geologist Sees* in every chapter, we seek to instill what words sometimes cannot: a sense of wonder about the planet we call home.

Organization

Visualizing Geology 4e is organized as follows:

- In Chapters 1 through 4 we outline Earth system science as an approach to the study of our planet and our environment. We describe the various kinds of rocks and minerals, explain the ways in which geologists learn about Earth's changes over time, and present the unifying theory of plate tectonics.
- In Chapters 5 and 6 we discuss the hazards of earthquakes and volcanoes and explain how they relate to the tectonic cycle, and the formation of magma, lava, and igneous rock.
- Chapters 7 through 10 describe the major processes of the rock cycle—weathering, erosion, sedimentation, lithification, and metamorphism. In addition, students will learn about folding, faulting, and structural geology, and the basics of geologic maps and cross-sections.
- In Chapters 11 through 13 we turn our attention to the water cycle and explain the ubiquitous effects of water on Earth's surface, underground, and in the atmosphere. We devote a full chapter to deserts and glaciers, the two extreme environments that in recent years have become bellwethers of climate change.
- In Chapter 14 we address the record of climate changes, with up-to-date figures, data, and analysis from the IPCC 5th Assessment Report.
- Finally, Chapters 15 and 16 reintegrate the various parts of the Earth system to draw conclusions about two topics of great interest to students and to society as a whole: the history of life on Earth, and the future of the natural resources on which humanity depends.

Changes in the New Edition

The fourth edition has been updated and modified in response to suggestions and reviews by many of our users. We have added many new examples and case studies; refreshed almost all of the *Where A Geologist Clicks* resources; added new material to the Instructor Resources and student Self-Test Questions; and expanded, deepened, and updated the coverage on many topics.

Remember This! is a new feature that appears several times in each chapter, inviting students to think about the connections between the topics in that chapter and previous chapters of the book. It is extremely important for students to think beyond the structure imposed by the book's chapters, to appreciate the fundamental connections between various Earth processes. New *Ask Yourself* and *Think Critically* exercises also will help students develop their critical analytical skills. And of course, as usual, we have added a number of new *Amazing Places*, chapter-opening vignettes, and *Case Studies*.

We have added new vocabulary terms to our basic Glossary, while retaining our goal of avoiding unnecessarily terminology-heavy language. We also have compiled a Glossary of "Level 2" terms—the terms that are italicized (rather than bolded) throughout the book—and these will be available for use by instructors who want to raise the level of scientific terminology in their courses.

This book is intended as a textbook for an introductory college-level course in geology; it is also used in senior high school-level courses. We try to keep the writing accessible and engaging, but rigorous. Because our emphasis is on physical processes, the book could be used as well for an introductory physical geology or physical geography course. We do not expect that most of the students who read this book will go on to become geologists, but we hope that all readers will come to have a better understanding of, and appreciation for, their home planet. For those students do who want to take further courses in geology—and we hope there are many—we aim to provide a solid, sufficient, and challenging background to do so with confidence.

– the Authors

HOW DOES WILEY VISUALIZING SUPPORT INSTRUCTORS?

Wiley Visualizing Site

The Wiley Visualizing site hosts a wealth of information for instructors using Wiley Visualizing, including ways to maximize the visual approach in the classroom and a white paper titled "How Visuals Can Help Students Learn," by Matt Leavitt, instructional design consultant. Visit Wiley Visualizing at www.wiley.com/college/visualizing.

Wiley Custom Select

Wiley Custom Select gives you the freedom to build your course materials exactly the way you want them. Offer your students a cost-efficient alternative to traditional texts. In a simple three-step process create a solution containing the content you want, in the sequence you want, delivered how you want. Visit Wiley Custom Select at http://customselect.wiley.com.

Book Companion Site www.wiley.com/college/murck

All instructor resources (the Test Bank, PowerPoint presentations, and all textbook illustrations and photos available as chapter PowerPoint slides) are housed on the book companion site (www.wiley.com/college/murck). Student resources include self-quizzes and flashcards.

PowerPoint Presentations (available in *WileyPLUS* and on the book companion site)

A complete set of highly visual PowerPoint presentations—one per chapter—by Karen Savage, California State University, Northridge, and revised for the fourth edition by Amy Mui, University of Toronto, is available online and in *WileyPLUS* to enhance classroom presentations. Tailored to the text's topical coverage and learning objectives, these presentations are designed to convey key text concepts, illustrated by embedded text art. We offer three different types of PowerPoint presentations for each chapter: PowerPoints with just the text art and PowerPoints with text art and presentation notes.

Test Bank (available in *WileyPLUS* and on the book companion site)

The visuals from the textbook are also included in the Test Bank by Richard Josephs, Plymouth State University, who also authored the Pre-Lecture Clicker questions. The Test Bank has a diverse selection of test items, including multiple-choice and essay questions, with at least 20 percent of them incorporating visuals from the book. The test bank is available online in MS Word files, and within *WileyPLUS*.

Art PowerPoints

All photographs, figures, maps, and other visuals from the text are online and in *WileyPLUS* and can be used as you wish in the classroom. These online electronic files allow you to easily incorporate images into your PowerPoint presentations as you choose, or to create your own handouts.

HOW HAS WILEY VISUALIZING BEEN SHAPED BY CONTRIBUTORS?

Wiley Visualizing and the *WileyPLUS* learning environment would not have come about without lots of people, each of whom played a part in sharing their research and contributing to this new approach.

Academic Research Consultants

Richard Mayer, Professor of Psychology, UC Santa Barbara. His *Cognitive Theory of Multimedia Learning* provided the basis on which we designed our program. He continues to provide guidance to our author and editorial teams on how to develop and implement strong, pedagogically effective visuals and use them in the classroom.

Jan L. Plass, Professor of Educational Communication and Technology in the Steinhardt School of Culture, Education, and Human Development at New York University. He co-directs the NYU Games for Learning Institute and is the founding director of the CREATE: Consortium for

Research and Evaluation of Advanced Technology in Education.

Matthew Leavitt, Instructional Design Consultant. He advises the Visualizing team on the effective design and use of visuals in instruction and has made virtual and live presentations to university faculty around the country regarding effective design and use of instructional visuals.

Independent Research Studies

SEG Research, an independent research and assessment firm, conducted a national, multisite effectiveness study of students enrolled in entry-level college Psychology and Geology courses. The study was designed to evaluate the effectiveness of Wiley Visualizing. You can view the full research paper at www.wiley.com/college/visualizing/huffman/efficacy.html.

Instructor and Student Contributions

Throughout the process of developing the concept of guided visual pedagogy for Wiley Visualizing, we benefited from the comments and constructive criticism provided by the instructors and colleagues listed below. We offer our sincere appreciation to these individuals for their helpful reviews and general feedback:

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Brian Skinner was born and raised in Australia, studied at the University of Adelaide in South Australia, worked in the mining industry in Tasmania, and in 1951 entered the Graduate School of Arts and Sciences, Harvard University, from which he obtained his Ph.D. in 1954. Following a period as a research scientist in the United States Geological Survey in Washington D.C., he joined the faculty at Yale in 1966, where he continues his teaching and research as the Eugene Higgins Professor of Geology and Geophysics. Brian Skinner has been president of the Geochemical Society, the Geological Society of America, and the Society of Economic Geologists. He holds an honorary Doctor of Science from the University of Toronto and an honorary Doctor of Engineering from the Colorado School of Mines.

THANKS FOR PARTICIPATING IN A SPECIAL PROJECT

The *Visualizing* series continues to grow, and continues to meet the needs of students and professors in the U.S., Canada, and around the world. The groundbreaking series, demonstrated to improve student learning and engagement, now includes 14 titles, three of them in their fourth edition. With the fourth edition of *Visualizing Geology*, we know that we will find many new ways to engage and inspire our readers.

As usual, many highly professional colleagues at John Wiley & Sons and associated organizations have contributed their efforts and expertise to this book, and we owe them all a huge debt of gratitude. All of these people have been so helpful and so involved, it is difficult to single out any one of them—but we will do it anyway. We just want give a little shout-out to Ryan Flahive as he bids farewell to Geology and Geography to move to his new home as Executive Editor in Biology. We'll miss you, Ryan!

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– Brian Skinner and Barbara Murck

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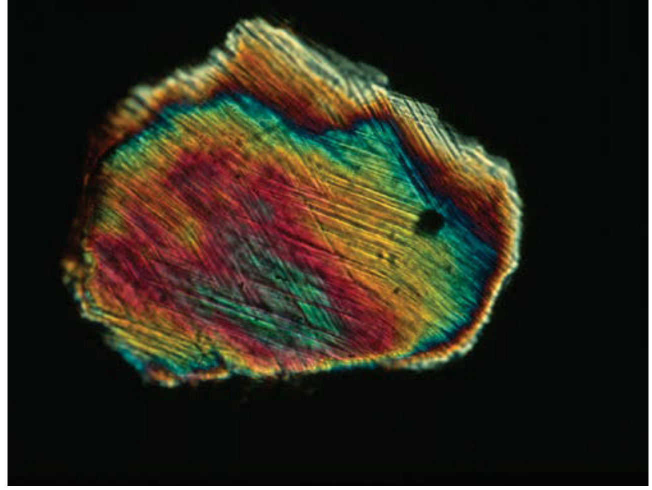

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Amazing Places

In every chapter in this book, we take you to an "Amazing Place" that is both beautiful and of geologic interest.

Here is our itinerary:

Chapter 1: Meteorite Impact Craters, to see evidence of the way Earth was assembled
Chapter 2: Naica Mine in Chihuahua, Mexico, for a look at the world's largest crystals
Chapter 3: Famous Unconformities, to see evidence of ancient uplift and erosion
Chapter 4: The Hawaiian Islands, to see plate tectonics and volcanoes in action
Chapter 5: Point Reyes, California, to explore the most famous fault in America, the San Andreas fault
Chapter 6: Sierra Nevada Batholith and Yosemite National Park, for examples of processes that formed the batholith
Chapter 7: Mt. Monadnock—and Monadnocks, for a look at the power of erosion
Chapter 8: The Navajo Sandstone, for its beautiful sedimentary rock formations
Chapter 9: The Canadian Rockies, for spectacular examples of folding and thrusting
Chapter 10: The Source of Olmec jade, for evidence of high-pressure metamorphism
Chapter 11: Lechuguilla Cave, in New Mexico, for incredible shapes made by groundwater
Chapter 12: The Florida Keys Reef, to visit a geologic formation that is also alive
Chapter 13: The Northwest Passage, Alaska, to explore the successful and unsuccessful sailings through the centuries
Chapter 14: Fossil Forests of the High Arctic, to see remarkable preservation of forests that grew in the now-frozen north
Chapter 15: The Burgess Shale, for its fossil record of the first animals on Earth
Chapter 16: Saugus Iron Works, Massachusetts, to see the first iron-smelting operation in North America

The most amazing place of all, however, is Earth itself—the only world in the universe where we know that life exists.

NASA

1 EARTH AS A PLANET

CHAPTER OUTLINE

Goddard Institute for SpaceStudies/NASA

THE BLUE MARBLE

Photographs of Earth from space have profoundly influenced our thoughts about Earth. Getting a whole-Earth photograph is difficult—planes don't do the job; you must be out in space, and the Sun has to be directly behind the camera so that Earth is shadow free. A striking whole-Earth photograph was taken by the *Apollo 17* astronauts on their way to the Moon in 1972. When they were 45,000 kilometers out, they looked back, and there was the fully illuminated Earth, like a blue marble suspended in space. The name stuck. NASA now has a stunning group of whole-Earth images called the Blue Marble series.

This particular version of a blue marble image was obtained in 1997. It is one of the most detailed images ever made of Earth. There is a huge storm off the west coast of North America—it is Hurricane Linda—and the Moon is rising over Earth in the upper left. Hurricane Linda reminds us that the different parts of Earth—rocks, water, atmosphere, living things—all interact. The Moon reminds us that Earth is a member of the solar system. To know Earth, we must understand its parts and the system to which it belongs.

✓ CHAPTER PLANNER

- Study the picture and read the opening story.
- Scan the Learning Objectives in each section: p. 2 p. 12 p. 20
- Read the text and study all visuals. Answer any questions.

Analyze key features
- Geology Insight, p. 3
- What a Geologist Sees, p. 8
- Case Study, p. 11
- Process Diagram, p. 14 p. 17 p. 22
- Amazing Places, p. 16
- Stop: Answer the Concept Checks before you go on: p. 12 p. 19 p. 24

End of chapter
- Review the Summary and Key Terms.
- Answer the Critical and Creative Thinking Questions.
- Answer What is happening in this picture?
- Complete the Self-Test and check your answers.

WHAT IS GEOLOGY?

Learning Objectives

1. **Describe** some of the branches of geology.
2. **Explain** how scientists use the scientific method.
3. **Explain** what is meant by a systems approach to geology.
4. **Explain** how Earth's major subsystems interact, using the concept of cycles.

The word **geology** comes from two Greek roots: *geo-,* meaning "Earth," and *logis,* meaning "study" or "science." The science called geology encompasses the study of our planet: how it formed; the nature of its interior; the materials of which it is composed; its water, glaciers, mountains, and deserts; its earthquakes and volcanoes; its resources; and its history—physical, chemical, and biological. Scientists who make a career of geology are geologists. Geology, like all other sciences, is based on factual observations, testable hypotheses, reproducible procedures, and open communication of information.

geology The scientific study of Earth.

The Branches of Geology

The study of geology is traditionally divided into two broad subject areas: physical geology and historical geology. **Physical geology** is concerned with understanding the *processes* that operate at or beneath the surface of Earth and the *materials* on which those processes operate. Some examples of geologic processes are mountain building, volcanic eruptions, earthquakes, river flooding, and the formation of ore deposits. Some examples of materials are minerals, soils, rocks, air, and water.

Historical geology, on the other hand, is concerned with the sequence of *events* that have occurred in the past. These events can be inferred from the evidence left in Earth's rocks. Through the findings of historical geology, scientists seek to resolve questions such as the following: When did the oceans form? Why did the dinosaurs die out? When did the Rocky Mountains rise? and When and where did the first trees appear? Historical geology gives us a perspective on the past. It also establishes a context for thinking about present-day changes in our natural environment. This book is concerned mainly with physical geology, but it includes many lessons we can learn from historical geology.

Within the traditional domains of physical and historical geology are many specialized disciplines, some of which are illustrated in **Figure 1.1**. Economic geology, for example, is concerned with the formation and occurrence of, and the search for, valuable mineral deposits. Environmental geology focuses on how materials and processes in the natural geologic environment affect—and are affected by—human activities. Volcanologists study volcanoes and eruptions, past and present; seismologists study earthquakes; mineralogists undertake the microscopic study of minerals and crystals; paleontologists study fossils and the history of life on Earth; structural geologists study how rocks break and bend. These specialties are needed because geology encompasses a broad range of topics.

To a certain extent we are all geologists, even though only a few of us make a career out of geology. Everyone living on this planet relies on geologic resources: water, soil, building stones, metals, fossil fuels, gemstones, plastics (from petroleum), ceramics (from clay minerals), glass (from silica sand), salt (a mineral called halite), and many others. Geologic processes affect us every day. Sometimes we must make decisions based on our understanding of geology, such as how to manage erosion of a coastal property, or whether to buy a home located on a cliff or next to a river. We also influence the geologic environment through our daily activities, whether we are drinking water that came from an aquifer, digging a trench, or planting trees to control soil erosion. This book will help you to become better informed and more mindful of these interactions. As a result, you will be better equipped to make decisions about Earth materials and processes that affect your life.

Science and the Scientific Method

Science is an approach that we use to study, observe, classify, investigate, test, and understand the behavior and characteristics of the world around us. The term *science* also refers to the vast body of knowledge about the natural world that has been built up, little by little, over many centuries of systematic investigation by scientists. **Technology** is the application of scientific knowledge for practical purposes. Civilization and our entire modern way of life are based on this body of knowledge and its applications.

science A systematic approach to studying the natural world.

Scientific knowledge changes constantly; it grows and evolves through testing, interpretation, discussion, and reexamination. When scientists appear to argue or debate their findings, it means that science is working as it should: Scientists tear apart and debate each other's work to test the validity and robustness of the interpretations. It is difficult or even impossible for scientists to be completely detached from the materials and processes they are studying, but they strive to be as objective as they can be. Each new interpretation is grounded in the context of the scientific understanding that preceded it. The entire body of scientific knowledge is open to be studied and tested by anyone who is willing to put in the effort to do so.

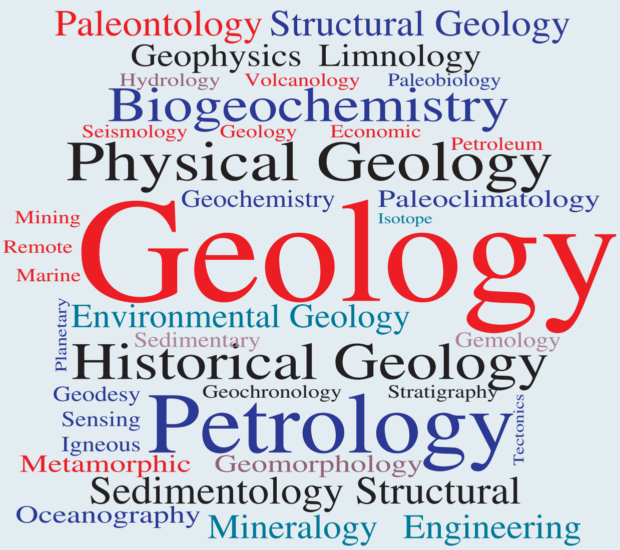
Geology InSight — Faces and places of geology • Figure 1.1

THE PLANNER

Geologists are privileged to work in some of the most exotic places on Earth—and beyond.

NASA

a. Harrison (Jack) Schmitt, a planetary geologist, is the only scientist (so far) to walk on the Moon, for the *Apollo 17* mission in 1972. Here, he is collecting a lunar sample to take back to Earth.



b. Volcanologists get uncomfortably close to the 2002 eruption of Mount Etna in Sicily, Italy, to record the sounds of the eruption.

Peter Carsten/NG Image Collection

Maria Stenzel/NG Image Collection

c. Climatologists collect an ice core from a floe off thecoast of Antarctica. Ice samples can tell us about the changes in Earth's climate over hundreds or thousands of years.

Jonathan Blair/NG Image Collection

d. A paleontologist dives into the waters off the Bahama Islands to study stromatolites, a living algal formation reminiscent of Earth's oldest fossils.

Jim Richardson/NG Image Collection

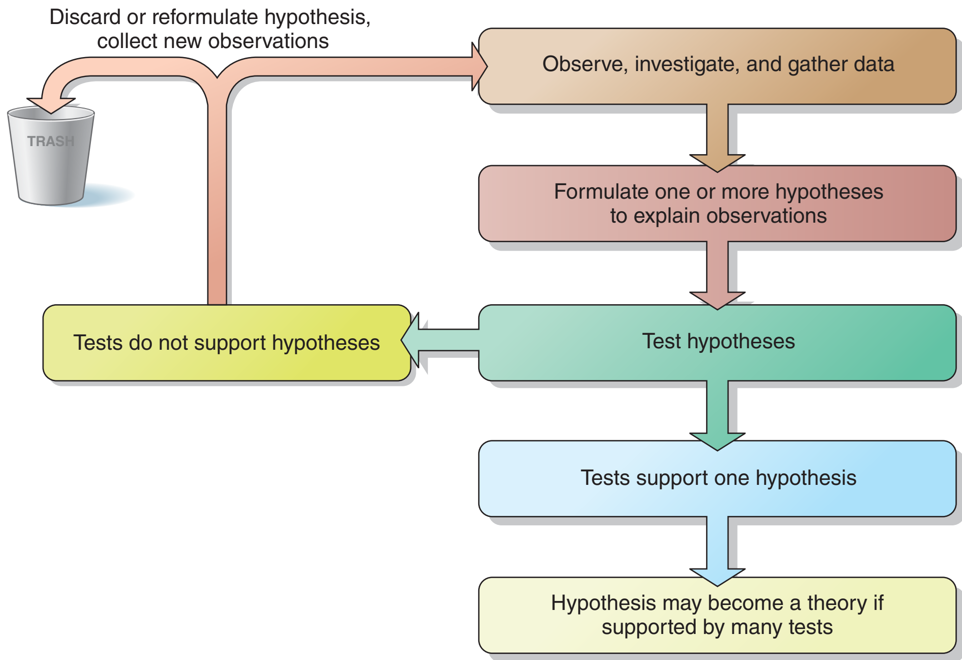
e. A seismologist (expert on earthquakes) inspects one of the fissures that opened up in the Santa Cruz Mountains in California during the Loma Prieta earthquake of 1989.

THINK CRITICALLY

Which of these examples represent physical geology, and which represent historical geology? Do some of them include aspects of both physical and historical geology?

Using the scientific method • Figure 1.2

This is a schematic diagram of the scientific method. The formation of a theory occurs only at the end, after many investigations and confirmation by many different scientists.



Like all other scientists, geologists use a logical research strategy called the **scientific method**, which has developed through trial and error over many years. The scientific method is based on observations and the collection of evidence that can be seen and tested by anyone who cares to do so. Although it varies in details, it includes the basic steps outlined in **Figure 1.2**.

> **scientific method** The way a scientist approaches a problem; the steps include observing, formulating a hypothesis, testing, and evaluating results.

Let's consider how the scientific method might be applied in a real geologic situation.

Observe and gather data. Scientists start with a question and acquire trustworthy evidence about it, especially measurements. In **Figure 1.3**, a geologist asks the question "How did this group of rocks form?" She observes and measures the sequence of layered rocks in question. She sees that the layers are *horizontal* and *parallel*—important clues. Furthermore, each layer consists of innumerable *small grains*, and the size of the grains varies from layer to layer but is approximately the same within each layer.

Formulate a hypothesis. Scientists explain their observations by developing a **hypothesis**. The geologist in our example develops three hypotheses. She hypothesizes that the rocks were formed from material that was transported and deposited where she has found it; but how was it transported? Hypothesis 1 is that a *glacier* was the transporting agent. Hypothesis 2 is that *wind* did the transporting. Hypothesis 3 is that *water* did the transporting.

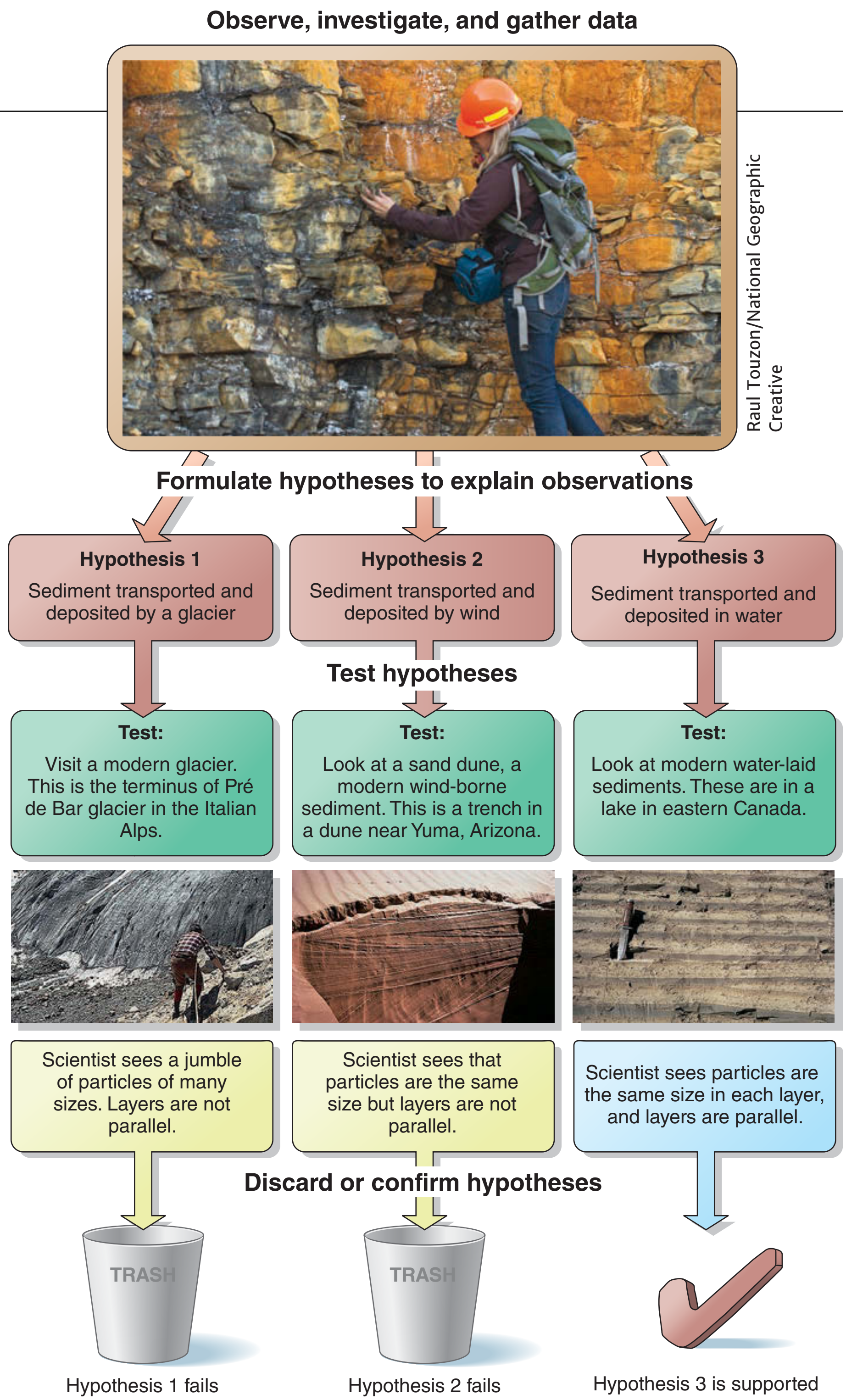
> **hypothesis** A plausible but yet-to-be-proved explanation for how something happens.

A scientist's hypotheses are often influenced by prior experience or knowledge. In Chapters 7 and 8 you will learn why the three hypotheses in our current example are reasonable explanations. Note that the scientist does not have to select one hypothesis at this point. In fact, choosing a "leading candidate" too early may prejudice the scientist and cause her to overlook some relevant clues. T. C. Chamberlin, a 19th-century geologist, argued that scientists should consider *all* reasonable explanations—an approach he called the "method of multiple working hypotheses."

Test the hypotheses. Scientists use a hypothesis—or multiple hypotheses—to make predictions and to develop tests. The tests may involve controlled experiments in a laboratory, further observations and measurements in the field, or possibly the development of a mathematical model. Geologists in particular like to test their hypotheses against real observations. Here's how our geologist tests the hypotheses:

- She travels to a modern glacier and studies the jumble of debris it deposits. She notes that the grains are different sizes, all mixed up, and not in neatly defined layers. So, Hypothesis 1 fails.
- Then the geologist goes to a desert region where she sees wind-transported material deposited in dunes. She observes that particle sizes are approximately the same, but they aren't in parallel layers; the layers are at odd angles. So, Hypothesis 2 fails.

Formulating and testing hypotheses • Figure 1.3



Top, the geologist observes and measures rock layers that are parallel. She also sees that the particles within each layer have a uniform size.

Middle, the geologist formulates three hypotheses about how the layers might have formed. She then tests the hypotheses by visiting three geologic sites.

Bottom, she concludes that the tests do not support the first two hypotheses. The third hypothesis best explains the observations.

(Inset from left to right: Courtesy Stephen C. Porter; University of Washington Libraries, Special Collections, John SheltonCollection, KC9807; Courtesy Stephen C. Porter)

- Finally, our scientist visits a lake and observes materials transported by a river and deposited in lake water. Now she sees layers that are parallel, and the particles in each layer are approximately the same size. Hypothesis 3 has potential, but more testing is needed.

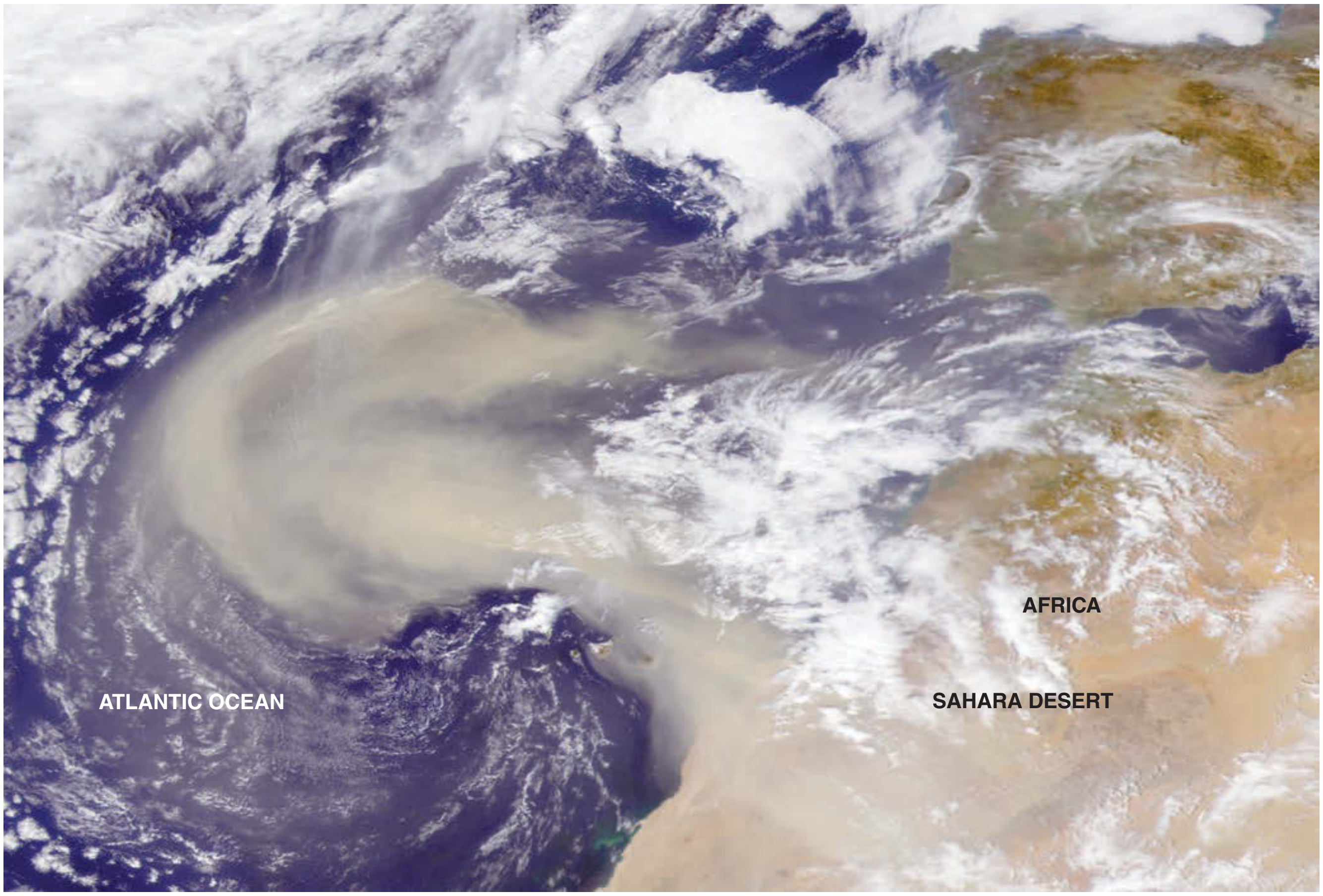
Retest, test again, and formulate a theory. While visiting the lake, our scientist notes that plants are growing in the lake. To further verify Hypothesis 3, she takes an additional step and hypothesizes that if the material that formed the rocks really was deposited in a lake, the remains of aquatic plants might still be present. If, on further observation, she finds fossilized freshwater plant remains in the layered rocks, she will be even more confident that she is on the right track. Verification of Hypothesis 3 is now stronger.

Once a hypothesis has withstood numerous tests, scientists become more confident in its validity. If it becomes clear that the hypothesis has withstood testing and retesting, and that it has general applicability to more than one specific circumstance, it may be elevated to a **theory**. This is still not

> **theory** A hypothesis that has been tested and is strongly supported by experimentation, observation, and scientific evidence.

Earth from space • Figure 1.4

Satellite images can reveal interactions among Earth systems. In this photo, dust storms from the Sahara Desert blow far out into the Atlantic. Geologists have found African dust all the way across the Atlantic Ocean, and some think that it might contribute to the death of coral reefs off the coast of Florida and elsewhere.



Courtesy NASA

the final word, however; a theory is always open to further testing. (*Note*: In everyday speech, people often misuse the term *theory* to mean "hypothesis" by saying dismissively, "That's just a theory." What they really mean is, "That's just a hypothesis." In science, by the time a statement attains the stature of a theory, it is very substantial and must be taken seriously.)

Ultimately, a theory or group of theories that are widely applicable may be formulated into a **law** or **principle**. Laws and principles are statements about some natural phenomenon invariably observed to happen in the same way, and no deviations have ever been observed. For example, in geology the law of original horizontality states that sediment deposited in water is always in horizontal layers (or nearly so, because a lake or seafloor might have slight irregularities) and the layers are parallel to Earth's surface (or nearly so). No exceptions have ever been observed.

Earth System Science

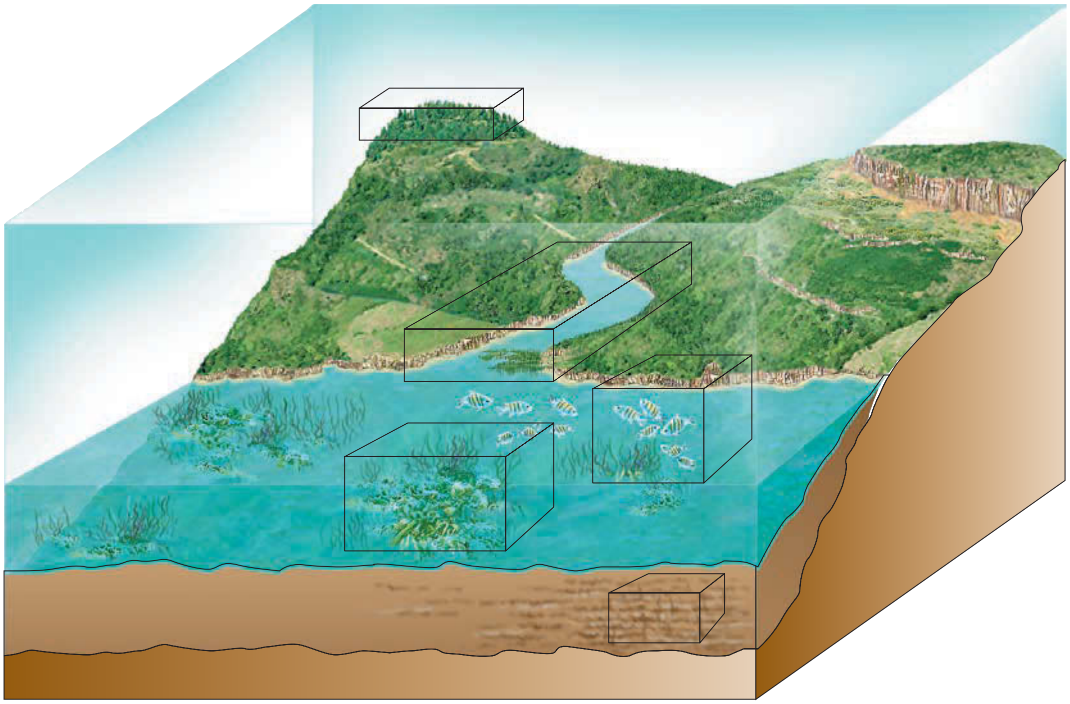
Traditionally, scientists have studied Earth by focusing on separate units—the atmosphere, the oceans, or a single mountain range—in isolation from the other units. However, the first photographs of Earth taken from space (like the chapter-opening photograph) caused a dramatic rethinking of this traditional view. For the first time, it was possible to see the whole planet in one sweeping view. We could see everything at a glance—clouds, oceans, polar ice caps, and continents—all at the same time and in their proper scale. The astronauts, like the rest of us, marveled at Earth's "overwhelming beauty . . . the stark contrast between bright colorful home and stark black infinity" (Rusty Schweikart, *Apollo 9*).

Yet from space it was also clear how small Earth is—just a dust speck compared to the vastness of the solar system and the universe. On such a small planet, it no longer made sense to study all the pieces separately. There was only one geology that mattered, not the geology of America or the Atlantic Ocean but the geology of the whole Earth.

Instruments carried by satellites in space have also given us new ways to study the relationships of the parts on a global scale, as we never could before (**Figure 1.4**). This new, more all-inclusive view of geology is called **Earth system science**.

Systems • Figure 1.5

This figure shows a variety of systems and smaller subsystems. The entire diagram—mountains, river, and lake—illustrates one kind of system: a coastal watershed. The individual pieces enclosed by boxes, such as the river, are also systems. Even small volumes of water or lake sediment (foreground boxes) are systems in their own right.



The System Concept A systems approach is a helpful way to break down a large, complex problem into smaller pieces that are easier to study without losing sight of the connections between those pieces. The scientific definition of a **system** allows the observer to choose the boundaries and limitations of the system. That is why a system is only a concept; you choose its limits for the convenience of your study. A system may be large or small, simple or complex (**Figure 1.5**). It could be the contents of the beaker in a laboratory experiment or the contents of an ocean. A leaf is a system, but it is also part of a larger system (a tree), which is part of a still larger system (a forest).

system A portion of the universe that can be isolated for the purpose of observing and measuring change.

The fact that we distinguish a system from the rest of the universe for specific study does not mean that we ignore its surroundings. In fact, the nature of a system's boundaries is one of its most important defining characteristics, and it helps us understand how a system is influenced by its surroundings. For example, a **closed system** has boundaries that do not allow any matter to enter or escape the system. The boundaries may (and in the real world, always do) allow energy, such as sunlight, to pass through. An example of a closed system would be a perfectly sealed oven, which would allow the material inside to be heated but would not allow any of that material to escape. (Note that in real life, ovens do allow some vapor to escape, so they are not perfect examples of closed systems.)

A second kind of system, an **open system**, can exchange *both* matter and energy across its boundaries. An island offers a simple example (see *What a Geologist Sees* on the next page). The system concept can also be applied to artificial environments. For example, urban geographers and land-use planners sometimes use a systems approach in the study of cities. Enormous flows of energy and materials occur across city borders, both in and out.

The Earth System Earth itself is a very close approximation of a closed system. Energy enters the Earth system as solar radiation. The energy is used in various biologic and geologic processes and then departs in the form of heat. Very little matter crosses the boundaries of the Earth system. We do lose some hydrogen and helium atoms from the outer atmosphere, and we gain some material in the form of meteorites. However, for most purposes, especially over the short term, we can treat Earth as a closed system.

The fact that Earth is a closed system (on the scale of the time that humans have existed) has three important consequences. First, *because the amount of matter in a closed system is fixed and finite,* the mineral and fossil fuel resources on this planet are all we have and all we will ever have until we learn to mine other planets. Second, *all the*

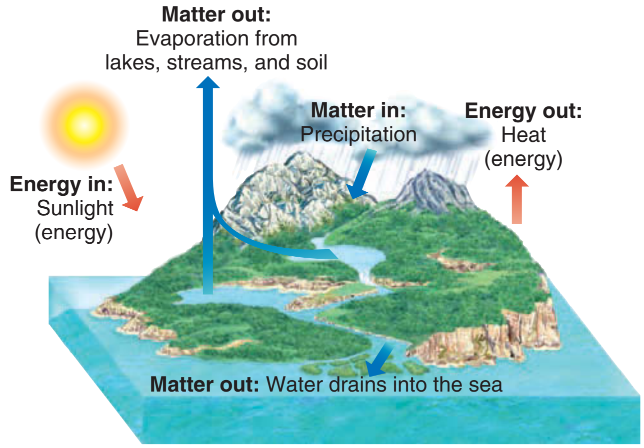
What a Geologist Sees

THE PLANNER

An Island Is Not a Closed System

To a casual tourist, the island of Bora Bora (shown here, left) may seem like a closed system, isolated from the rest of the world, a great place to "get away from it all." But how isolated is it, really?

Todd Gipstein/NG Image Collection



A geologist would look at this volcanic island and see the forested slopes as evidence of abundant precipitation; the flat area between the mountain and the sea as evidence of erosion transferring material from the mountain toward the sea; and, in the foreground, coral reefs growing on the shallow, submerged part of the island as evidence of warm waters and plentiful nutrients. A geologist, like all other scientists, would conclude that the island is an open system.

Recall that an open system allows both matter and energy to cross its boundaries. Energy (in the form of sunlight) and matter (in the form of precipitation) reach the island from outside sources. Energy leaves the island as heat. Matter in the form of water either evaporates or drains into the sea. Birds may fly into and out of the system. In the modern era, humans may also bring materials into and out of the system by importing and exporting resources. In all of these ways, the system exchanges matter and energy with its surroundings.

THINK CRITICALLY

Bora Bora (shown in the photo) is a volcanic island. The volcano is considered to be extinct, but suppose it were just dormant and waiting to erupt again. How would you modify the diagram to describe the inputs and outputs of matter and energy during an eruption?

waste materials we develop remain within the confines of the Earth system; or, as environmentalists say, "There is no away to throw things to." Third, *if changes are made in one part of a closed system, the results of those changes eventually will affect other parts of the system.* For instance, when we divert a river to provide drinking water for a city, we may deplete the water resources somewhere else (**Figure 1.6**).

Earth's Interconnected Subsystems

The Earth system can be divided into four very large subsystems: the **geosphere**, **biosphere**, **atmosphere**, and **hydrosphere** (**Figure 1.7**). These can be further subdivided into many subsystems of interest to geologists; for example, the hydrosphere consists of oceans, glacial ice, streams, lakes, groundwater, and so on.

geosphere The solid Earth, as a whole.

biosphere The system consisting of all living and recently dead organisms on Earth.

atmosphere The envelope of gases that surrounds Earth.

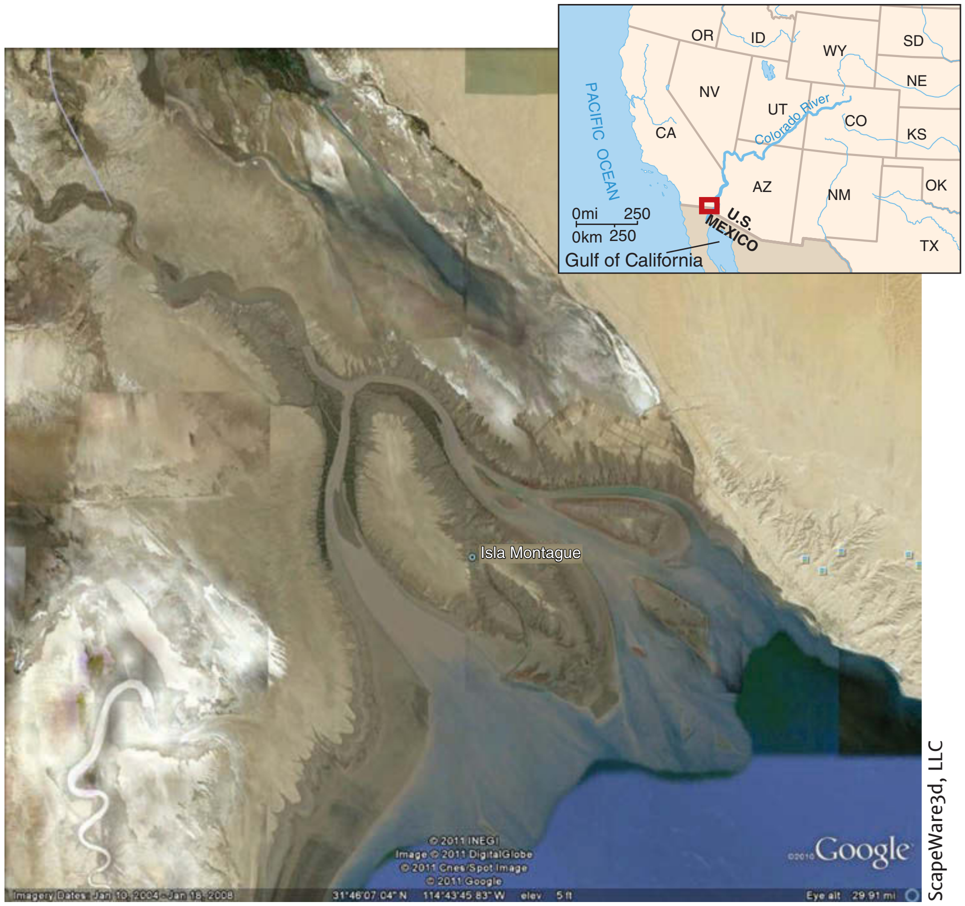
hydrosphere The system comprising all of Earth's bodies of water and ice, both on the surface and underground.

The geosphere may come to mind as being most important for geologists, but in fact all four spheres play important roles in geology. Plants draw nutrients from the lithosphere and incorporate them into the biosphere. When they die and decompose, the material they contain may enter the atmosphere or return to the lithosphere. Rocks erode, and the minerals they contain become salts in the hydrosphere; evaporation returns these salts to the geosphere. The exchanges of materials between spheres never stop.

The four major Earth reservoirs interact most intensively in a narrow **life zone**, a region that extends to about 10 kilometers above and

Upstream changes have downstream impacts • Figure 1.6

The Colorado River and its tributaries provide drinking water to 25 million people and irrigate 1.4 million hectares of agricultural fields. Because of massive upstream diversions, little water makes it all the way to the Gulf of California in Mexico. Consequently, the river has become a broad mudflat where it enters the gulf, as seen in this photo. This demonstrates how changes made in one part of a system eventually affect other parts of the system.



ScapeWare3d, LLC

Earth's subsystems: The four "spheres" • Figure 1.7

Earth's four principal subsystems are the geosphere, biosphere, atmosphere, and hydrosphere. Both matter and energy cycle among these subsystems, making them open systems.