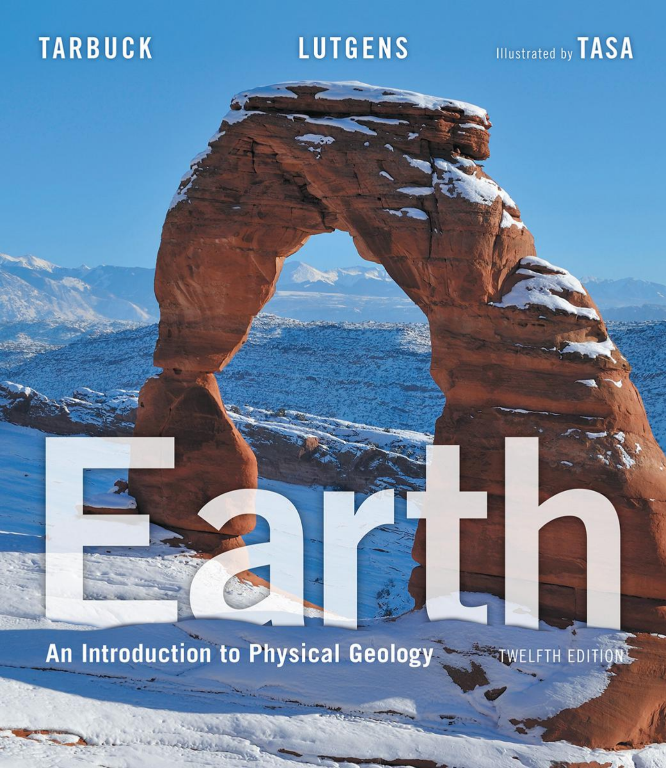
TARBUCK LUTGENS Illustrated by TASA

Earth

An Introduction to Physical Geology

TWELFTH EDITION



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An Introduction to Physical Geology

EDWARD J. TARBUCK

FREDERICK K. LUTGENS

Illustrated by

DENNIS TASA

PEARSON

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To Our Grandchildren

Shannon, Amy, Andy, Ali, and Michael

Allison and Lauren

Each is a bright promise for the future.

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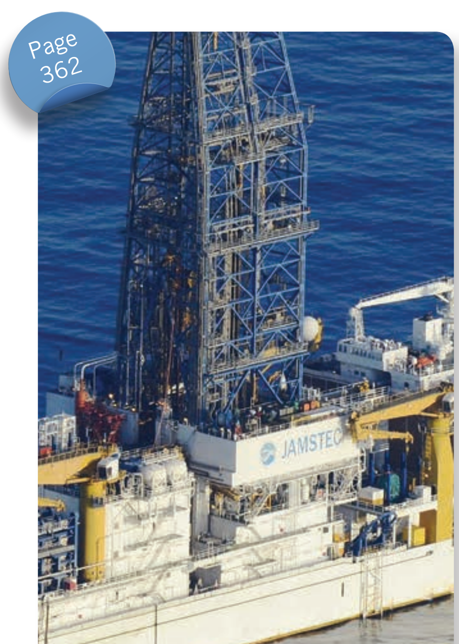
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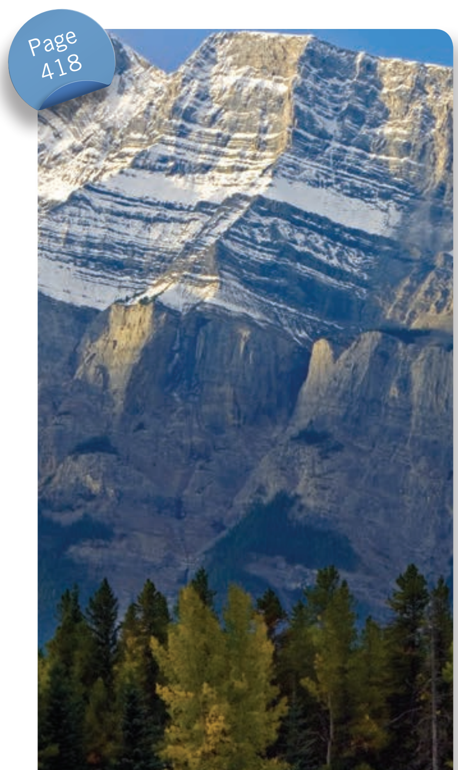
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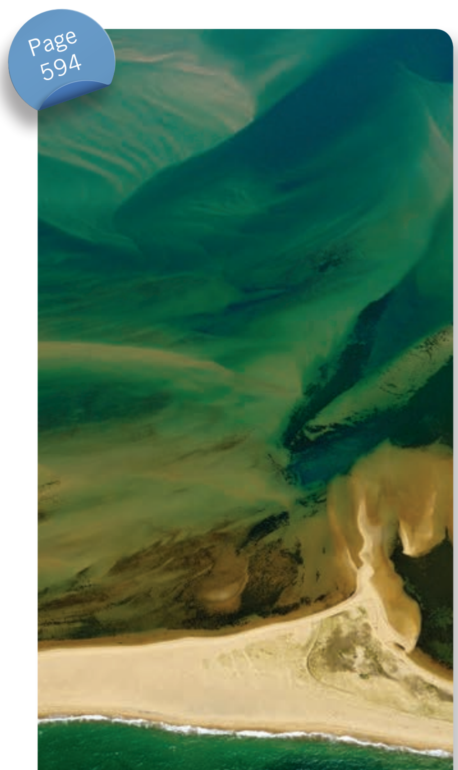

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SmartFigures

Using a cutting-edge technology called augmented reality, Pearson's BouncePages app launches engaging, interactive videos and animations that bring textbook pages to life. Use your mobile device to scan a SmartFigure identified by the BouncePages icon, and an animation/video/interactive illustrating the SmartFigure's concept launches immediately. No slow websites or hard-to-remember logins required. BouncePages' augmented reality technology transforms textbooks into convenient digital platforms, breathes life into your learning experience, and helps you grasp difficult academic concepts. Learning geology from a textbook will never be the same.

Preface

Earth is a very small part of a vast universe, but it is our home. It provides the resources that support our modern society and the ingredients necessary to maintain life. Knowledge of our physical environment is critical to our well-being and vital to our survival. A basic geology course can help a person gain such an understanding, and can also take advantage of the interest and curiosity many of us have about our planet—its landscapes and the processes that create and alter our physical environment.

This 12th edition of *Earth: An Introduction to Physical Geology*, like its predecessors, is a college-level text that is intended to be a meaningful, nontechnical survey for students taking their first course in geology. In addition to being informative and up-to-date, a major goal of *Earth* is to meet the need for a readable and user-friendly text, a book that is a highly usable tool for students learning the basic principles and concepts of geology.

Although many topical issues are examined in the 12th edition of *Earth*, it should be emphasized that the main focus of this new edition remains the same as the focus of earlier editions: to promote student understanding of basic principles. As much as possible, we have attempted to provide the reader with a sense of the observational techniques and reasoning processes that constitute the science of geology.

New and Important Features

The 12th edition represents an extensive and thorough revision of *Earth* that integrates improved textbook resources with new online features to enhance the learning experience,

- **Significant updating and revision of content.** A basic function of a college science textbook is to present material in a clear, understandable way that is accurate, engaging, and up-to-date. In the long history of this textbook, our number-one goal has always been to keep *Earth* current, relevant, and highly readable for beginning students. To that end, every part of this text has been examined carefully. Many discussions, case studies, examples, and illustrations have been updated and revised.
- **SmartFigures that make *Earth* much more than a traditional textbook.** Through its many editions, an important strength of *Earth* has always been clear, logically organized, and well-illustrated explanations. Now, complementing and reinforcing this strength are a series of SmartFigures. Simply by scanning a SmartFigure with a mobile device and **Pearson's BouncePages Augmented Reality app** (FREE and available for iOS and Android), students can link to hundreds of unique and innovative digital learning opportunities that will increase their insight and understanding of important ideas and concepts. We have also placed short URLs in the caption for every SmartFigure. This will ensure that students who may not have a smart phone, will have the ability to access these videos easily. SmartFigures are truly art that teaches! This 12th edition of *Earth* has more than 200 SmartFigures, of five different types:
  1. **SmartFigure Tutorials.** Each of these 2- to 4-minute tutorials, prepared and narrated by Professor Callan Bentley, is a mini-lesson that examines and explains the concepts illustrated by the figure
  2. **SmartFigure Mobile Field Trips.** Scattered throughout this new edition are 24 video field trips that explor classic geologic sites from Iceland to Hawaii. On each trip you will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to see and learn about landscapes that relate to discussions in the chapter.
  3. **SmartFigure Condor Videos.** The 10 *Condor* videos take you to sites in the American West. By coupling aerial footage acquired by a quadcopter aircraft with ground-level views, effective narratives, and helpful animations, these videos will engage you in real-life case studies.
  4. **SmartFigure Animations.** Scanning the many figures with this designation brings art to life. These animations and accompanying narrations illustrate and explain many difficult-to-visualize topics and ideas more effectively than static art alone.
  5. **SmartFigure Videos.** Rather than providing a single image to illustrate an idea, these figures include short video clips that help illustrate such diverse subjects as mineral properties and the structure of ice sheets.

As mentioned, please visit your iOS or Android App Stores to download the FREE Pearson BouncePages App. By scanning one of the two QR codes to the right, you will be taken directly to the BouncePages App.

Android Store iTunes App Store

- **Enhanced Modular, learning objective-driven, active learning path.** *Earth* is designed for learning. Every chapter begins with *Focus on Concepts*. Each numbered learning objective corresponds to a major section in the chapter. The statements identify the knowledge and skills students should master by the end of the chapter and help students prioritize key concepts. Within the chapter, each major section concludes with *Concept Checks* that allow students to check their understanding and comprehension of important ideas and terms before moving on to the next section. Two end-of-chapter features complete the learning path. *Concepts in Review* coordinates with the *Focus on Concepts* at the start of the chapter and with the numbered sections within the chapter. It is a concise overview of key ideas, with photos, diagrams, and questions that help students focus on important ideas and test their understanding of key concepts. Chapters conclude with *Give It Some Thought* questions that challenge learners by involving them in activities that require higher-order thinking skills, such as application, analysis, and synthesis of chapter material.

- **An unparalleled visual program.** In addition to more than 100 new, high-quality photos and satellite images, dozens of figures are new or have been redrawn by the gifted and highly respected geoscience illustrator Dennis Tasa. Maps and diagrams are frequently paired with photographs for greater effectiveness. Further, many new and revised figures have additional labels that narrate the process being illustrated and guide students as they examine the figures. *Earth*'s visual program is clear and easy to understand.
- **MasteringGeology.** MasteringGeology delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help students learn course material and understand difficult concepts. Assignable activities in MasteringGeology include SmartFigure (Tutorial, Condor, Animation, Mobile Field Trip, Video) activities, GigaPan activities, Encounter Earth activities using Google Earth, GeoTutor activities, Geoscience Animation activities, GEODe tutorials, and more. MasteringGeology also includes all instructor resources and a robust Study Area with resources for students.

The Teaching and Learning Package

MasteringGeology™ with Pearson eText

Used by over 1 million science students, the Mastering platform is the most effective and widely used online tutorial, homework, and assessment system for the sciences. Now available with *Earth*, 12th edition, **MasteringGeology™** offers tools for use before, during, and after class:

- **Before class:** Assign adaptive Dynamic Study Modules and reading assignments from the eText with Reading Quizzes to ensure that students come prepared to class, having done the reading.
- **During class:** Learning Catalytics, a "bring your own device" student engagement, assessment, and classroom intelligence system, allows students to use a smartphone, tablet, or laptop to respond to questions in class. With Learning Catalytics, you can assess students in real-time, using open-ended question formats to uncover student misconceptions and adjust lectures accordingly.
- **After class:** Assign an array of assessment resources such as Mobile Field Trips, Project Condor tutorials, Interactive Simulations, GeoDrone activities, Google Earth Encounter Activities, and much more. Students receive wrong-answer feedback personalized to their answers, which will help them get back on track.

MasteringGeology Student Study Area also provides students with self-study materials like geoscience animations, *GEODe: Earth* activities, *In the News* RSS feeds, Self Study Quizzes, Web Links, Glossary, and Flashcards.

For more information or access to MasteringGeology, please visit www.masteringgeology.com.

Instructor's Resource Materials (Download Only)

The authors and publisher have been pleased to work with a number of talented people who have produced an excellent supplements package.

Instructor's Resource Materials (IRM)

The IRM puts all your lecture resources in one easy-to-reach place:

- *All* of the line art, tables, and photos from the text in .jpg files
- PowerPoint presentations
  - The IRM provides three PowerPoint files for each chapter. Cut down on your preparation time, no matter what your lecture needs, by taking advantage of these components of the PowerPoint files:
- **Exclusive art.** All of the photos, art, and tables from the text, in order, loaded into PowerPoint slides.
- **Lecture outlines.** This set averages 50 slides per chapter and includes customizable lecture outlines with supporting art.
- **Classroom Response System (CRS) questions.** Authored for use in conjunction with classroom response systems, these PowerPoints allow you to electronically poll your class for responses to questions, pop quizzes, attendance, and more.

Instructor Manual (Download Only)

The Instructor Manual has been designed to help seasoned and new professors alike, offering the following for each chapter: an introduction to the chapter, an outline, and learning objectives/ Focus on Concepts; teaching strategies; teacher resources; and answers to *Concept Checks*, *Eye on Earth*, and *Give It Some Thought* questions from the textbook.

TestGen Computerized Test Bank (Download Only)

TestGen is a computerized test generator that lets instructors view and edit Test Bank questions, transfer questions to tests, and print tests in a variety of customized formats. The Test Bank includes more than 2,000 multiple-choice, matching, and essay questions. Questions are correlated to Bloom's Taxonomy, each chapter's learning objectives, the Earth Science Learning Objectives, and the Pearson Science Global Outcomes to help instructors better map the assessments against both broad and specific teaching and learning objectives. The Test Bank is also available in Microsoft Word and can be imported into Blackboard.

Blackboard
Already have your own website set up? We will provide a Test Bank in Blackboard or formats for importation upon request. Additional course resources are available on the IRC and are available for use, with permission.

Acknowledgments

Writing a college textbook requires the talents and cooperation of many people. It is truly a team effort, and the authors are fortunate to be part of an extraordinary team at Pearson Education. In addition to being great people to work with, all of them are committed to producing the best textbooks possible. Special thanks to our geology editor, Andy Dunaway, who invested a great deal of time, energy, and effort in this project. We appreciate his enthusiasm, hard work, and quest for excellence. We also appreciate our conscientious project managers, Crissy Dudonis and Nicole Antonio, whose job it was to keep track of all that was going on—and a lot was going on. As always, our marketing managers, Neena Bali and Mary Salzman, who talk with faculty daily, provide us with helpful advice and many good ideas. The 12th edition of *Earth* was certainly improved by the talents of our developmental editor, Veronica Jurgena. Many thanks. It was the job of the production team, led by Heidi Allgair at Cenveo® Publisher Services, to turn our manuscript into a finished product. The team also included copyeditor Kitty Wilson, compositor Annamarie Boley, proofreader Heather Mann, and photo researcher Kristin Piljay. We think these talented people did great work. All are true professionals, with whom we are very fortunate to be associated.

The authors owe special thanks to three people who were very important contributors to this project:

- Working with Dennis Tasa, who is responsible for all of the text's outstanding illustrations and several of its animations, is always special for us. He has been part of our team for more than 30 years. We not only value his artistic talents, hard work, patience, and imagination but his friendship as well.
- As you read this text, you will see dozens of extraordinary photographs by Michael Collier. Most are aerial shots taken from his nearly 60-year-old Cessna 180. Michael was also responsible for preparing the 24 remarkable Mobile Field Trips that are scattered through the text. Among his many awards is the American Geological Institute Award for Outstanding Contribution to the Public Understanding of Geosciences. We think that Michael's photographs and field trips are the next best thing to being there. We were very fortunate to have had Michael's assistance on *Earth*, 12th edition. Thanks, Michael.
- Callan Bentley has been an important addition to the *Earth* team. Callan is an assistant professor of geology at Northern Virginia Community College in Annandale, where he has been honored many times as an outstanding teacher. He is a frequent contributor to *EARTH* magazine and is author of the popular geology blog *Mountain Beltway*. Callan was responsible for preparing the SmartFigure Tutorials that appear throughout the text. As you take advantage of these outstanding learning aids, you will hear his voice explaining the ideas. We appreciate Callan's contributions to this new edition of *Earth*.

Great thanks also go to our colleagues who prepared in-depth reviews. Their critical comments and thoughtful input helped guide our work and clearly strengthened the text. Special thanks to:

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Last but certainly not least, we gratefully acknowledge the support and encouragement of our wives, Joanne Bannon and Nancy Lutgens. Preparation of this edition of *Earth* would have been far more difficult without their patience and understanding.

Ed Tarbuck
Fred Lutgens

Augmented Reality Enhances the Reading Experience, Bringing the Textbook to Life

Using a cutting-edge technology called augmented reality, Pearson's BouncePages app launches engaging, interactive videos and animations that bring textbook pages to life. Use your mobile device to scan a SmartFigure identified by the BouncePages icon, and an animation or video illustrating the SmartFigure's concept launches immediately. No slow websites or hard-to-remember logins required.

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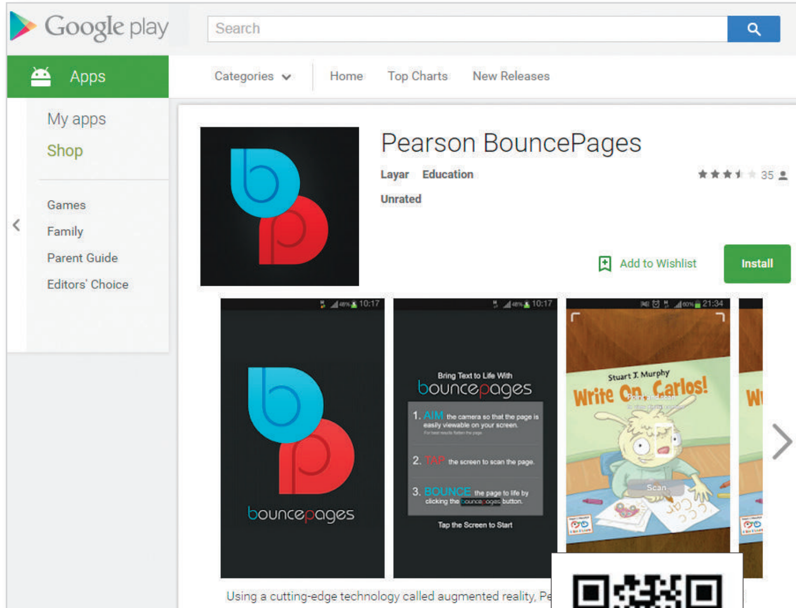

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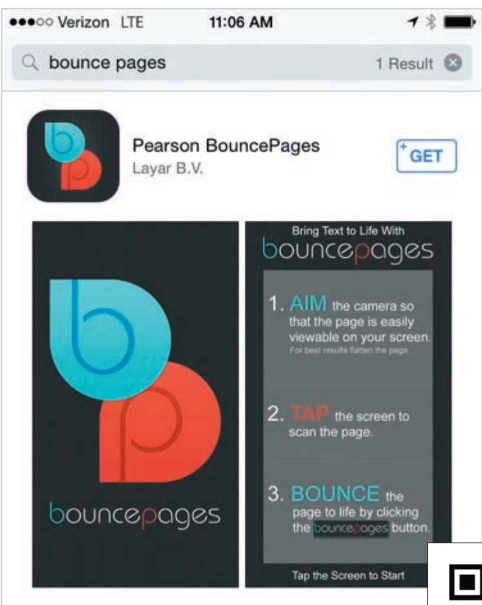
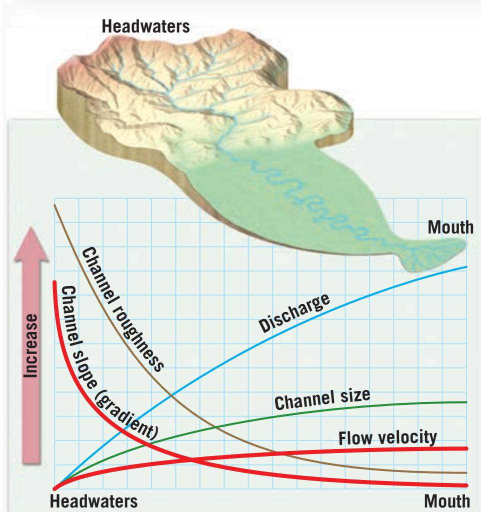


https://itunes.apple.com/us/app/pearson-bouncepages/id659370955?mt=8

By scanning figures associated with the BouncePages icon, students will be immediately connected to the digital world and will deepen their learning experience with the printed text.



SmartFigure 16.14
Channel changes from head to mouth
Although the gradient decreases toward the mouth of a stream, increases in discharge and channel size and decreases in roughness more than offset the decrease in slope. Consequently, flow velocity usually increases toward the mouth. (https://goo.gl/6srX2s)

Tutorial

Bring the Field to YOUR Teaching and Learning Experience

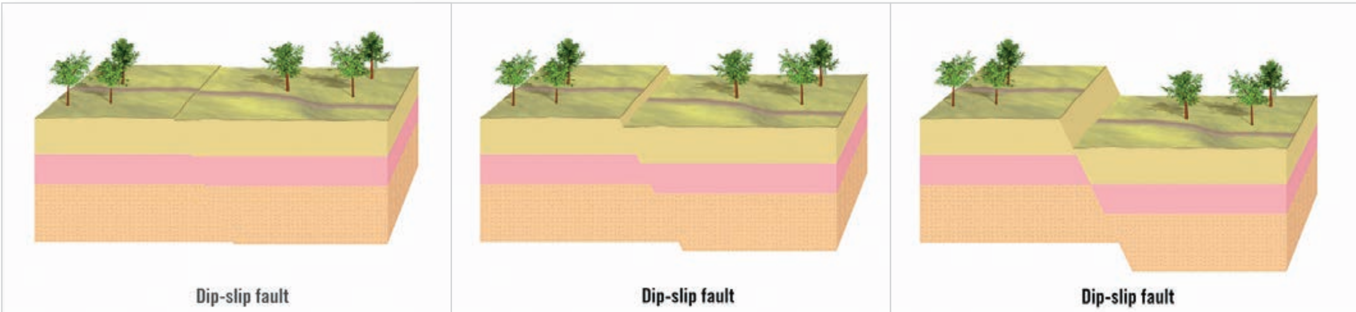
NEW! SmartFigure: Condor Videos. Bringing Physical Geology to life for GenEd students, three geologists, using a quadcopter with a GoPro camera mounted to it, have ventured out into the field to film 10 key geologic locations. These process-oriented videos, accessed through BouncePages technology, are designed to bring the field to the classroom or dorm room and enhance the learning experience in our texts.

Condor Video

NEW! SmartFigure: Mobile Field Trips. Scattered throughout this new edition of Earth are **24 video field trips**. On each trip, you will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to see and learn about iconic landscapes that relate to discussions in the chapter. These extraordinary field trips are accessed by using the BouncePages app to scan the figure in the chapter—usually one of Michael's outstanding photos.

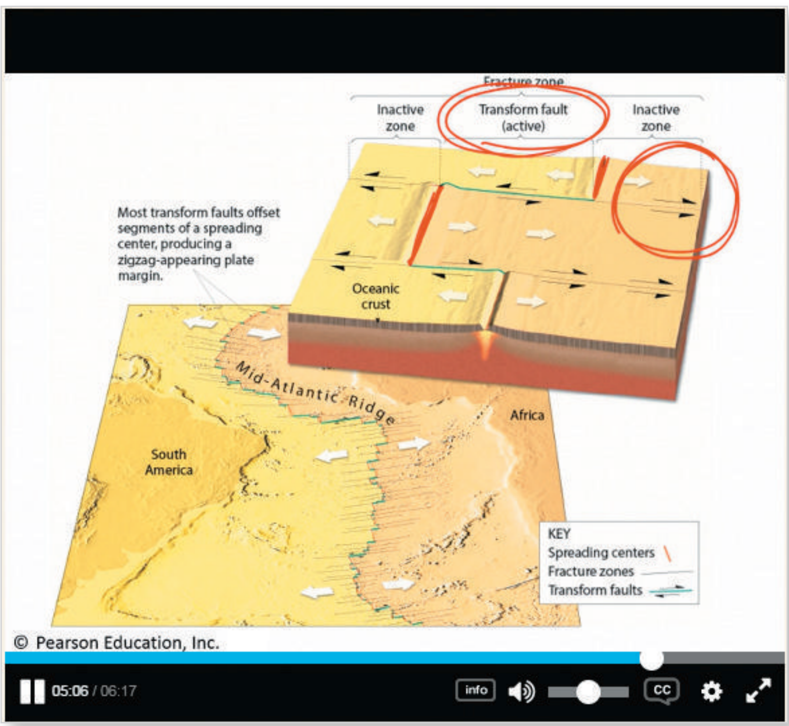
Mobile Field Trip

Visualize Processes and Tough Topics



NEW! SmartFigure: Animations are brief videos, many created by text illustrator Dennis Tasa, that animate a process or concept depicted in the textbook's figures. This technology allows students to view moving figures rather than static art to depict how a geologic process actually changes through time. The videos can be accessed using Pearson's BouncePages app for use on mobile devices, and will also be available via MasteringGeology.

Animation



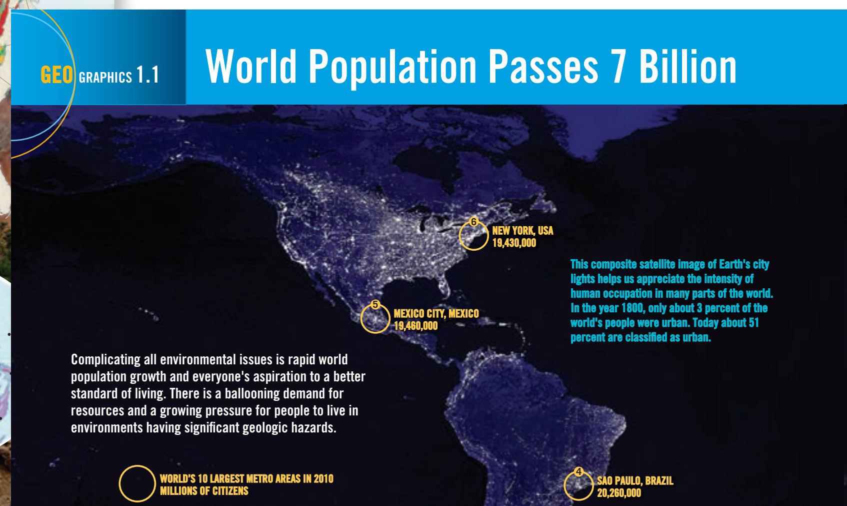
SmartFigure: Tutorials bring key chapter illustrations to life! Found throughout the book, these Tutorials are sophisticated, annotated illustrations that are also narrated videos. They are accessible on mobile devices via scannable BouncePages printed in the text and through the Study Area in MasteringGeology.

Tutorial

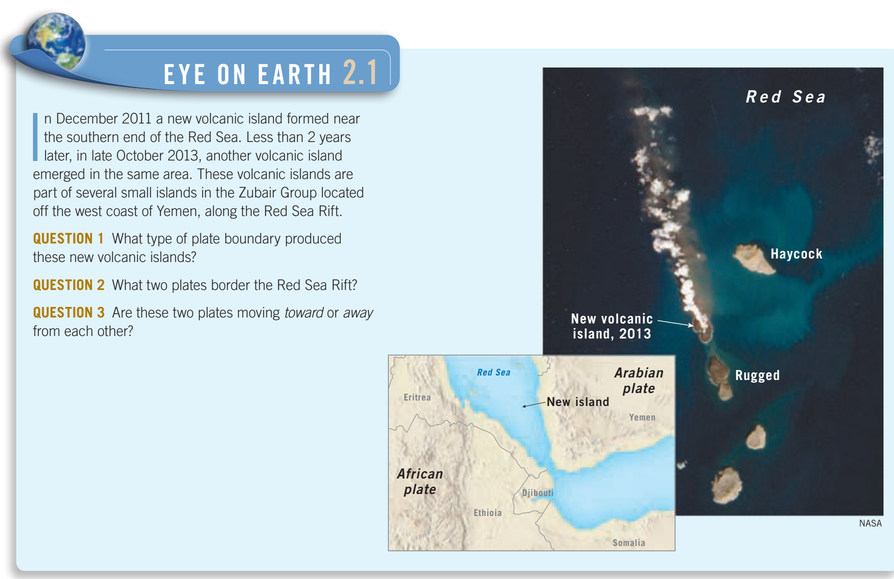
Callan Bentley, SmartFigure Tutorial author, is a Chancellor's Commonwealth Professor of Geology at Northern Virginia Community College (NOVA) in Annandale, Virginia. Trained as a structural geologist, Callan teaches introductory level geology at NOVA, including field-based and hybrid courses. Callan writes a popular geology blog called *Mountain Beltway*, contributes cartoons, travel articles, and book reviews to *EARTH* magazine, and is a digital education leader in the two-year college geoscience community.

Improved Geospatial and Data Visualizations

GEOgraphics use contemporary, compelling visual representations to illustrate complex concepts, enhancing students' ability to synthesize and recall information and important data.



Eye on Earth features engage students in active learning, asking them to perform critical thinking and visual analysis tasks to evaluate data and make predictions.



Modular Approach Driven by Learning Objectives

The new edition is designed to support a four-part learning path, an innovative structure which facilitates active learning and allows students to focus on important ideas as they pause to assess their progress at frequent intervals.

The chapter-opening **Focus on Concepts** lists the learning objectives for each chapter. Each section of the chapter is tied to a specific learning objective, providing students with a clear learning path to the chapter content.

10

Crustal Deformation

Wyoming's Grand Tetons are the result of crustal deformation created by tectonic forces that operate in Earth's interior. (Photo by Michael Collier)

FOCUS ON CONCEPTS

Each statement represents the primary LEARNING OBJECTIVE for the corresponding major heading within the chapter. After you complete the chapter you should be able to:

10.1 Describe the three types of differential stress and name the type of plate boundary most commonly associated with each.

10.2 Compare and contrast brittle and ductile deformation.

10.3 List and describe five common folded structures.

10.4 Sketch and briefly describe the relative motion of rock bodies located on opposite sides of normal, reverse, and thrust faults as well as both types of strike-slip faults.

10.5 Explain how strike and dip are measured and how these measurements tell geologists about the orientations of rock structures located mainly below Earth's surface.

Each chapter section concludes with **Concept Checks,** a feature that lists questions tied to the section's learning objective, allowing students to monitor their grasp of significant facts and ideas.

10.5 Concept Checks

1. Distinguish between the two measurements used to establish the orientation of deformed strata.
2. Briefly describe the method geologists use to infer the orientation of rock structures that lie mainly below Earth's surface.

Concepts in Review, a fresh approach to the typical end-of-chapter material, provides students with a structured and highly visual review of each chapter. Consistent with the Focus on Concepts and Concept Checks, the **Concepts in Review** is structured around the section title and the corresponding learning objective for each section.

10 Concepts in Review Crustal Deformation

10.1 What Causes Rock to Deform

Describe the three types of differential stress and name the type of plate boundary most commonly associated with each.

KEY TERMS deformation, rock structure (geologic structure), stress, confining pressure, differential stress, compressional stress, tensional stress, shear stress, strain

- Rock structures are generated when rocks are deformed by bending or breaking due to differential stress. Crustal deformation produces geologic structures that include folds, faults, joints, foliation, and rock cleavage.
- Stress is the force that drives rock deformation. When stress has the same magnitude in every direction, it is called confining pressure. Alternatively, when the amount of stress coming from one direction is greater in magnitude than the stress coming from another direction, we call it differential stress. There are three main types of differential stress: compressional, tensional, and shear stress.
- Strain is the change in the shape of a rock body caused by stress.

Q Classify the following everyday situations as illustrating confining pressure, compressional stress, tensional stress, or shear stress: (a) a watermelon being run over by a steamroller, (b) a person diving to the bottom of the deep end of a swimming pool, (c) playing a game of tug-of-war, (d) kneading bread dough, and (e) slipping on a banana peel.

10.2 How Do Rocks Deform?

Compare and contrast brittle and ductile deformation.

KEY TERMS elastic deformation, brittle deformation, ductile deformation, outcrop

- There are several types of deformation. Elastic deformation is a temporary stretching of the chemical bonds in a rock. When the stress is released, the bonds snap back to their original lengths. When stress is greater than the strength of the bonds, the rock deforms in either a brittle or ductile fashion. Brittle deformation occurs when rocks break into smaller pieces, whereas ductile deformation is a solid-state flow that allows a rock to bend without fracturing.
- The type of deformation (ductile or brittle) that occurs depends mainly on temperature, confining pressure, rock type, and time. In Earth's upper crust where temperatures and pressure are low, rocks tend to exhibit brittle behavior and break or fracture. At depth rocks tend to deform by flowing or bending.
- Igneous rocks tend to be strong and are more likely to deform in a brittle fashion, whereas sedimentary rocks are weaker and usually deform in a ductile fashion.
- The rate at which differential stress is applied also affects how rocks deform. Silly Putty provides a good analogy: If pulled apart quickly, Silly Putty tends to break, whereas if pulled apart slowly, it tends to stretch (ductile flow) without breaking.

Q Examine the accompanying illustration of a collision between two tectonic plates. At which location (A or B) would brittle deformation be more prevalent than ductile deformation?

Location A

Location B

10.3 Folds: Rock Structures Formed by Ductile Deformation

List and describe five common folded structures.

KEY TERMS fold, anticline, syncline, dome, basin, monocline

- Folds are wavelike undulations in layered rocks that develop through ductile deformation in rocks undergoing compressional stress.
- Folds may be described in terms of their geometric configuration: If the limbs of a fold dip down from the hinge, the fold has an arch-like structure and is called an anticline. If the limbs of a fold dip upward, the fold has a trough-like structure and is called a syncline. Anticlines and synclines may be symmetrical, asymmetrical, overturned, or recumbent.
- The shape of a fold does not necessarily correlate to the shape of the landscape above it. Rather, surface topography usually reflects patterns of differential weathering.
- A fold is said to plunge when its axis penetrates the ground at an angle. This results in a V-shaped outcrop pattern of the folded layers.
- Domes and basins are large folds that produce nearly circular-shaped outcrop patterns. The overall shape of a dome or basin is like a saucer or a bowl, either right-side-up (basin) or inverted (dome).
- Monoclines are large steplike folds in otherwise horizontal strata that result from subsurface faulting. Imagine a carpet draped over a short staircase to envision how the strata can go from horizontal to tilted and back to horizontal again.

10.4 Faults and Joints: Structures Formed by Brittle Deformation

Sketch and briefly describe the relative motion of rock bodies located on opposite sides of normal, reverse, and thrust faults as well as both types of strike-slip faults.

KEY TERMS fault, dip-slip fault, hanging wall block, footwall block, normal fault, fault-block mountain, horst, graben, half-graben, detachment fault, reverse fault, thrust fault, klippe, strike-slip fault, transform fault, oblique-slip fault, megathrust fault, fault scarp, slickenside, joint

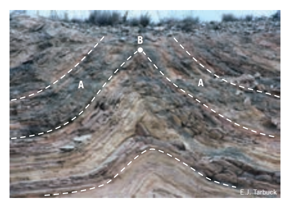
- Faults are fractures along which one rock body slides past another.
- The direction of offset on a fault may be determined by comparing the blocks of rock on either side of the fault surface. Faults in which movement is primarily parallel to the dip of the fault surface are called dip-slip faults. Dip-slip faults are classified as normal faults if the hanging wall moves *down* relative to the footwall and as reverse faults if the hanging wall moves *up* relative to the footwall. Large

Give It Some Thought

1. Is granite or mica schist more likely to fold or flow rather than fracture when subjected to differential stress? Explain.
2. What type of deformation is illustrated by a coin that was run over by a passing train?

Anthony Pleva/Alamy

3. Refer to the accompanying photo to answer the following questions:
   a. Name the type of fold shown.
   b. Would you describe this fold as symmetrical or asymmetrical?



   c. What name is given to the part of the fold labeled A?
   d. Is the white dot labeled B located along the fold line, hinge line, or dip line of this particular fold?
4. Refer to the accompanying diagrams to answer the following:
   a. What type of dip-slip fault is shown in Diagram 1? Were the dominant forces during faulting tensional, compressional, or shear?

Give It Some Thought (GIST) is found at the end of each chapter and consists of questions and problems asking students to analyze, synthesize, and think critically about Geology. GIST questions relate back to the chapter's learning objectives, and can easily be assigned using MasteringGeology.

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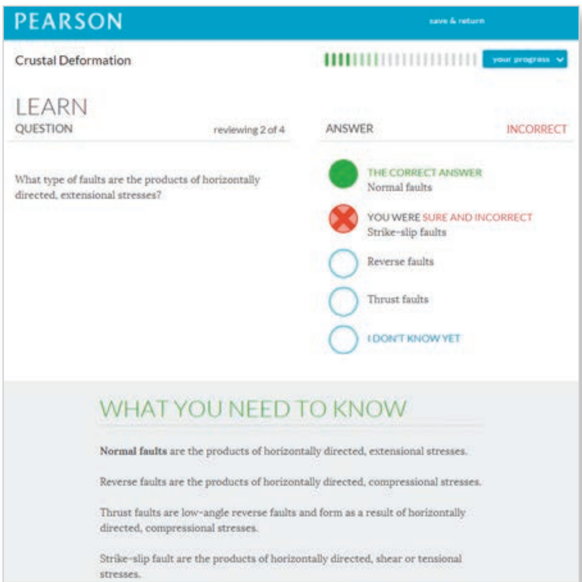

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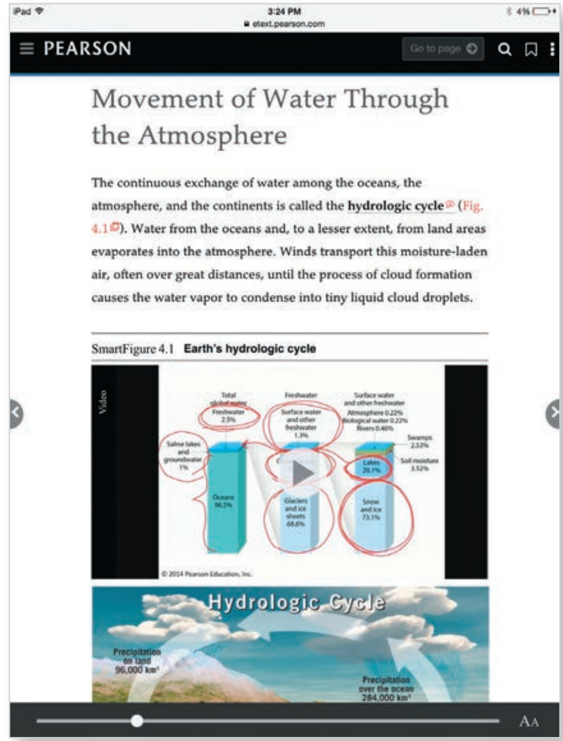

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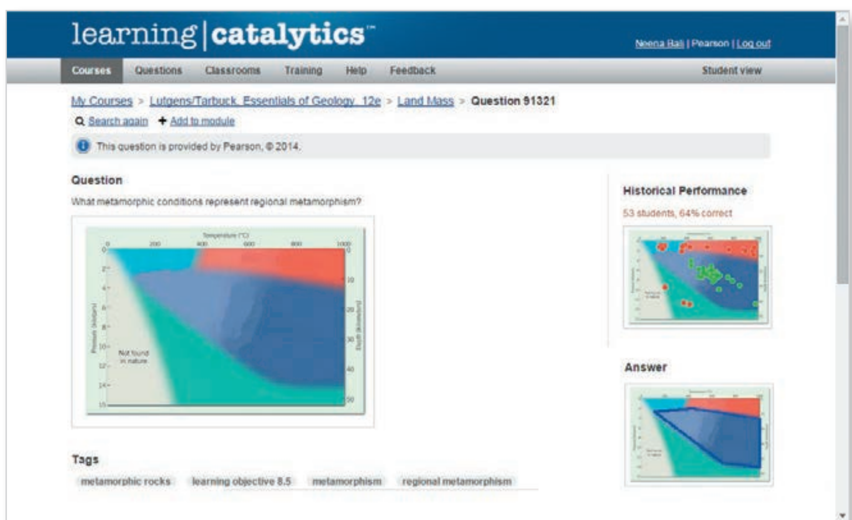

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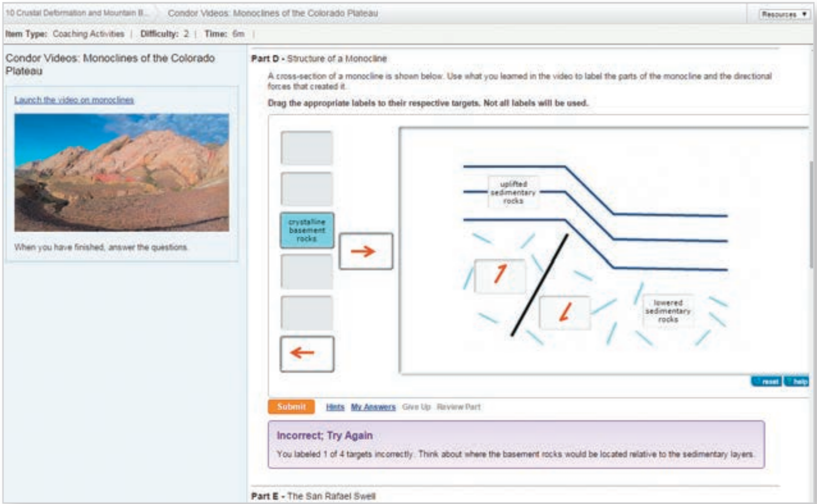
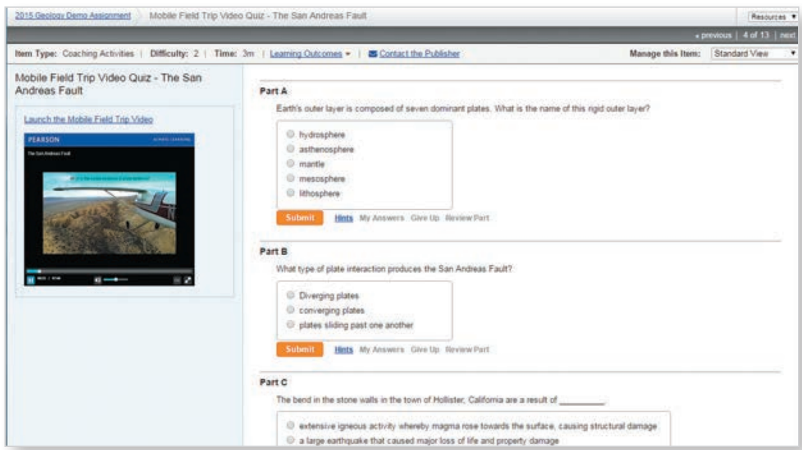
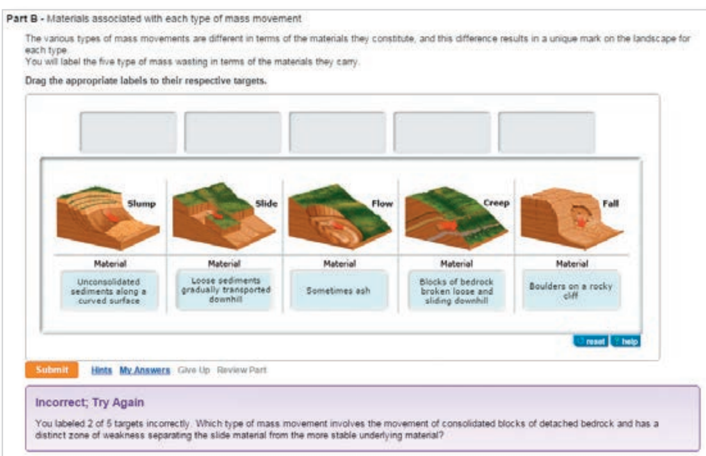


NEW! Project Condor Videos capture stunning footage of the Mountain West region with a quadcopter and a GoPro camera. A series of videos have been created with annotations, sketching, and narration to improve the way students learn about faults and folds, streams, volcanoes, and so much more. In Mastering, these videos are accompanied by questions designed to assess students on the main takeaways from each video.

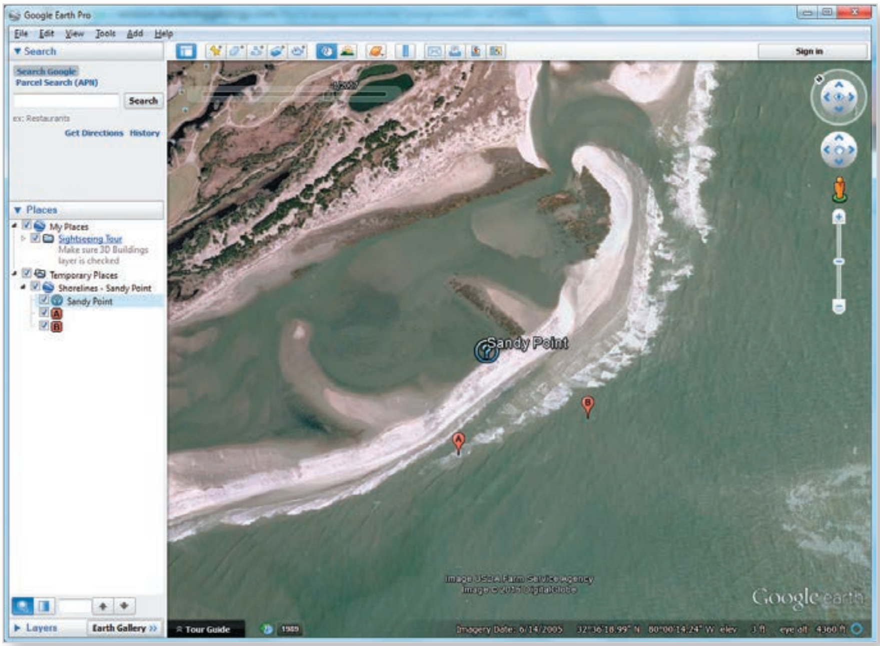
NEW! 24 Mobile Field Trips take students to classic geologic locations as they accompany geologist–pilot–photographer–author Michael Collier in the air and on the ground to see and learn about landscapes that relate to concepts in the chapter. In Mastering, these videos will be accompanied by auto-gradable assessments that will track what students have learned.





GeoTutor coaching activities help students master important geologic concepts with highly visual, kinesthetic activities focused on critical thinking and application of core geoscience concepts.

MasteringGeology™



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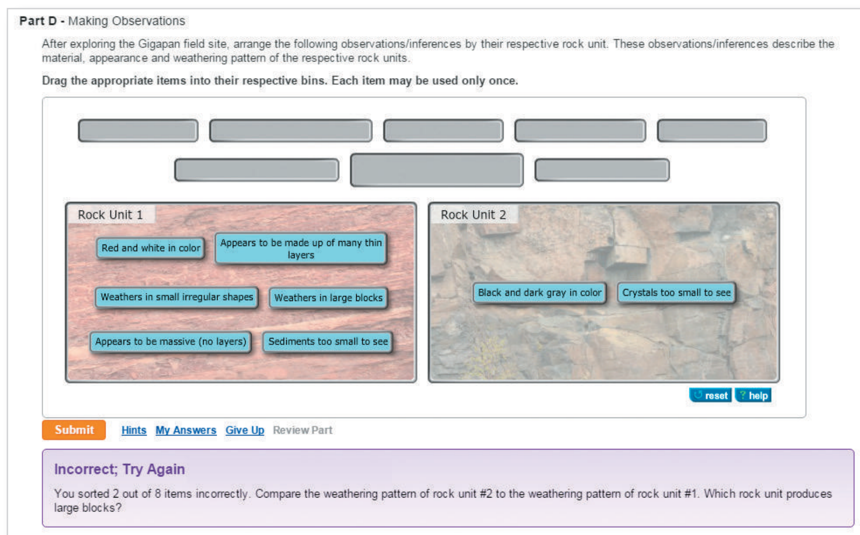

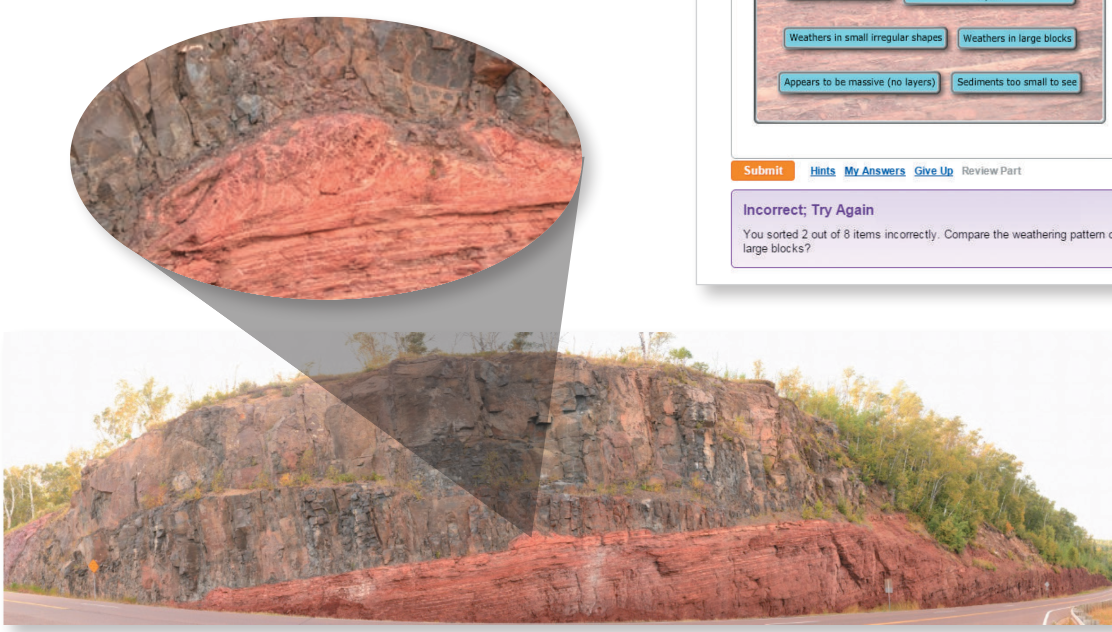

Additional MasteringGeology assignments available:

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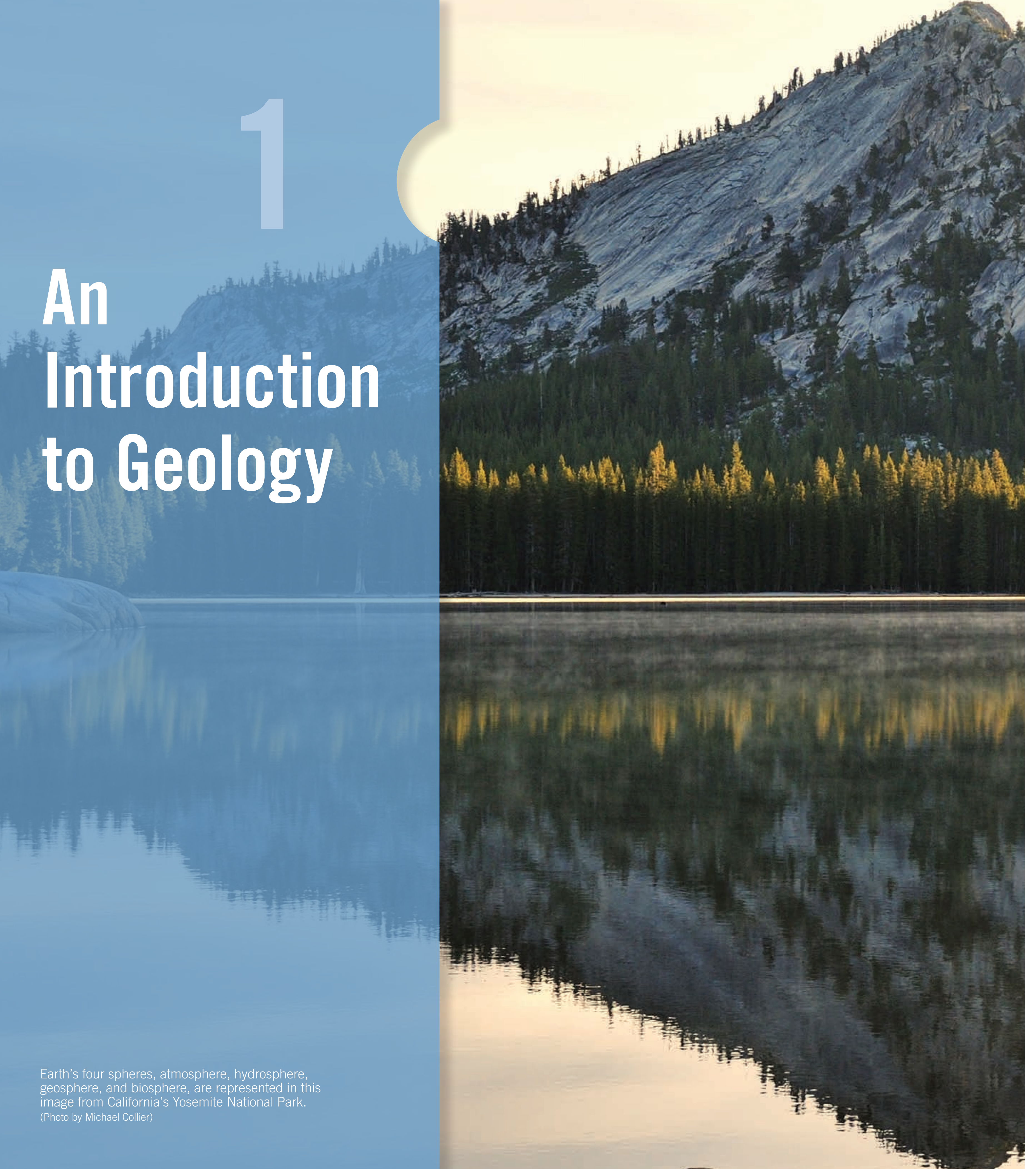
1

An Introduction to Geology



Earth's four spheres, atmosphere, hydrosphere, geosphere, and biosphere, are represented in this image from California's Yosemite National Park.
(Photo by Michael Collier)

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1.1 **Distinguish between physical and historical geology and describe the connections between people and geology.**

1.2 **Summarize early and modern views on how change occurs on Earth and relate them to the prevailing ideas about the age of Earth.**

1.3 **Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.**

1.4 **List and describe Earth's four major spheres. Define *system* and explain why Earth is considered to be a system.**

1.5 **Outline the stages in the formation of our solar system.**

1.6 **Sketch Earth's internal structure and label and describe the main subdivisions.**

1.7 **Sketch, label, and explain the rock cycle.**

1.8 **List and describe the major features of the continents and ocean basins.**

The spectacular eruption of a volcano, the terror brought by an earthquake, the magnificent scenery of a mountain range, and the destruction created by a landslide or flood are all subjects for a geologist. The study of geology deals with many fascinating and practical questions about our physical environment. What forces produce mountains? When will the next major earthquake occur in California? What was the Ice Age like, and will there be another? How are ore deposits formed? Where should we search for water? Will we find plentiful oil if we drill a well in a particular location? Geologists seek to answer these and many other questions about Earth, its history, and its resources.

1.1 Geology: The Science of Earth

Distinguish between physical and historical geology and describe the connections between people and geology.

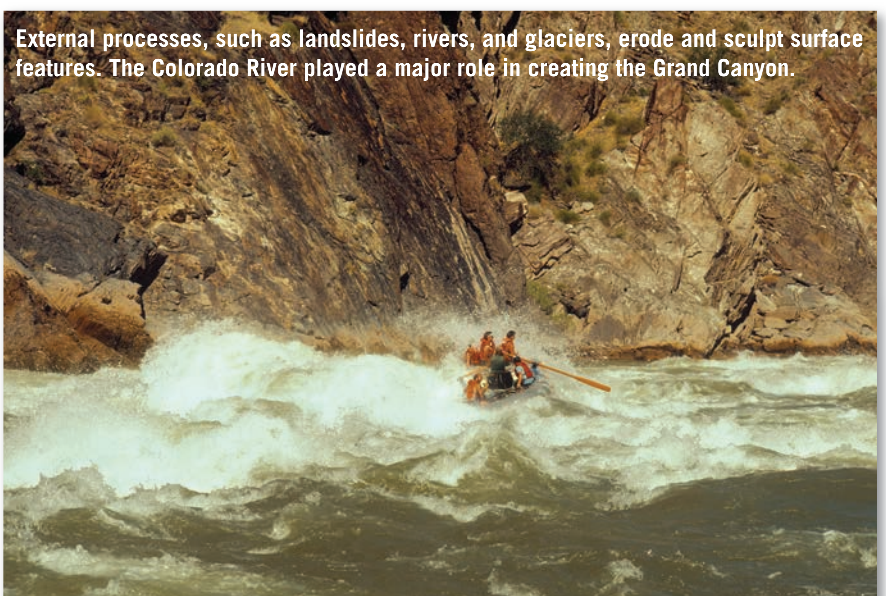
The subject of this text is **geology**, from the Greek *geo* (Earth) and *logos* (discourse). Geology is the science that pursues an understanding of planet Earth. Understanding Earth is challenging because our planet is a dynamic body with many interacting parts and a complex history. Throughout its long existence, Earth has been changing. In fact, it is changing as you read this page and will continue to do so. Sometimes the changes are rapid and violent, as when landslides or volcanic eruptions occur. Just as often, change takes place so slowly that it goes unnoticed during a lifetime. Scales of size and space also vary greatly among the phenomena that geologists study. Sometimes geologists must focus on phenomena that are microscopic, such as the crystalline structure of minerals, and at other times they must deal with processes that are continental or global in scale, such as the formation of major mountain ranges.

Physical and Historical Geology

Geology is traditionally divided into two broad areas—physical and historical. **Physical geology**, which is the primary focus of this book, examines the materials composing Earth and seeks to understand the many processes that operate beneath and upon its surface (Figure 1.1). The aim of **historical geology**, on the other hand, is to understand Earth's origins and its development through time. Thus, it strives to establish an orderly chronological arrangement of the multitude of physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of Earth history because we must first understand how Earth works before we attempt to unravel its past. It should also be pointed out that physical and historical

Figure 1.1
Internal and external processes The processes that operate beneath and upon Earth's surface are an important focus of physical geology. (River photo by Michael Collier; volcano photo by AM Design/Alamy Live News/Alamy Images)

A.



External processes, such as landslides, rivers, and glaciers, erode and sculpt surface features. The Colorado River played a major role in creating the Grand Canyon.

B.

Internal processes are those that occur beneath Earth's surface. Sometimes they lead to the formation of major features at the surface, such as Italy's Mt. Etna.

geology are divided into many areas of specialization. Every chapter of this book represents one or more areas of specialization in geology.

Geology is perceived as a science that is done outdoors—and rightly so. A great deal of geology is based on observations, measurements, and experiments conducted in the field. But geologists also work in the laboratory, where, for example, their analysis of minerals and rocks provides insights into many basic processes and the microscopic study of fossils unlocks clues to past environments (**Figure 1.2**). Geologists must also understand and apply knowledge and principles from physics, chemistry, and biology. Geology is a science that seeks to expand our knowledge of the natural world and our place in it.

A.

B.

Figure 1.2
In the field and in the lab Geology involves not only outdoor fieldwork but work in the laboratory as well. **A.** This research team is gathering data at Mount Nyiragongo, an active volcano in the Democratic Republic of the Congo. (Carsten Peter/National Geographic Image Collection/Alamy) **B.** This researcher is using a petrographic microscope to study the mineral composition of rock samples. (Photo by Jon Wilson/Science Source)

Geology, People, and the Environment

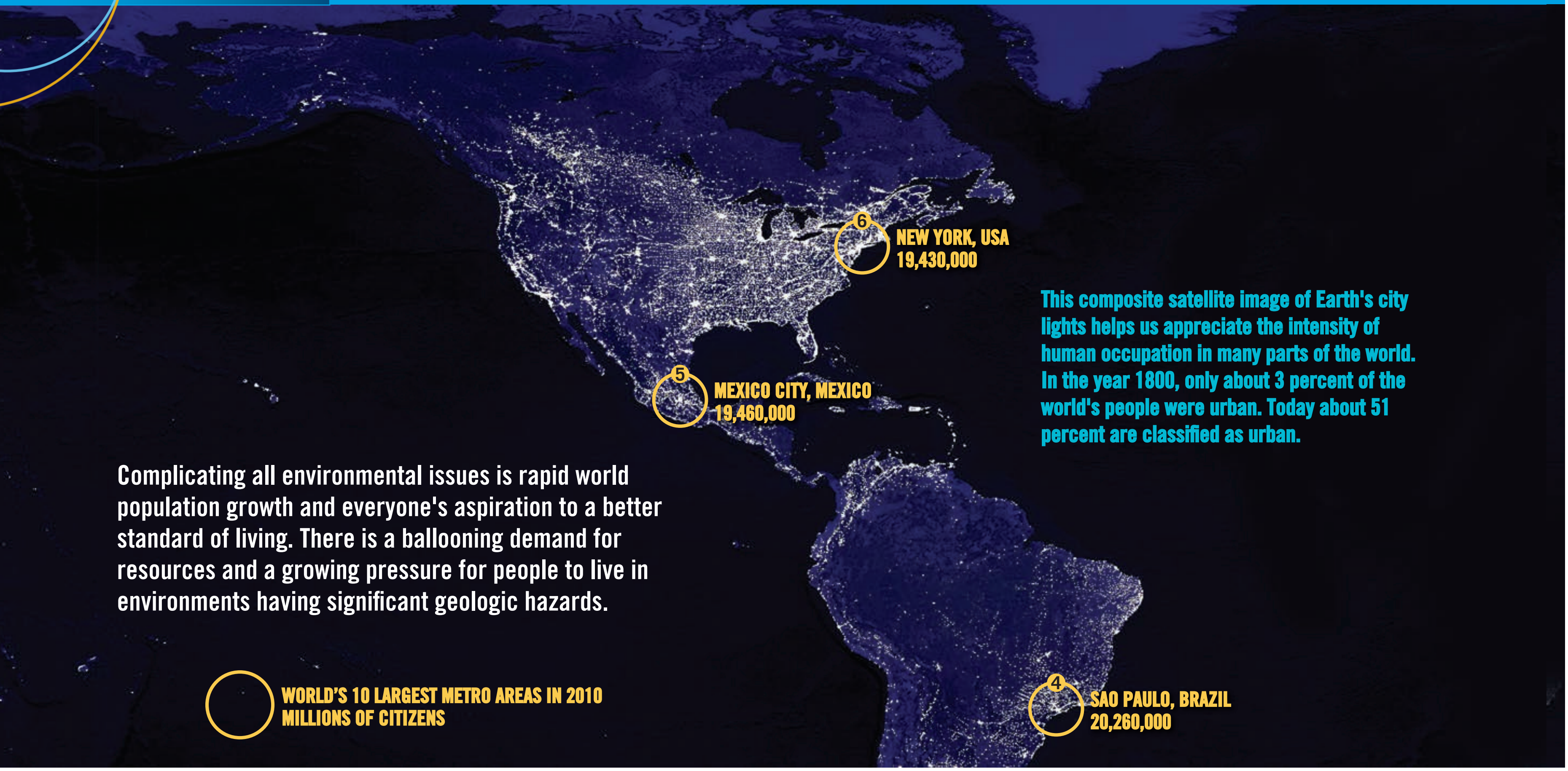
The primary focus of this book is to develop your understanding of basic geologic principles, but along the way, we explore numerous important relationships between people and the natural environment. Many of the problems and issues that geologists address are of practical value.

Natural hazards are a part of living on Earth. Every day they adversely affect millions of people worldwide and are responsible for staggering damages. Among the hazardous Earth processes that geologists study are volcanoes, floods, tsunamis, earthquakes, and landslides. Of course, geologic hazards are *natural* processes. They become hazards only when people try to live where these processes occur (**Figure 1.3**).

Figure 1.3
Tsunami destruction Undersea earthquakes sometimes create large, fast-moving ocean waves that can cause significant death and destruction in coastal areas. This tsunami struck densely populated Fukushima, Japan, in 2011, causing major damage to a nuclear power plant. Geologic hazards are natural processes. They become hazards only when people try to live where these processes occur. (Photo by Mainichi Newspaper/Aflo /Newscom)

GEOGRAPHICS 1.1

World Population Passes 7 Billion



According to the United Nations, more people live in cities than in rural areas (see GEOgraphics 1.1). This global trend toward urbanization concentrates millions of people into megacities, many of which are vulnerable to natural hazards. Coastal sites are especially vulnerable because development often destroys natural defenses such as wetlands and sand dunes. In addition, threats associated with human influences on the Earth system are increasing; one example is sea-level rise linked to global climate change. Some megacities are exposed to seismic (earthquake) and volcanic hazards because inappropriate land use and poor construction practices, coupled with rapid population growth, increase the risk of death and damage.

Resources are another important focus of geology that is of great practical value to people. They include water and soil, a great variety of metallic and nonmetallic minerals, and energy (Figure 1.4). Together these form the very foundation of modern civilization. Geology deals not only with how and where these vital resources form but also with maintaining supplies and with the environmental impacts of their extraction and use.

Geologic processes clearly have an impact on people. Conversely, we humans can dramatically influence geologic processes. For example, landslides and river flooding occur naturally, but the magnitude and frequency of these processes can be affected significantly by human activities such as clearing forests, building cities, and constructing roads and dams. Unfortunately, natural systems do not always adjust to artificial changes in ways that we can anticipate. Thus, an alteration to the environment that was intended to benefit society sometimes has the opposite effect.

At appropriate places throughout this book, you will examine different aspects of our relationship with the physical environment. Nearly every chapter addresses some aspect of natural hazards, resources, and the environmental issues associated with each. Significant parts of some chapters provide the basic geologic knowledge and principles needed to understand environmental problems.

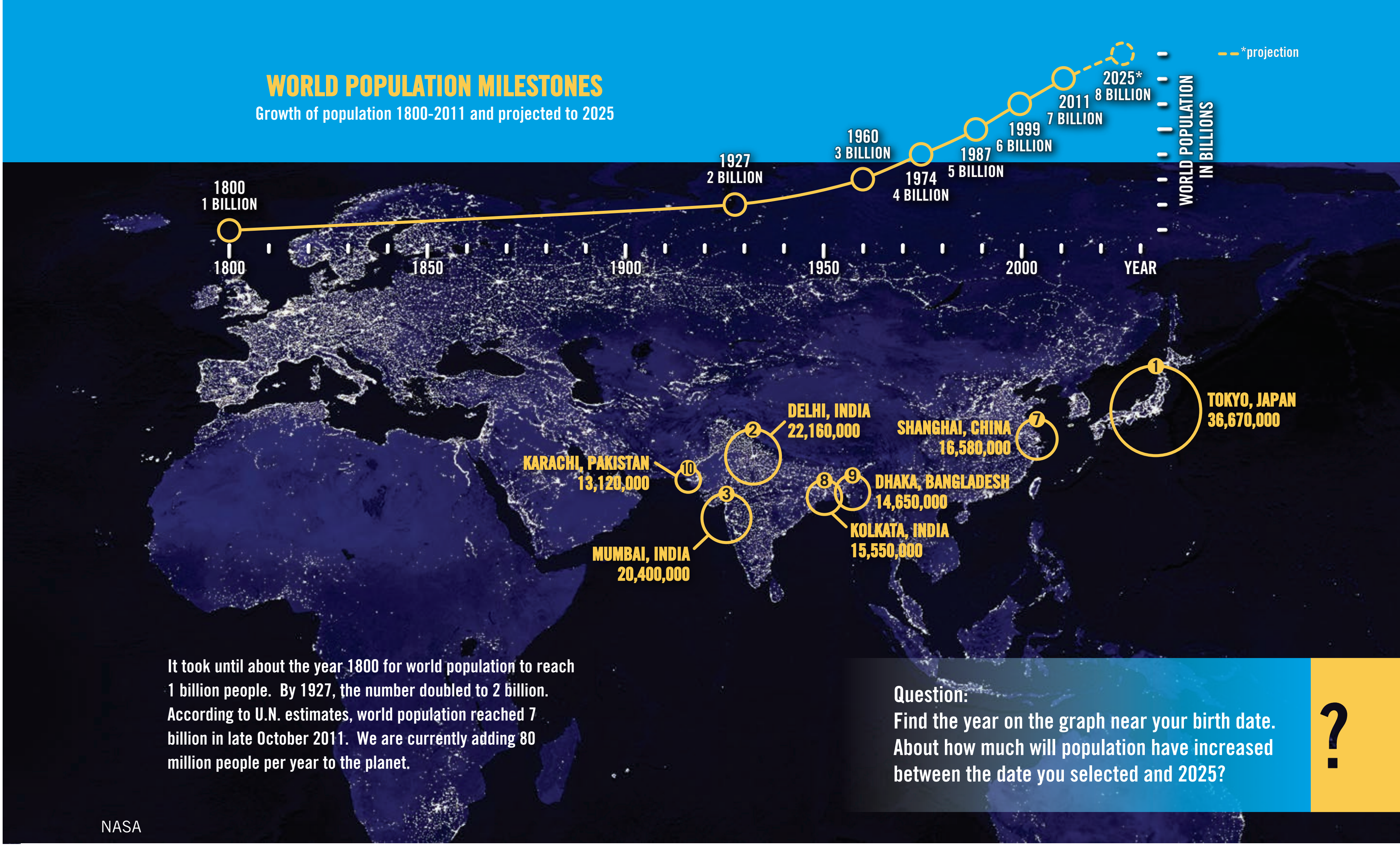


Figure 1.4
Mineral resources represent an important link between people and geology
Each year an average American requires huge quantities of Earth materials—more than 6 tons of stone, 4.5 tons of sand and gravel, nearly a half ton of cement, almost 400 pounds of salt, 360 pounds of phosphate, and about a half ton of other nonmetals. In addition, per capita consumption of metals such as iron, aluminum, and copper exceeds 700 pounds. This open pit copper mine is in southern Arizona. (Ball Miwako/Alamy)

1.1 Concept Checks

1. Name and distinguish between the two broad subdivisions of geology.
2. List at least three different geologic hazards.
3. Aside from geologic hazards, describe another important connection between people and geology.

1.2 The Development of Geology

Summarize early and modern views on how change occurs on Earth and relate them to the prevailing ideas about the age of Earth.

The nature of our Earth—its materials and processes—has been a focus of study for centuries. Writings about such topics as fossils, gems, earthquakes, and volcanoes date back to the early Greeks, more than 2300 years ago.

Certainly the most influential Greek philosopher was Aristotle. Unfortunately, Aristotle's explanations about the natural world were not based on keen observations and experiments. He arbitrarily stated that rocks were created under the "influence" of the stars and that earthquakes occurred when air crowded into the ground, was heated by central fires, and escaped explosively. When confronted with a fossil fish, he explained that "a great many fishes live in the earth motionless and are found when excavations are made." Although Aristotle's explanations may have been adequate for his day, they continued to be viewed as authoritative for many centuries, thus inhibiting the acceptance of more up-to-date ideas. After the Renaissance of the 1500s, however, more people became interested in finding answers to questions about Earth.

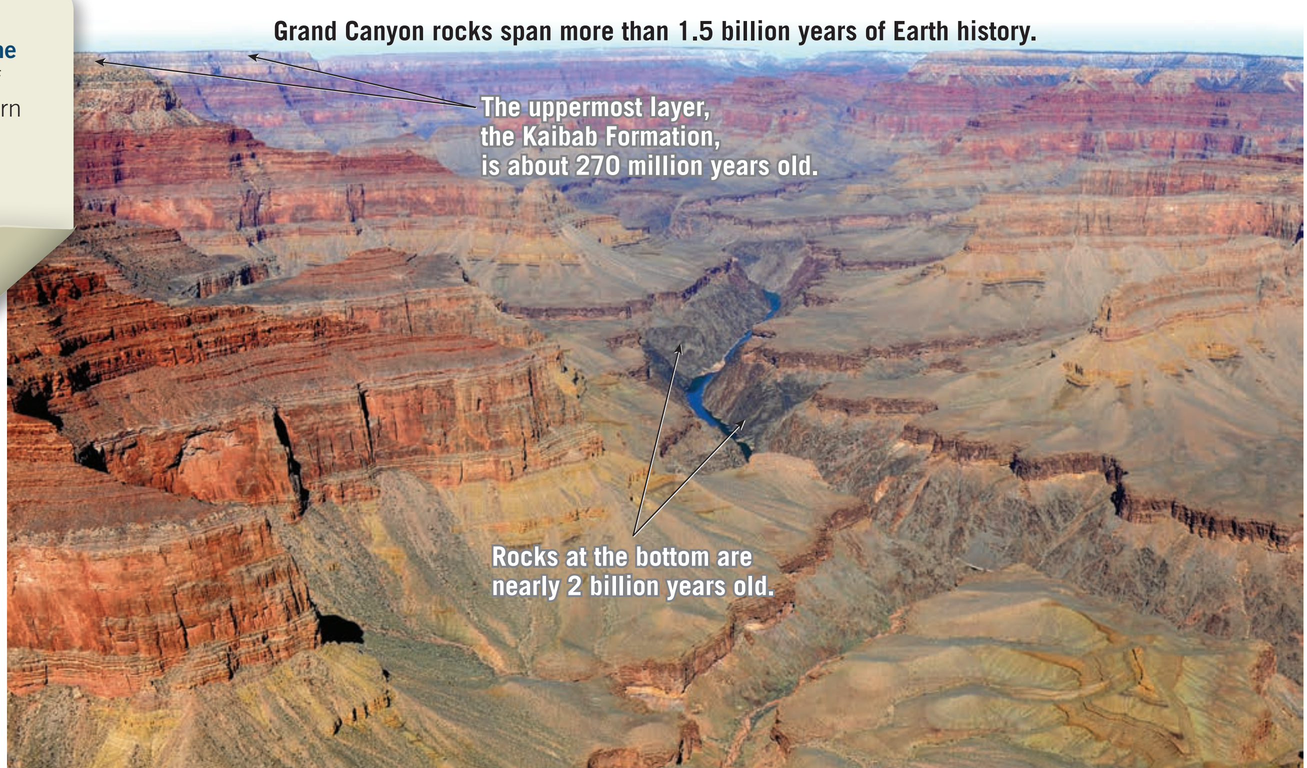
Catastrophism

In the mid-1600s James Ussher, Archbishop of Armagh, Primate of all Ireland, published a major work that had immediate and profound influences. A respected biblical scholar, Ussher constructed a chronology of human and Earth history in which he calculated that Earth was only a few thousand years old, having been created in 4004 B.C.E. Ussher's treatise was widely accepted by Europe's scientific and religious leaders, and his chronology was soon printed in the margins of the Bible itself.

During the seventeenth and eighteenth centuries, Western thought about Earth's features and processes was strongly influenced by Ussher's calculation. The result was a guiding doctrine called **catastrophism**. Catastrophists believed that Earth's landscapes were shaped primarily by great catastrophes. Features such as mountains and canyons, which today we know take great spans of time to form, were explained as resulting from sudden, often worldwide disasters produced by unknowable causes that no longer operate. This philosophy was an attempt to fit the rates of Earth processes to then-current ideas about the age of Earth.

The Birth of Modern Geology

Against the backdrop of Aristotle's views and a conception of an Earth created in 4004 B.C.E., a Scottish physician and gentleman farmer, James Hutton, published *Theory of the Earth* in 1795. In this work, Hutton put forth a fundamental principle that is a pillar of geology today: **uniformitarianism**. It states that the *physical, chemical, and biological processes that operate today have also operated in the geologic past.* This means



SmartFigure 1.5 Earth history—Written in the rocks The Grand Canyon of the Colorado River in northern Arizona. (Photo by Dennis Tasa) (http://goo.gl/7KwQLk)

Mobile Field Trip

that the forces that we observe presently shaping our planet have been at work for a very long time. Thus, to understand ancient rocks, we must first understand present-day processes and their results. This idea is commonly stated as *the present is the key to the past*.

Prior to Hutton's *Theory of the Earth*, no one had effectively demonstrated that geologic processes occur over extremely long periods of time. However, Hutton persuasively argued that seemingly small forces can, over long spans of time, produce effects that are just as great as those resulting from sudden catastrophic events. Unlike his predecessors, Hutton carefully cited verifiable observations to support his ideas.

For example, when Hutton argued that mountains are sculpted and ultimately destroyed by weathering and the work of running water, and that their waste materials are carried to the oceans by observable processes, he said, "We have a chain of facts which clearly demonstrate . . . that the materials of the wasted mountains have traveled through the rivers"; and further, "There is not one step in all this progress . . . that is not to be actually perceived." He then summarized this thought by asking a question and immediately providing the answer: "What more can we require? Nothing but time."

Geology Today

Today the basic tenets of uniformitarianism are just as viable as in Hutton's day. Indeed, we realize more strongly than ever before that the present gives us insight into the past and that the physical, chemical, and biological laws that govern geologic processes remain unchanging through time. However, we also understand that the doctrine should not be taken too literally. To say that geologic processes in the past were the same as those occurring today is not to suggest that they have always had the same relative importance or that they have operated at precisely the same rate. Moreover, some important geologic processes are not currently observable, but there is well-established evidence that they occur. For example, we know that Earth has experienced impacts from large meteorites even though we have no human witnesses to those impacts. Nevertheless, such events have altered Earth's crust, modified its climate, and strongly influenced life on the planet.

Acceptance of uniformitarianism meant the acceptance of a very long history for Earth. Although Earth processes vary in intensity, they still take a very long time to create or destroy major landscape features. The Grand Canyon provides a good example (**Figure 1.5**).

The rock record contains evidence showing that Earth has experienced many cycles of mountain building and erosion (**Figure 1.6**). Concerning the ever-changing nature of Earth through great expanses of geologic time, Hutton famously stated in 1788: "The results, therefore,

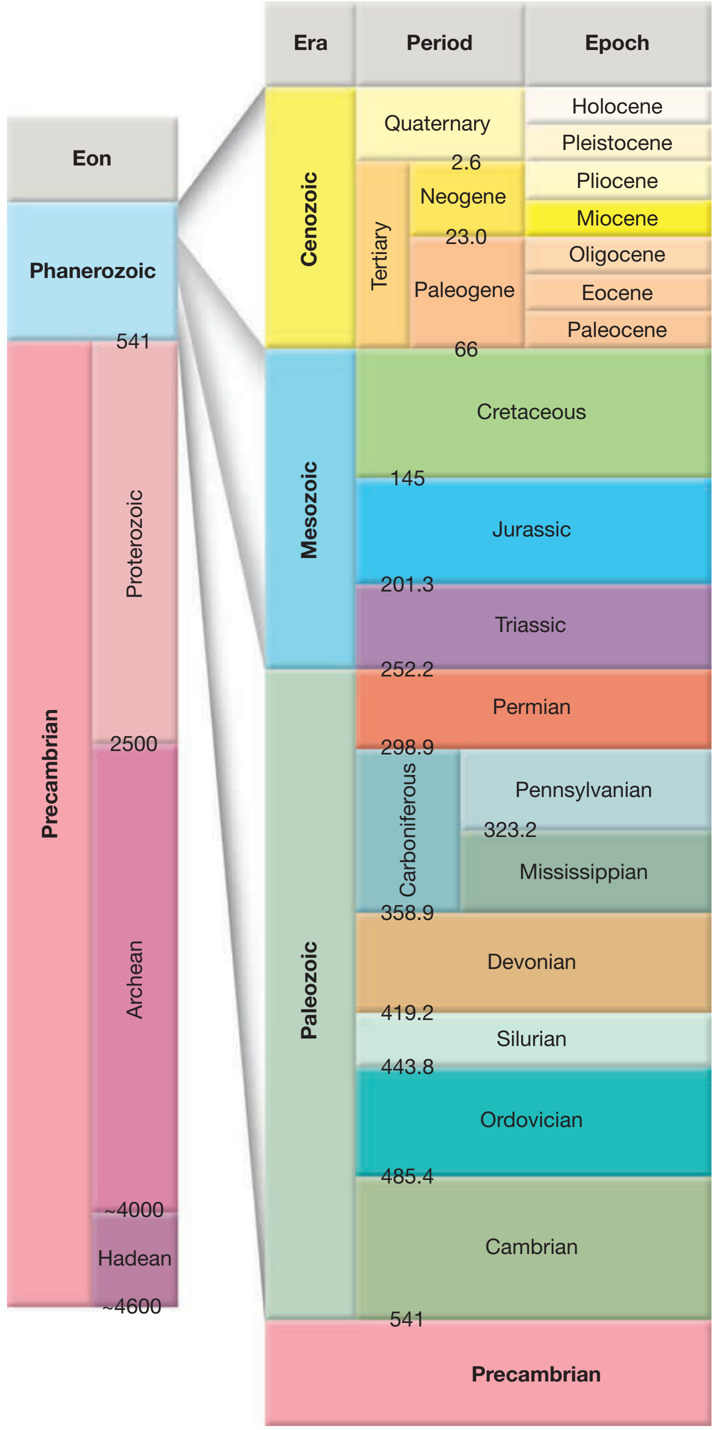
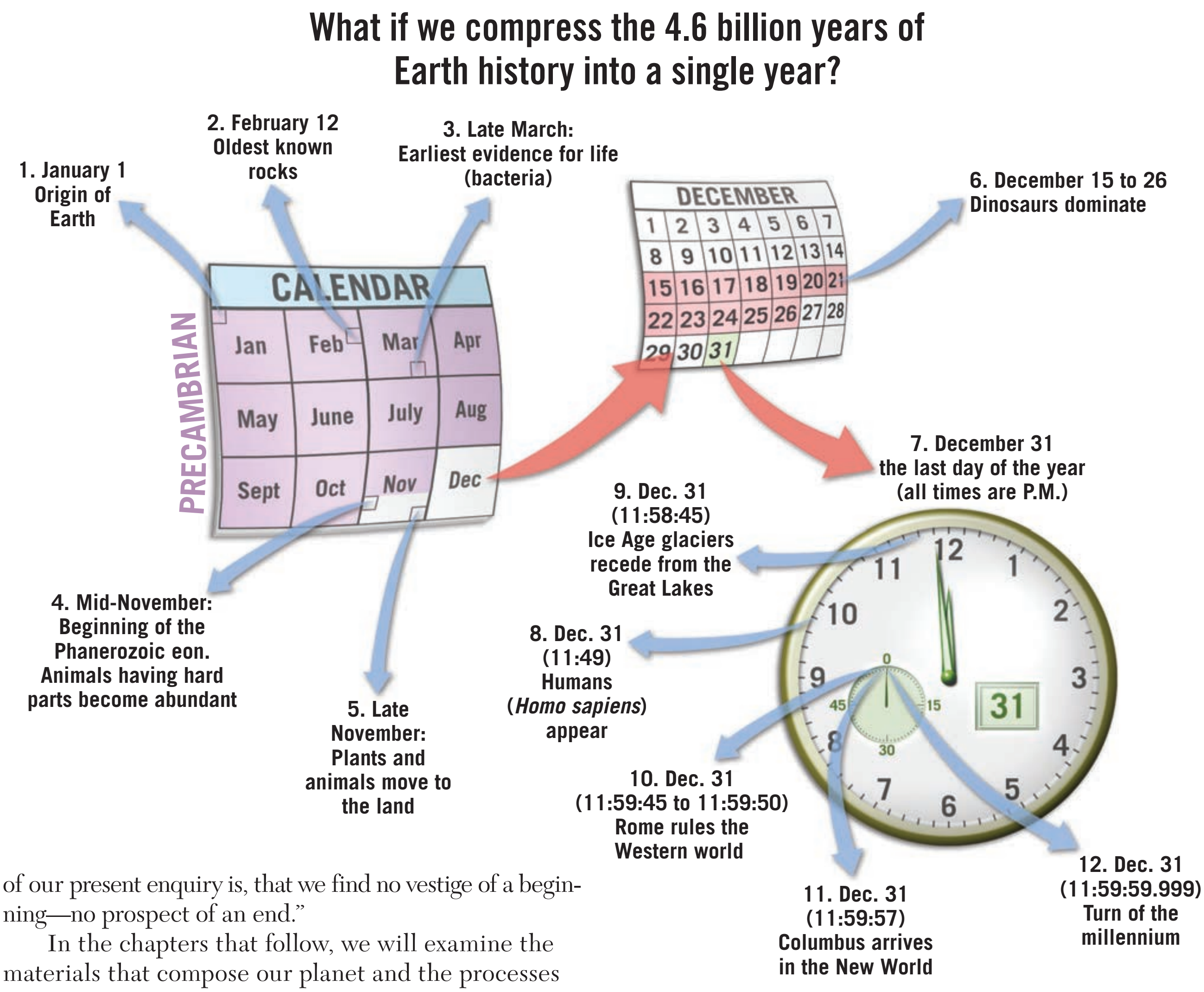


Figure 1.6

Geologic time scale: A basic reference The time scale divides the vast 4.6-billion-year history of Earth into eons, eras, periods, and epochs. Numbers on the time scale represent time in millions of years before the present. The Precambrian accounts for more than 88 percent of geologic time. The geologic time scale is a dynamic tool that is periodically updated. Numerical ages appearing on this time scale are those that were currently accepted by the International Commission on Stratigraphy (ICS) in 2014. The color scheme used on this chart was selected because it is similar to that used by the ICS. The ICS is responsible for establishing global standards for the time scale.

SmartFigure 1.7
Magnitude of geologic time
(https://goo.gl/odwyUE)
Tutorial



of our present enquiry is, that we find no vestige of a beginning—no prospect of an end."

In the chapters that follow, we will examine the materials that compose our planet and the processes that modify it. It is important to remember that, although many features of our physical landscape may seem to be unchanging over the decades we observe them, they are nevertheless changing—but on time scales of hundreds, thousands, or even many millions of years.

The Magnitude of Geologic Time

Among geology's important contributions to human knowledge is the discovery that Earth has a very long and complex history. Although Hutton and others recognized that geologic time is exceedingly long, they had no methods to accurately determine the age of Earth. Early time scales simply placed the events of Earth history in the proper sequence or order, without knowing how long ago in years they occurred.

Today our understanding of radioactivity—and the fact that rocks and minerals contain certain radioactive isotopes having decay rates ranging from decades to billions of years—allows us to accurately determine numerical dates for rocks that represent important events in Earth's distant past (Figure 1.6). For example, we know that the dinosaurs died out about 65 million years ago. Today geologists put the age of Earth at about 4.6 billion years. Chapter 9 is devoted to a much more complete discussion of geologic time and the geologic time scale.

The concept of geologic time is new to many nongeologists. People are accustomed to dealing with increments of time measured in hours, days, weeks, and years. History books often examine events over spans of centuries, but even a century is difficult to appreciate fully. For most of us, someone or something that is 90 years old is *very old*, and a 1000-year-old artifact is *ancient*.

By contrast, geologists must routinely deal with vast time periods—millions or billions (thousands of millions) of years. When viewed in the context of Earth's 4.6-billion-year history, a geologic event that occurred 100 million years ago may be characterized as "recent" by a geologist, and a rock sample that has been dated at 10 million years may be called "young." An appreciation for the magnitude of geologic time is important in the study of geology because many processes are so gradual that vast spans of time are needed before significant changes occur. How long is 4.6 billion years? If you were to begin counting at the rate of one number per second and continued 24 hours a day, 7 days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.6 billion! **Figure 1.7** provides another interesting way of viewing the expanse of geologic time. Although helpful in conveying the magnitude of geologic time, this figure and other analogies, no matter how clever, only begin to help us comprehend the vast expanse of Earth history.

1.2 Concept Checks

1. **Describe Aristotle's influence on geology.**
2. **Contrast catastrophism and uniformitarianism. How did each view the age of Earth?**
3. **How old is Earth?**
4. **Refer to Figure 1.6 and list the eon, era, period, and epoch in which we live.**
5. **Why is an understanding of the magnitude of geologic time important for a geologist?**

1.3 The Nature of Scientific Inquiry

Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.

In our modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Science is a process of producing knowledge, based on making careful observations and on creating explanations that make sense of the observations. Developing an understanding of how science is done and how scientists work is an important theme appearing throughout this book. You will explore the difficulties in gathering data and some of the ingenious methods that have been developed to overcome these difficulties. You will also see many examples of how hypotheses are formulated and tested, and you will learn about the evolution and development of some major scientific theories.

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then use that knowledge to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by knowing how oil deposits form, geologists can predict the most favorable sites for exploration and, perhaps as importantly, avoid regions that have little or no potential.

EYE ON EARTH 1.1

These rock layers consist of sediments such as sand, mud, and gravel that were deposited by rivers, waves, wind, and glaciers. The material was buried and eventually compacted and cemented into solid rock. Later, erosion uncovered the layers.

QUESTION 1 Can you establish a relative time scale for these rocks? That is, can you determine which one of the layers shown here is likely oldest and which is probably youngest?

QUESTION 2 Explain the logic you used.

(Photo by David Carriere/AGE Fotostock)

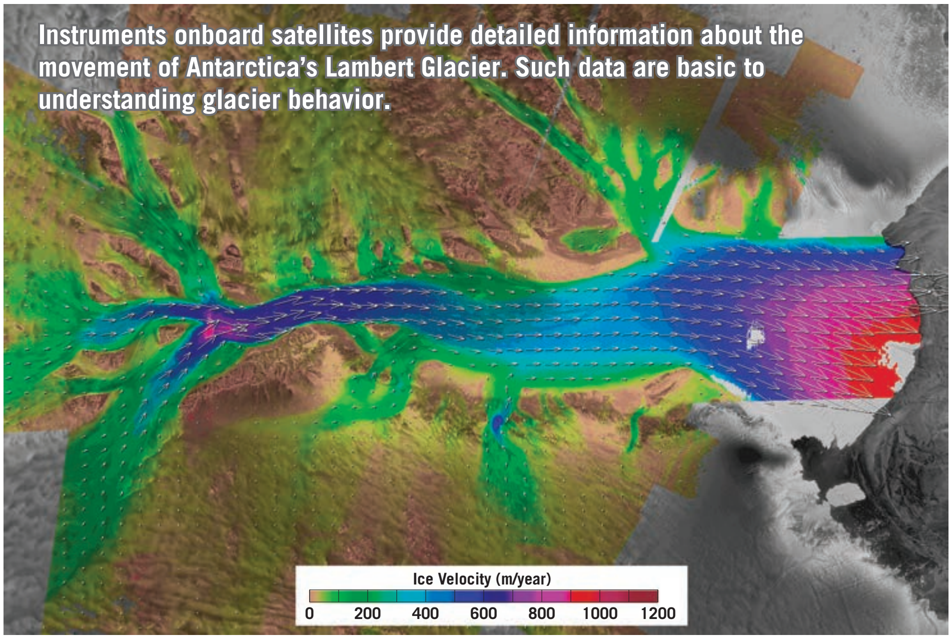


Figure 1.8
Observation and measurement Scientific data are gathered in many ways. (Satellite image by NASA)

The development of new scientific knowledge involves basic logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect data through observation and measurement (**Figure 1.8**). The data collected often help answer well-defined questions about the natural world. Because some error is inevitable, the accuracy of a particular measurement or observation is always open to question. Nevertheless, these data are essential to science and serve as a springboard for the development of scientific theories.

Hypothesis

Once data have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happen in the manner observed. They often do this by constructing a tentative (or untested) explanation, which is called a scientific **hypothesis**. It is best if an investigator can formulate more than one hypothesis to explain a given set of observations. If an individual scientist cannot devise multiple hypotheses, others in the scientific community will almost always develop alternative explanations. A spirited debate frequently ensues. As a result, proponents of opposing hypotheses conduct extensive research, and scientific journals make the results available to the wider scientific community.

Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. If a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it might seem. The verification process requires that *predictions* be made, based on the hypothesis being considered, and that the predictions be tested through comparison with objective observations. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are ultimately discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. As mathematician Jacob Bronowski so ably stated, "Science is a great many things, but in the end they all return to this: Science is the acceptance of what works and the rejection of what does not."

Theory

When a hypothesis has survived extensive scrutiny and when competing hypotheses have been eliminated, it may be elevated to the status of a scientific **theory**. In everyday speech, we often hear that something is "only a theory." But a scientific theory is a well-tested and widely accepted view that the scientific community agrees best explains certain observable facts. Some theories that are extensively documented and extremely well supported are comprehensive in scope. For example, the theory of plate tectonics provides a framework for understanding the origins of mountains, earthquakes, and volcanic activity. Plate tectonics also explains the evolution of the continents and the ocean basins through time—ideas that are explored in detail in Chapters 2, 13, and 14.

Scientific Methods

The process just described, in which researchers gather data through observations and formulate scientific hypotheses and theories, is called the **scientific method**. Contrary to popular belief, the scientific method is not a standard recipe that scientists apply in a routine manner to unravel the secrets of our natural world; rather, it is an endeavor that involves creativity and insight. Rutherford and Ahlgren put it this way: "Inventing hypotheses or theories to imagine how the world works and then figuring out how they can be put to the test of reality is as creative as writing poetry, composing music, or designing skyscrapers."*

*F. James Rutherford and Andrew Ahlgren, *Science for All Americans* (New York: Oxford University Press, 1990), p. 7.

There is no fixed path that scientists always follow that leads unerringly to scientific knowledge. However, many scientific investigations involve the steps outlined in Figure 1.9. In addition, some scientific discoveries result from purely theoretical ideas that stand up to extensive examination. Some researchers use high-speed computers to create models that simulate what is happening in the "real" world. These models are useful when dealing with natural processes that occur on very long time scales or take place in extreme or inaccessible locations. Still other scientific advancements are made when a totally unexpected happening occurs during an experiment. These serendipitous discoveries are more than pure luck, for as the nineteenth-century French scientist Louis Pasteur said, "In the field of observation, chance favors only the prepared mind."

Scientific knowledge is acquired through several avenues, so it might be best to describe the nature of scientific inquiry as the methods of science rather than as the scientific method. In addition, we should always remember that even the most compelling scientific theories are still simplified explanations of the natural world.

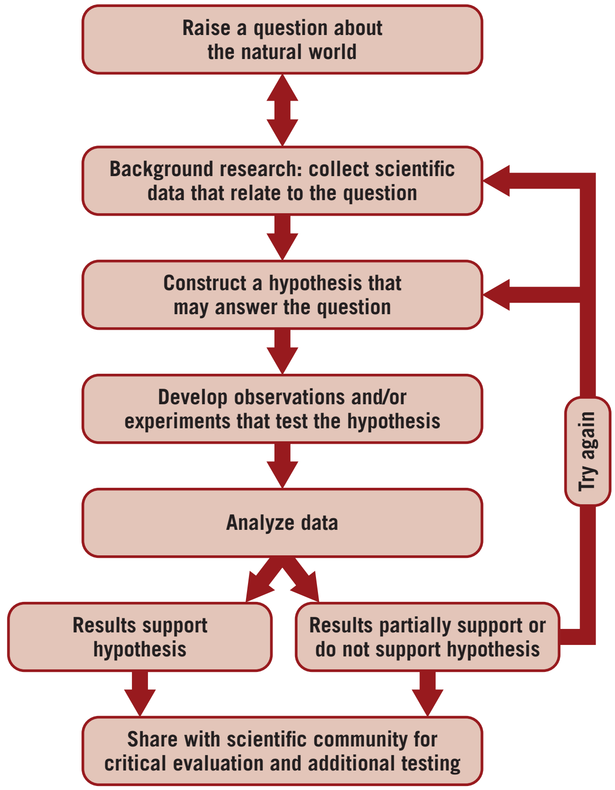


Figure 1.9
Steps frequently followed in scientific investigations
The diagram depicts the steps involved in the process many refer to as the *scientific method*.

Plate Tectonics and Scientific Inquiry

This book offers many opportunities to develop and reinforce your understanding of how science works and, in particular, how the science of geology works. You will learn about data-gathering methods and the observational techniques and reasoning processes used by geologists.

Chapter 2 provides an excellent example. During the past several decades, we have learned a great deal about the workings of our dynamic planet. This period has seen an unequaled revolution in our understanding of Earth. The revolution began in the early part of the twentieth century, with the radical proposal of *continental drift*—the idea that the continents move about the face of the planet. This hypothesis contradicted the established view that the continents and ocean basins are permanent and stationary features on the face of Earth. For that reason, the notion of drifting continents was received with great skepticism and even ridicule. More than 50 years passed before enough data were gathered to transform this controversial hypothesis into a sound theory that wove together the basic processes known to operate on Earth. The theory that finally emerged, called the *theory of plate tectonics*, provided geologists with the first comprehensive model of Earth's internal workings.

In Chapter 2, you will not only gain insights into the workings of our planet, you will also see an excellent example of the way geologic "truths" are uncovered and reworked.

1.3 Concept Checks

1. How is a scientific hypothesis different from a scientific theory?
2. Summarize the basic steps followed in many scientific investigations.

1.4 Earth as a System

List and describe Earth's four major spheres. Define *system* and explain why Earth is considered to be a system.

Anyone who studies Earth soon learns that our planet is a dynamic body with many separate but interacting parts, or *spheres*. The hydrosphere, atmosphere, biosphere, and geosphere and all of their components can be studied separately. However, the parts are *not* isolated. Each is related in some way to the others, producing a complex and continuously interacting whole that we call the *Earth system*.

Earth's Spheres

The images in Figure 1.10 are considered to be classics because they let humanity see Earth differently than ever before. These early views profoundly altered our conceptualizations of Earth and remain powerful images decades after they were first viewed. Seen from space, Earth is breathtaking in its beauty and startling in its solitude. The photos remind us that our home is, after all, a planet—small, self-contained, and in some ways even fragile.

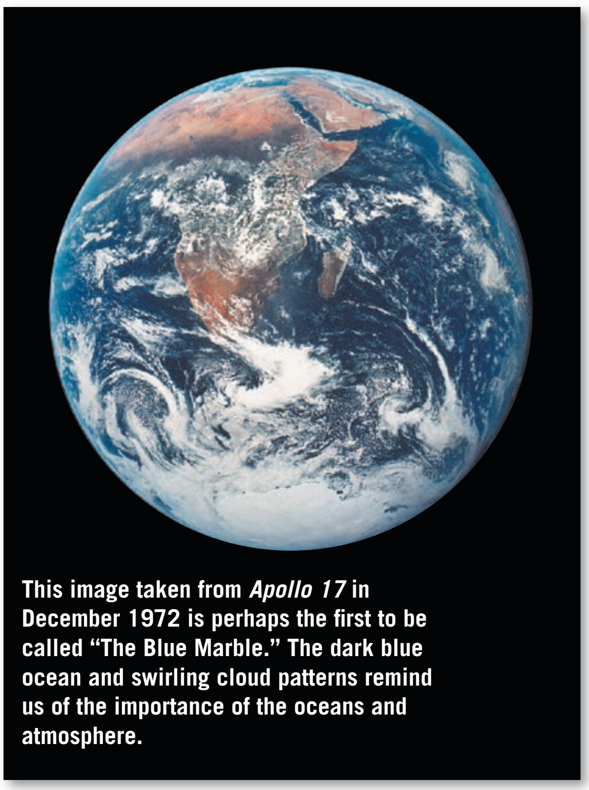
As we look closely at our planet from space, it becomes apparent that Earth is much more than rock and soil. In fact, among the most conspicuous features in both views of Earth in Figure 1.10 are swirling clouds suspended above the surface of the vast global ocean. These features emphasize the importance of water on our planet.

The closer view of Earth from space shown in Figure 1.10 helps us appreciate why the physical environment is traditionally divided into three major parts: the water portion of our planet, the *hydrosphere*; Earth's gaseous envelope, the *atmosphere*; and, of course, the solid Earth, or *geosphere*. It needs to be emphasized that our environment is highly integrated and not dominated by rock, water, or air alone. Rather, it is characterized by continuous interactions as air comes in contact with rock, rock with water, and water with air. Moreover, the *biosphere*, which is the totality of all plant and animal life on our planet, interacts with each of the three physical realms and is an equally integral part of the planet. Thus, Earth can be thought of as consisting of four major spheres: the hydrosphere, atmosphere, geosphere, and biosphere.

The interactions among Earth's spheres are incalculable. Figure 1.11 provides us with one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air. In this scene, ocean waves created by the drag of air moving across the water are breaking against the rocky shore.

Figure 1.10 **Two classic views of Earth from space** (NASA)

View called "Earthrise" that greeted *Apollo 8* astronauts as their spacecraft emerged from behind the Moon in December 1968. This classic image let people see Earth differently than ever before.



This image taken from *Apollo 17* in December 1972 is perhaps the first to be called "The Blue Marble." The dark blue ocean and swirling cloud patterns remind us of the importance of the oceans and atmosphere.

Hydrosphere Earth is sometimes called the *blue planet*. Water, more than anything else, makes Earth unique. The **hydrosphere** is a dynamic mass of water that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface to an average depth of about 3800 meters (12,500 feet). It accounts for about 97 percent of Earth's water (Figure 1.12). However, the hydrosphere also includes the freshwater found underground and in streams, lakes, and glaciers. Moreover, water is an important component of all living things.

Although these latter sources constitute just a tiny fraction of the total, they are much more important than their meager percentages indicates. In addition to providing the freshwater that is so vital to life on land, streams, glaciers, and groundwater are responsible for sculpting and creating many of our planet's varied landforms.

Atmosphere Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (Figure 1.13). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth (about 6400 kilometers [4000 miles]), the atmosphere is a very shallow layer. Despite its modest dimensions, this thin blanket of

Figure 1.11
Interactions among Earth's spheres The shoreline is one obvious interface—a common boundary where different parts of a system interact. In this scene at California's Montano del Oro State Park, ocean waves (hydrosphere) that were created by the force of moving air (atmosphere) break against a rocky shore (geosphere). The force of the water can be powerful, and the erosional work that is accomplished can be great. (Photo by Michael Collier)

air is an integral part of the planet. It not only provides the air we breathe but also protects us from the Sun's intense heat and dangerous ultraviolet radiation. The energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call *weather* and *climate*. Climate has a strong influence on the nature and intensity of Earth's external processes. When climate changes, these processes respond.

If, like the Moon, Earth had no atmosphere, our planet would be lifeless, and many of the processes and interactions that make the surface such a dynamic place could not operate. Without weathering and erosion, the face of our planet might more closely resemble the lunar surface, which has not changed appreciably in nearly 3 billion years.

Biosphere The **biosphere** includes all life on Earth (**Figure 1.14**). Ocean life is concentrated in the sunlit surface waters of the sea. Most life on land is also concentrated near the surface, with tree roots and burrowing animals tunneling a few meters underground and flying insects and birds reaching a kilometer or so into the atmosphere. A surprising variety of life-forms are also adapted to extreme environments. For example, on the ocean floor, where pressures are extreme and no light penetrates, there are places where vents spew hot, mineral-rich fluids that support communities of exotic life-forms. On land, some bacteria thrive in rocks as deep as 4 kilometers (2.5 miles) and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth's surface.

Plants and animals depend on the physical environment for the basics of life. However, organisms do not just respond to their physical environment. Through countless interactions, life-forms help maintain and alter the physical environment. Without life, the makeup and nature of the geosphere, hydrosphere, and atmosphere would be very different.

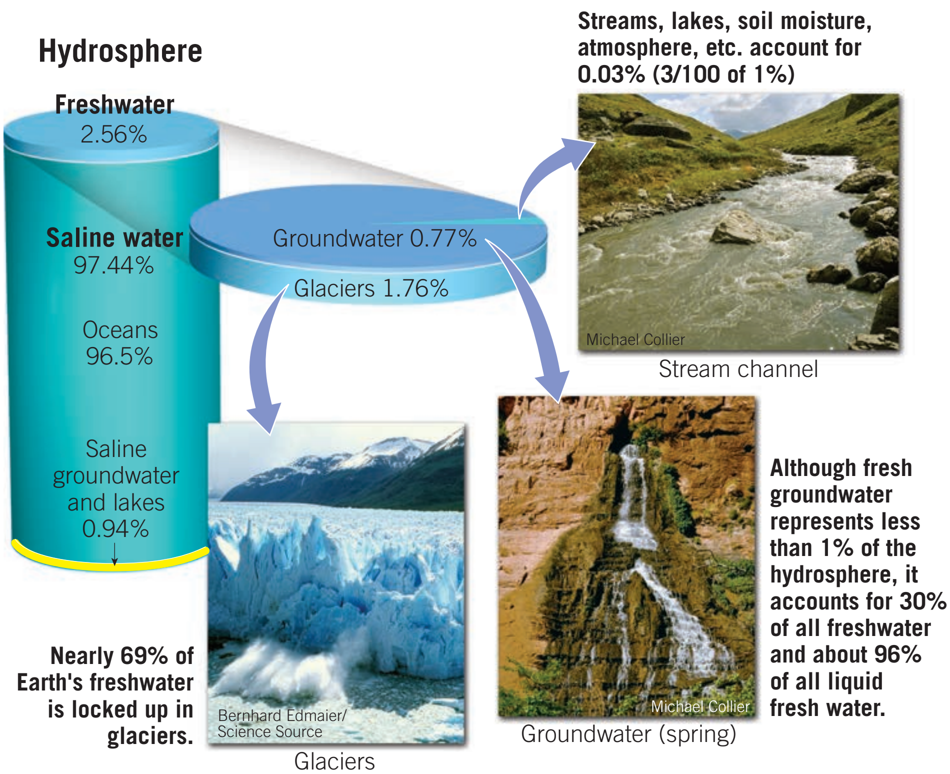
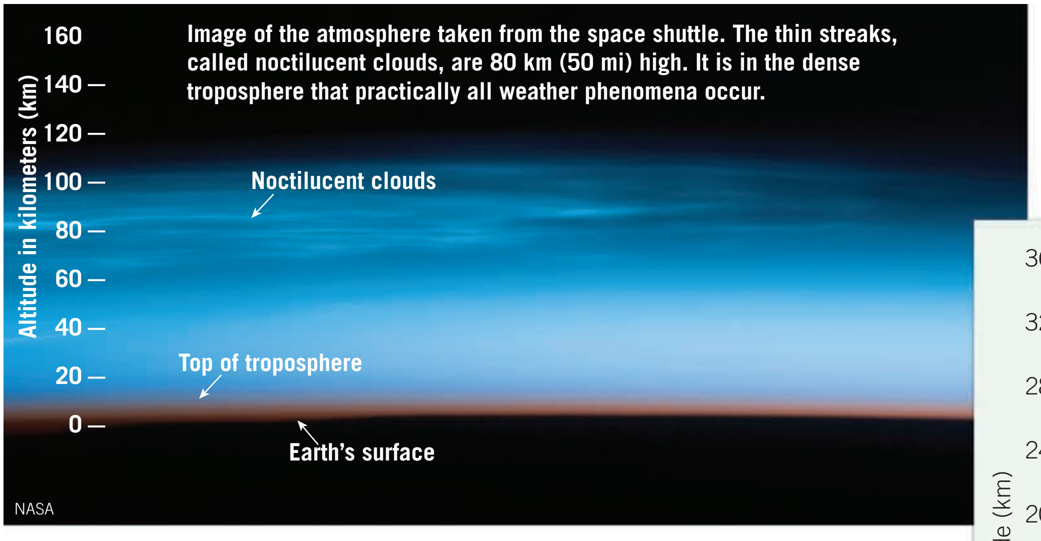


Figure 1.12
The water planet Distribution of water in the hydrosphere.



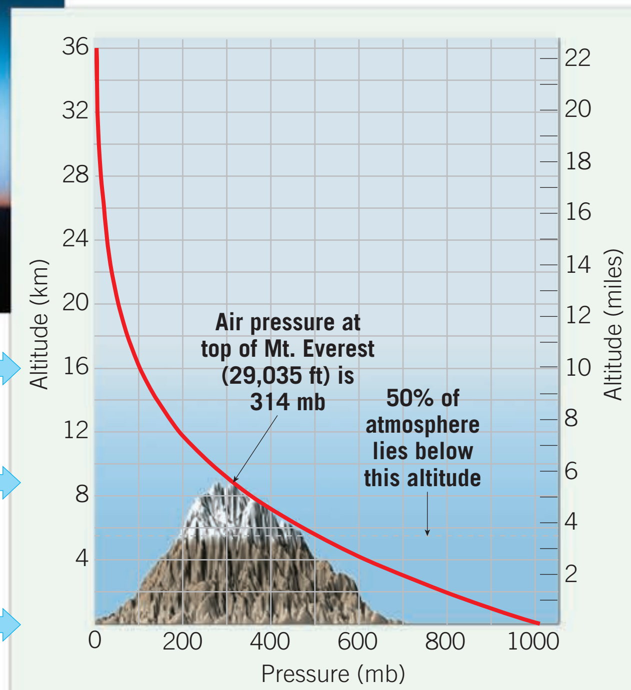


Figure 1.13
A shallow layer The atmosphere is an integral part of the planet. (NASA)

Figure 1.14
The biosphere The biosphere, one of Earth's four spheres, includes all life. (Coral reef photo by Darryl Leniuk /AGE Fotostock; rain forest photo by AGE Fotostock/SuperStock)

Geosphere Beneath the atmosphere and the oceans is the solid Earth, or **geosphere**. The geosphere extends from the surface to the center of the planet, a depth of nearly 6400 kilometers (nearly 4000 miles), making it by far the largest of Earth's four spheres. Much of our study of the solid Earth focuses on the more accessible surface features. Fortunately, many of these features represent the outward expressions of the dynamic behavior of Earth's interior. Examining the most prominent surface features and their global extent gives us clues to the dynamic processes that have shaped our planet. A first look at the structure of Earth's interior and at the major surface features of the geosphere comes later in the chapter.

Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered

EYE ON EARTH 1.2

This jet is cruising at an altitude of 10 kilometers (6.2 miles).

QUESTION 1 Refer to the graph in Figure 1.13. What is the approximate air pressure at the altitude where the jet is flying?

QUESTION 2 About what percentage of the atmosphere is below the jet (assuming that the pressure at the surface is 1000 millibars)?

(Photo by interlight/Shutterstock)

rock debris (geosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between the solid particles.

Earth System Science

A simple example of the interactions among different parts of the Earth system occurs every winter and spring, as moisture evaporates from the Pacific Ocean and subsequently falls as rain in coastal hills and mountains, triggering destructive debris flows. The processes that move water from the hydrosphere to the atmosphere and then to the solid Earth have a profound impact on the plants and animals (including humans) that inhabit the affected regions (**Figure 1.15**).

Scientists have recognized that in order to more fully understand our planet, they must learn how its individual components (land, water, air, and life-forms) are interconnected. This endeavor, called **Earth system science**, aims to study Earth as a *system* composed of numerous interacting parts, or *subsystems.* Rather than look through the limited lens of only one of the traditional sciences—geology, atmospheric science, chemistry, biology, and so on—Earth system science attempts to integrate the knowledge of several academic fields. Using an interdisciplinary approach, those engaged in Earth system science attempt to achieve the level of understanding necessary to comprehend and solve many of our global environmental problems.

A **system** is a group of interacting, or interdependent, parts that form a complex whole. Most of us hear and use the term *system* frequently. We may service our car's cooling *system*, make use of the city's transportation *system*, and participate in our political *system*. A news report might inform us of an approaching weather *system*. Further, we know that Earth is just a small part of a larger system known as the *solar system*, which in turn is a subsystem of an even larger system, the Milky Way Galaxy.

The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over. One familiar

Figure 1.15
Deadly debris flow This image provides an example of interactions among different parts of the Earth system. Extraordinary rains triggered this debris flow (popularly called a mudslide) on March 22, 2014, near Oso, Washington. The mass of mud and debris blocked the North Fork of the Stillaguamish River and engulfed an area of about 2.6 square kilometers (1 square mile). Forty-three people perished. (Photo by Michael Collier)

Figure 1.16
Change is a geologic constant When Mount St. Helens erupted in May 1980, the area shown here was buried by a volcanic mudflow. Now plants are reestablished, and new soil is forming. (Photo by Terry Donnelly/Alamy Images)

loop or subsystem is the *hydrologic cycle*. It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and geosphere. Water enters the atmosphere through evaporation from Earth's surface and transpiration from plants. Water vapor condenses in the atmosphere to form clouds, which in turn produce precipitation that falls back to Earth's surface. Some of the rain that falls onto the land infiltrates (soaks in) to be taken up by plants or become groundwater, and some flows across the surface toward the ocean.

Viewed over long time spans, the rocks of the geosphere are constantly forming, changing, and re-forming. The loop that involves the processes by which one rock changes to another is called the *rock cycle* and will be discussed at some length later in the chapter. The cycles of the Earth system are not independent of one another; to the contrary, these cycles come in contact and interact in many places.

The parts of the Earth system are linked so that a change in one part can produce changes in any or all of the other parts. For example, when a volcano erupts, lava from Earth's interior may flow out at the surface and block a nearby valley. This new obstruction influences the region's drainage system by creating a lake or causing streams to change course. The large quantities of volcanic ash and gases that can be emitted during an eruption might be blown high into the atmosphere and influence the amount of solar energy that can reach Earth's surface. The result could be a drop in air temperatures over the entire hemisphere.

Where the surface is covered by lava flows or a thick layer of volcanic ash, existing soils are buried. This causes soil-forming processes to begin anew to transform the new surface material into soil (Figure 1.16). The soil that eventually forms will reflect the interactions among many parts of the Earth system—the volcanic parent material, the climate, and the impact of biological activity. Of course, there would also be significant changes in the biosphere. Some organisms and their habitats would be eliminated by the lava and ash, whereas new settings for life, such as a lake formed by a lava dam, would be created. The potential climate change could also impact sensitive life-forms.

The Earth system is characterized by processes that vary on spatial scales from fractions of millimeters to thousands of kilometers. Time scales for Earth's processes range from seconds to billions of years. As we learn about Earth, it becomes increasingly clear that despite significant separations in distance or time, many processes are connected, and a change in one component can influence the entire system.

The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, in the hydrosphere, and at Earth's surface. Weather and climate, ocean circulation, and erosional processes are driven by energy from the Sun. Earth's interior is the second source of energy. Heat remaining from when our planet formed and heat that is continuously generated by radioactive decay power the internal processes that produce volcanoes, earthquakes, and mountains.

Humans are *part of* the Earth system, a system in which the living and nonliving components are entwined and interconnected. Therefore, our actions produce changes in all the other parts. When we burn gasoline and coal, dispose of our wastes, and clear the land, we cause other parts of the system to respond, often in unforeseen ways. Throughout this book you will learn about many of Earth's subsystems, including the hydrologic system, the tectonic (mountain-building) system, the rock cycle, and the climate system. Remember that these components *and we humans* are all part of the complex interacting whole we call the Earth system.

1.4 Concept Checks

1. List and briefly describe the four spheres that constitute the Earth system.
2. Compare the height of the atmosphere to the thickness of the geosphere.
3. How much of Earth's surface do oceans cover? What percentage of Earth's water supply do oceans represent?
4. What is a system? List three examples.
5. What are the two sources of energy for the Earth system?

1.5 Origin and Early Evolution of Earth

Outline the stages in the formation of our solar system.

Recent earthquakes caused by displacements of Earth's crust and lavas spewed from active volcanoes represent only the latest in a long line of events by which our planet has attained its present form and structure. The geologic processes operating in Earth's interior can be best understood when viewed in the context of much earlier events in Earth history.

Origin of Our Solar System

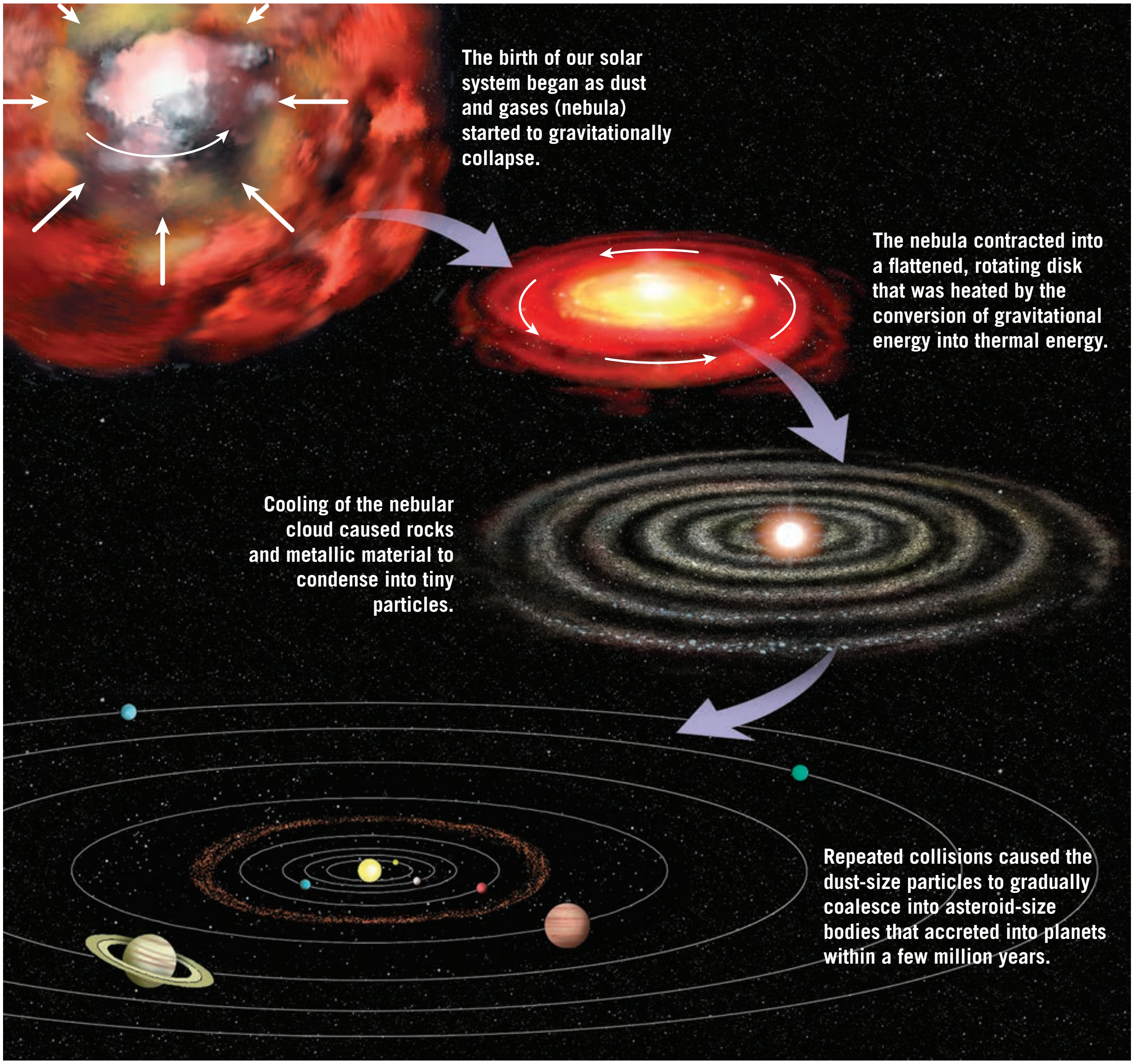
This section describes the most widely accepted views on the origin of our solar system. The theory described here represents the most consistent set of ideas we have to explain what we know about our solar system today. GEOgraphics 1.2 provides a useful perspective on size and scale in our solar system. In addition, the origins of Earth and other bodies of our solar system are discussed in more detail in Chapters 2 and 24.

The Universe Begins Our scenario begins about 13.7 billion years ago with the *Big Bang*, an incomprehensibly large explosion that sent all matter of the universe flying outward at incredible speeds. In time, the debris from this explosion, which was almost entirely hydrogen and helium, began to cool and condense into the first stars and galaxies. It was in one of these galaxies, the Milky Way, that our solar system and planet Earth took form.

The Solar System Forms Earth is one of eight planets that, along with several dozen moons and numerous smaller bodies, revolve around the Sun. The orderly nature of our solar system leads researchers to conclude that Earth and the other planets formed at essentially the same time and from the same primordial material as the Sun. The **nebular theory** proposes that the bodies of our solar system evolved from an enormous rotating cloud called the **solar nebula** (Figure 1.17). Besides the hydrogen and helium atoms generated during the Big Bang, the solar nebula consisted of microscopic dust grains and the ejected matter of long-dead stars. (Nuclear fusion in stars converts hydrogen and helium into the other elements found in the universe.)

Nearly 5 billion years ago, this huge cloud of gases and minute grains of heavier elements began to slowly contract due to the gravitational interactions among its particles. Some external influence, such as a shock wave traveling from a catastrophic explosion (*supernova*), may have triggered the collapse. As this slowly spiraling nebula contracted, it rotated faster and faster for the same reason ice skaters do when they draw their arms toward their bodies. Eventually the inward pull of gravity came into balance with the outward force caused by the rotational motion of the nebula (see Figure 1.17). By this time, the once-vast cloud had assumed a flat disk shape with a large concentration of material at its center called the *protosun* (pre-Sun). (Astronomers are fairly confident that the nebular cloud formed a disk because similar structures have been detected around other stars.)

During the collapse, gravitational energy was converted to thermal (heat) energy, causing the temperature of the inner portion of the nebula to dramatically rise. At these high temperatures, the dust grains broke up into molecules and extremely energetic atomic particles. However, at distances beyond the orbit of Mars, temperatures probably remained quite low. At –200°C (–328°F), the tiny particles in the outer portion of the nebula were likely covered with a thick layer of frozen water, carbon dioxide, ammonia, and methane. The disk-shaped cloud also contained appreciable amounts of the lighter gases hydrogen and helium.



SmartFigure 1.17
Nebular theory The nebular theory explains the formation of the solar system.
(https://goo.gl/dRZJBp)

Tutorial

The Inner Planets Form The formation of the Sun marked the end of the period of contraction and thus the end of gravitational heating. Temperatures in the region where the inner planets now reside began to decline. This decrease in temperature caused those substances with high melting points to condense into tiny particles that began to coalesce (join together). Materials such as iron and nickel and the elements of which the rock-forming minerals are composed—silicon, calcium, sodium, and so forth—formed metallic and rocky clumps that orbited the Sun (see Figure 1.17). Repeated collisions caused these masses to coalesce into larger asteroid-size bodies, called *planetesimals*, which in a few tens of millions of years accreted into the four inner planets we call Mercury, Venus, Earth, and Mars (Figure 1.18). Not all of these clumps of matter were incorporated into the planetesimals. Those rocky and metallic pieces that remained in orbit are called *meteorites* when they survive an impact with Earth.

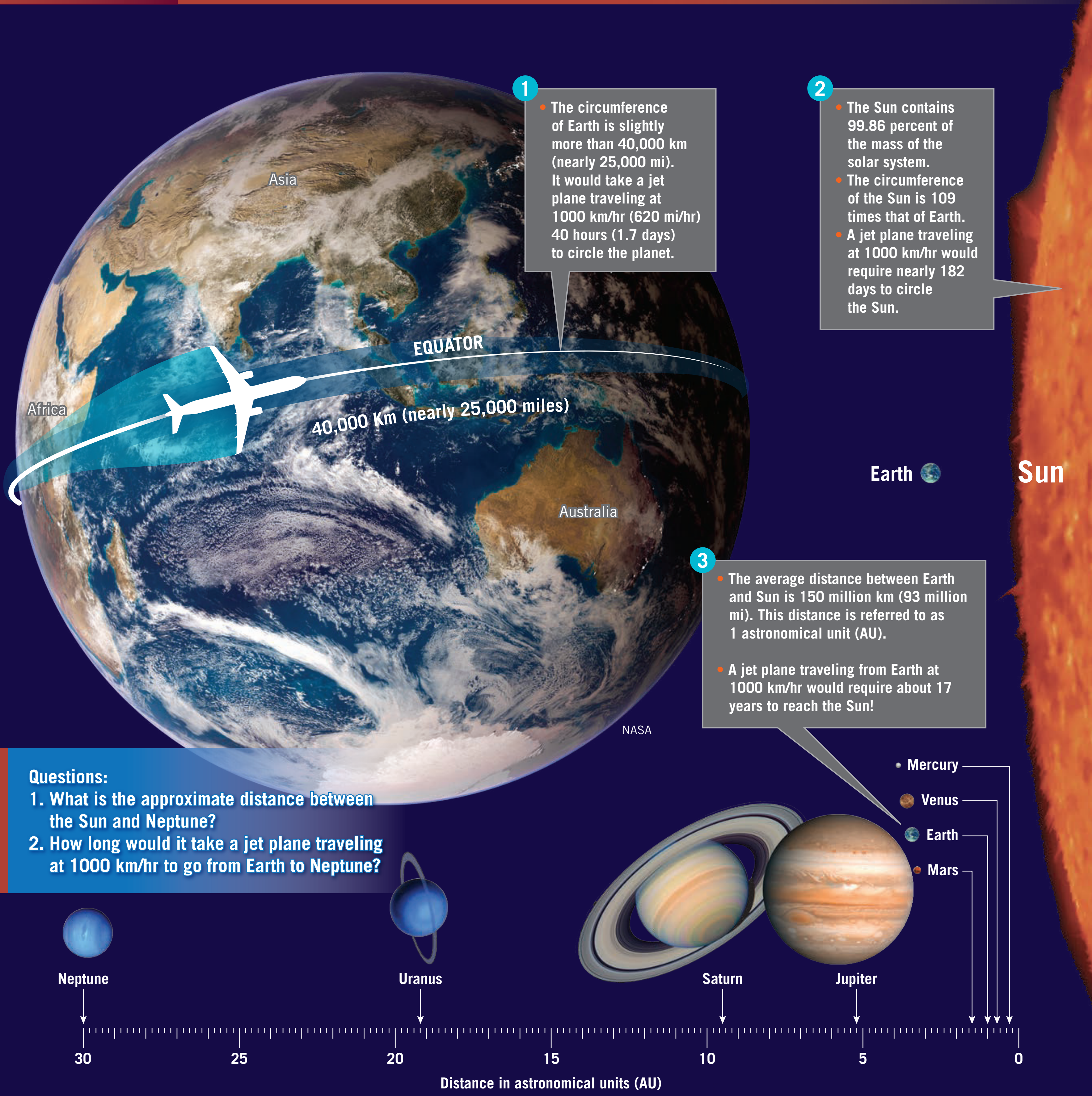
As more and more material was swept up by the planets, the high-velocity impact of nebular debris caused the temperatures of these bodies to rise. Because of their relatively high temperatures and weak gravitational fields, the inner planets were unable to accumulate much of the lighter components of the nebular cloud. The lightest of these, hydrogen and helium, were eventually whisked from the inner solar system by the solar wind.

The Outer Planets Develop At the same time that the inner planets were forming, the larger outer planets (Jupiter, Saturn, Uranus, and Neptune), along with their

GEO GRAPHICS 1.2

Solar System: Size and Scale

The Sun is the center of a revolving system trillions of miles across, consisting of 8 planets, their satellites, and numerous dwarf planets, asteroids, comets, and meteoroids.



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Questions:

1. What is the approximate distance between the Sun and Neptune?
2. How long would it take a jet plane traveling at 1000 km/hr to go from Earth to Neptune?

Figure 1.18
A remnant planetesimal This image of Asteroid 21 Lutetia was obtained by special cameras aboard the *Rosetta* spacecraft on July 10, 2010. Spacecraft instruments showed that Lutetia is a primitive body (planetesimal) left over from when the solar system formed. (NASA)

extensive satellite systems, were also developing. Because of low temperatures far from the Sun, the material from which these planets formed contained a high percentage of ices—frozen water, carbon dioxide, ammonia, and methane—as well as rocky and metallic debris. The accumulation of ices partly accounts for the large size and low density of the outer planets. The two most massive planets, Jupiter and Saturn, had a surface gravity sufficient to attract and hold large quantities of even the lightest elements—hydrogen and helium.

Formation of Earth's Layered Structure

As material accumulated to form Earth (and for a short period afterward), the high-velocity impact of nebular debris and the decay of radioactive elements caused the temperature of our planet to steadily increase. During this time of intense heating, Earth became hot enough that iron and nickel began to melt. Melting produced liquid blobs of dense metal that sank toward the center of the planet. This process occurred rapidly on the scale of geologic time and produced Earth's dense, iron-rich core.

Chemical Differentiation and Earth's Layers The early period of heating resulted in another process of chemical differentiation, whereby melting formed buoyant masses of molten rock that rose toward the surface and solidified to produce a primitive crust. These rocky materials were enriched in oxygen and "oxygen-seeking" elements, particularly silicon and aluminum, along with lesser amounts of calcium, sodium, potassium, iron, and magnesium. In addition, some heavy metals such as gold, lead, and uranium, which have low melting points or were highly soluble in the ascending molten masses, were scavenged from Earth's interior and concentrated in the developing crust. This early period of chemical differentiation established the three basic divisions of Earth's interior: the iron-rich *core*; the thin *primitive crust*; and Earth's largest layer, called the *mantle*, which is located between the core and crust.

An Atmosphere Develops An important consequence of the early period of chemical differentiation is that large quantities of gaseous materials were allowed to escape from Earth's interior, as happens today during volcanic eruptions. By this process, a primitive atmosphere gradually evolved. It is on this planet, with this atmosphere, that life as we know it came into existence.

Continents and Ocean Basins Evolve Following the events that established Earth's basic structure, the primitive crust was lost to erosion and other geologic processes, so we have no direct record of its makeup. When and exactly how the continental crust—and thus Earth's first landmasses—came into existence is a matter of ongoing research. Nevertheless, there is general agreement that the continental crust formed gradually over the past 4 billion years. (The oldest rocks yet discovered are isolated fragments found in the Northwest Territories of Canada that have radiometric dates of about 4 billion years.) In addition, as you will see in subsequent chapters, Earth is an evolving planet whose continents and ocean basins have continually changed shape and even location during much of this period.

1.5 Concept Checks

1. Name and briefly outline the theory that describes the formation of our solar system.
2. List the inner planets and outer planets. Describe basic differences in size and composition.
3. Explain why density and buoyancy were important in the development of Earth's layered structure.

1.6 Earth's Internal Structure

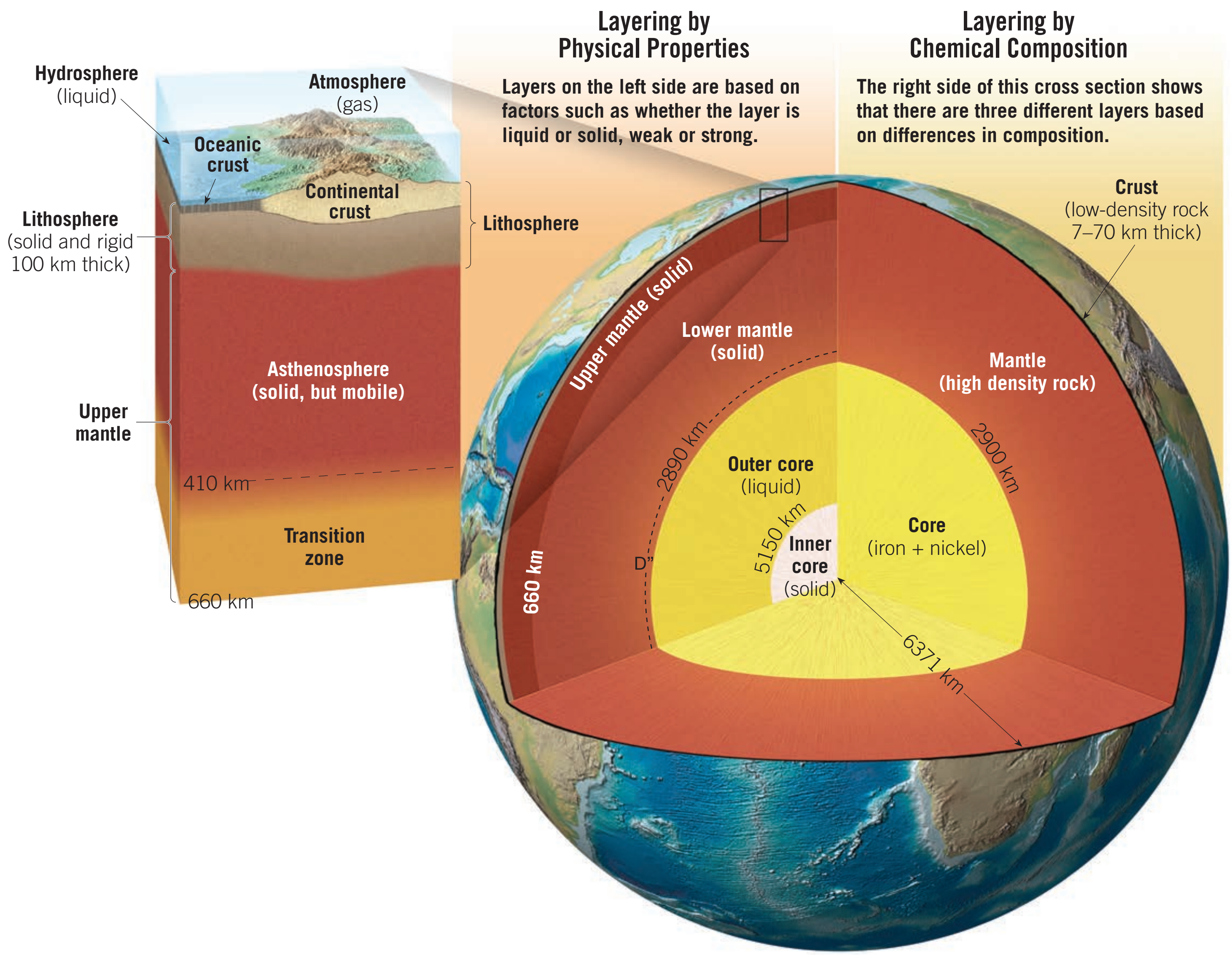
Sketch Earth's internal structure and label and describe the main subdivisions.

The preceding section outlined how differentiation of material early in Earth's history resulted in the formation of three major layers defined by their chemical composition: the crust, mantle, and core. In addition to these compositionally distinct layers, Earth is divided into layers based on physical properties. The physical properties used to define such zones include whether the layer is solid or liquid and how weak or strong it is. Important examples include the lithosphere, asthenosphere, outer core, and inner core. Knowledge of both chemical and physical layers is important to our understanding of many geologic processes, including volcanism, earthquakes, and mountain building. **Figure 1.19** shows different views of Earth's layered structure.

How did we learn about the composition and structure of Earth's interior? The nature of Earth's interior is primarily determined by analyzing seismic waves from earthquakes. As these waves of energy penetrate the planet, they change speed and are bent and reflected as they move through zones that have different properties. Monitoring stations around the world detect and record this energy. With the aid of computers, these data are analyzed and used to build a detailed picture of Earth's interior. There is more about this in Chapter 12.

SmartFigure 1.19
Earth's layers Structure of Earth's interior based on chemical composition (right side of diagram) and physical properties (left side of diagram). (https://goo.gl/70au1N)

Tutorial



Earth's Crust

The **crust**, Earth's relatively thin, rocky outer skin, is of two different types—continental crust and oceanic crust. Both share the word *crust*, but the similarity ends there. The oceanic crust is roughly 7 kilometers (4.5 miles) thick and composed of the dark igneous rock *basalt.* By contrast, the continental crust averages about 35 kilometers (22 miles) thick but may exceed about 70 kilometers (45 miles) in some mountainous regions such as the Rockies and Himalayas. Unlike the oceanic crust, which has a relatively homogeneous chemical composition, the continental crust consists of many rock types. Although the upper crust has an average composition of a *granitic rock* called *granodiorite*, it varies considerably from place to place.

Continental rocks have an average density of about 2.7 g/cm^3, and some have been discovered that are more than 4 billion years old. The rocks of the oceanic crust are younger (180 million years or less) and denser (about 3.0 g/cm^3) than continental rocks. For comparison, liquid water has a density of 1 g/cm^3; therefore, the density of basalt, the primary rock composing oceanic crust, is three times that of water.

Earth's Mantle

More than 82 percent of Earth's volume is contained in the **mantle**, a solid, rocky shell that extends to a depth of about 2900 kilometers (1800 miles). The boundary between the crust and mantle represents a marked change in chemical composition. The dominant rock type in the uppermost mantle is *peridotite*, which contains minerals richer in the metals magnesium and iron compared to the minerals found in either the continental or oceanic crust.

The Upper Mantle The upper mantle extends from the crust–mantle boundary down to a depth of about 660 kilometers (410 miles). The upper mantle can be divided into three different parts. The top portion of the upper mantle is part of the stronger *lithosphere*, and beneath that is the weaker *asthenosphere.* The bottom part of the upper mantle is called the *transition zone.*

The **lithosphere** ("rock sphere") consists of the entire crust plus the uppermost mantle and forms Earth's relatively cool, rigid outer shell (see Figure 1.19). Averaging about 100 kilometers (60 miles) thick, the lithosphere is more than 250 kilometers (155 miles) thick below the oldest portions of the continents. Beneath this stiff layer to a depth of about 410 kilometers (255 miles) lies a soft, comparatively weak layer known as the **asthenosphere** ("weak sphere"). The top portion of the asthenosphere has a temperature/pressure regime that results in a small amount of melting. Within this very weak zone, the lithosphere is mechanically detached from the layer below. The lithosphere thus is able to move independently of the asthenosphere, a fact we will consider in the next chapter.

It is important to emphasize here that the strength of various Earth materials is a function of both their composition and the temperature and pressure of their environment. You should not get the idea that the entire lithosphere behaves like a rigid or brittle solid similar to rocks found on the surface. Rather, the rocks of the lithosphere get progressively hotter and weaker (more easily deformed) with increasing depth. At the depth of the uppermost asthenosphere, the rocks are close enough to their melting temperature (some melting may actually occur) that they are very easily deformed. Thus, the uppermost asthenosphere is weak because it is near its melting point, just as hot wax is weaker than cold wax.

From about 410 kilometers (255 miles) to about 660 kilometers (410 miles) in depth is the part of the upper mantle called the **transition zone** (Figure 1.19). The top of the transition zone is identified by a sudden increase in density from about 3.5 to 3.7 g/cm^3. This change occurs because minerals in the rock peridotite respond to the increase in pressure by forming new minerals with closely packed atomic structures.

The Lower Mantle From a depth of 660 kilometers (410 miles) to the top of the core, at a depth of 2900 kilometers (1800 miles), is the **lower mantle**. Because of an increase in pressure (caused by the weight of the rock above), the mantle gradually strengthens with depth. Despite their strength, however, the rocks in the lower mantle are very hot and capable of extremely gradual flow.

In the bottom few hundred kilometers of the mantle is a highly variable and unusual layer called the D″ layer (pronounced "dee double-prime"). The nature of this boundary layer between the rocky mantle and the hot liquid iron outer core will be examined in Chapter 12.

Earth's Core

The **core** is composed of an iron–nickel alloy with minor amounts of oxygen, silicon, and sulfur—elements that readily form compounds with iron. At the extreme pressure found in the core, this iron-rich material has an average density of nearly 11 g/cm^3 and approaches 14 times the density of water at Earth's center.

The core is divided into two regions that exhibit very different mechanical strengths. The **outer core** is a *liquid layer* 2250 kilometers (1395 miles) thick. The movement of metallic iron within this zone generates Earth's magnetic field. The **inner core** is a sphere that has a radius of 1221 kilometers (757 miles). Despite its higher temperature, the iron in the inner core is *solid* due to the immense pressures that exist in the center of the planet.

1.6 Concept Checks

1. Name and describe the three major layers defined by their chemical composition.
2. Contrast the characteristics of the lithosphere and the asthenosphere.
3. Why is the inner core solid?

1.7 Rocks and the Rock Cycle

Sketch, label, and explain the rock cycle.

Rock is the most common and abundant material on Earth. To a curious traveler, the variety seems nearly endless. When a rock is examined closely, we find that it usually consists of smaller crystals called minerals. *Minerals* are chemical compounds (or sometimes single elements), each with its own composition and physical properties. The grains or crystals may be microscopically small or easily seen with the unaided eye.

The minerals that compose a rock strongly influence its nature and appearance. In addition, a rock's *texture*—the size, shape, and/or arrangement of its constituent minerals—also has a significant effect on its appearance. A rock's mineral composition and texture, in turn, reflect the geologic processes that created it (**Figure 1.20**). Such analyses are critical to understanding our planet. This understanding also has many practical applications, including finding energy and mineral resources and solving environmental problems.

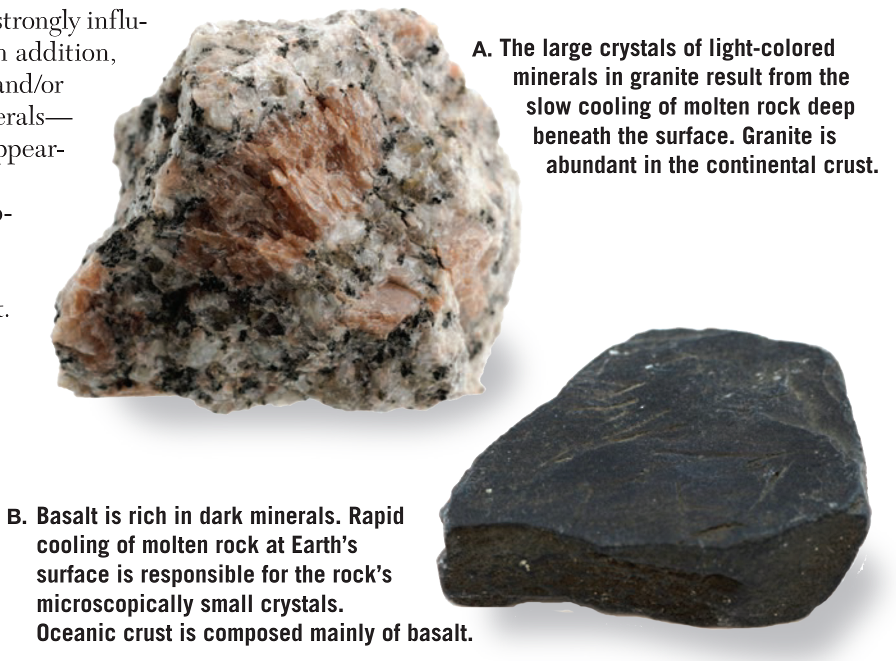


Figure 1.20
Two basic rock characteristics Texture and mineral composition are basic rock features. These two samples are the common igneous rocks granite (**A**) and basalt (**B**). (Photo A by geoz/alamy Images; photo B by Tyler Boyes/Shutterstock)

Geologists divide rocks into three major groups: igneous, sedimentary, and metamorphic. **Figure 1.21** provides some examples. As you will learn, each group is linked to the others by the processes that act upon and within the planet.

Earlier in this chapter, you learned that Earth is a system. This means that our planet consists of many interacting parts that form a complex whole. Nowhere is this idea better illustrated than when we examine the rock cycle (**Figure 1.22**). The **rock cycle** allows us to view many of the interrelationships among different parts of the Earth system. It helps us understand the origin of igneous, sedimentary, and metamorphic rocks and to see that each type is linked to the others by processes that act upon and within the planet. Consider the rock cycle to be a simplified but useful overview of physical geology. Learn the rock cycle well; you will be examining its interrelationships in greater detail throughout this book.

The Basic Cycle

Magma is molten rock that forms deep beneath Earth's surface. Over time, magma cools and solidifies. This process, called *crystallization*, may occur either beneath the surface or, following a volcanic eruption, at the surface. In either situation, the resulting rocks are called **igneous rocks**.

If igneous rocks are exposed at the surface, they undergo *weathering*, in which the day-in and day-out influences of the atmosphere, hydrosphere, and biosphere slowly disintegrate and decompose rocks. The materials that result are often moved downslope by gravity before being picked up and transported by any of a number of erosional agents, such as running water, glaciers, wind, or waves. Eventually these particles and dissolved substances, called **sediment**, are deposited. Although most sediment ultimately comes to rest in the ocean, other sites of deposition include river floodplains, desert basins, swamps, and sand dunes.

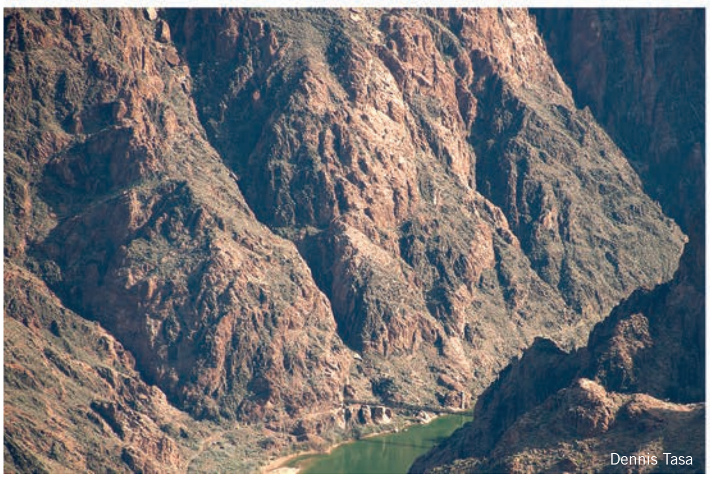
Next, the sediments undergo *lithification*, a term meaning "conversion into rock." Sediment is usually lithified into **sedimentary rock** when compacted by the weight of overlying layers or when cemented as percolating groundwater fills the pores with mineral matter.

If the resulting sedimentary rock is buried deep within Earth and involved in the dynamics of mountain building or intruded by a mass of magma, it is subjected to great pressures and/or intense heat. The sedimentary rock reacts to the changing environment and turns into the third rock type, **metamorphic rock**. When metamorphic rock is subjected to additional pressure changes or to still higher temperatures, it melts, creating magma, which eventually crystallizes into igneous rock, starting the cycle all over again.

Figure 1.21
Three rock groups Geologists divide rocks into three groups: igneous, sedimentary, and metamorphic.

Igneous rocks form when molten rock solidifies at the surface (extrusive) or beneath the surface (intrusive). The lava flow in the foreground is the fine-grained rock basalt and came from SP Crater in northern Arizona.

Sedimentary rocks consist of particles derived from the weathering of other rocks. This layer consists of durable sand-size grains of the glassy mineral quartz that are cemented into a solid rock. The grains were once a part of extensive dunes. This rock layer, called the Navajo Sandstone, is prominent in southern Utah.



The metamorphic rock pictured here, known as the Vishnu Schist, is exposed in the inner gorge of the Grand Canyon. Its formation is associated with environments deep below Earth's surface where temperatures and pressures are high and with the forces associated with ancient mountain-building processes that occurred in Precambrian time.

Where does the energy that drives Earth's rock cycle come from? Processes driven by heat from Earth's interior are responsible for creating igneous and metamorphic rocks. Weathering and erosion, external processes powered by energy from the Sun, produce the sediment from which sedimentary rocks form.

Alternative Paths

The paths shown in the basic cycle are not the only ones possible. To the contrary, other paths are just as likely to be followed as those described in the preceding section. These alternatives are indicated by the light blue arrows in Figure 1.22.

Rather than being exposed to weathering and erosion at Earth's surface, igneous rocks may remain deeply buried. Eventually these masses may be subjected to the strong compressional forces and high temperatures associated with mountain building. When this occurs, they are transformed directly into metamorphic rocks.

Metamorphic and sedimentary rocks, as well as sediment, do not always remain buried. Rather, overlying layers may be stripped away, exposing the once-buried rock. This exposed material is attacked by weathering processes and turned into new raw materials for sedimentary rocks.

Although rocks may seem to be unchanging masses, the rock cycle shows that they are not. The changes,