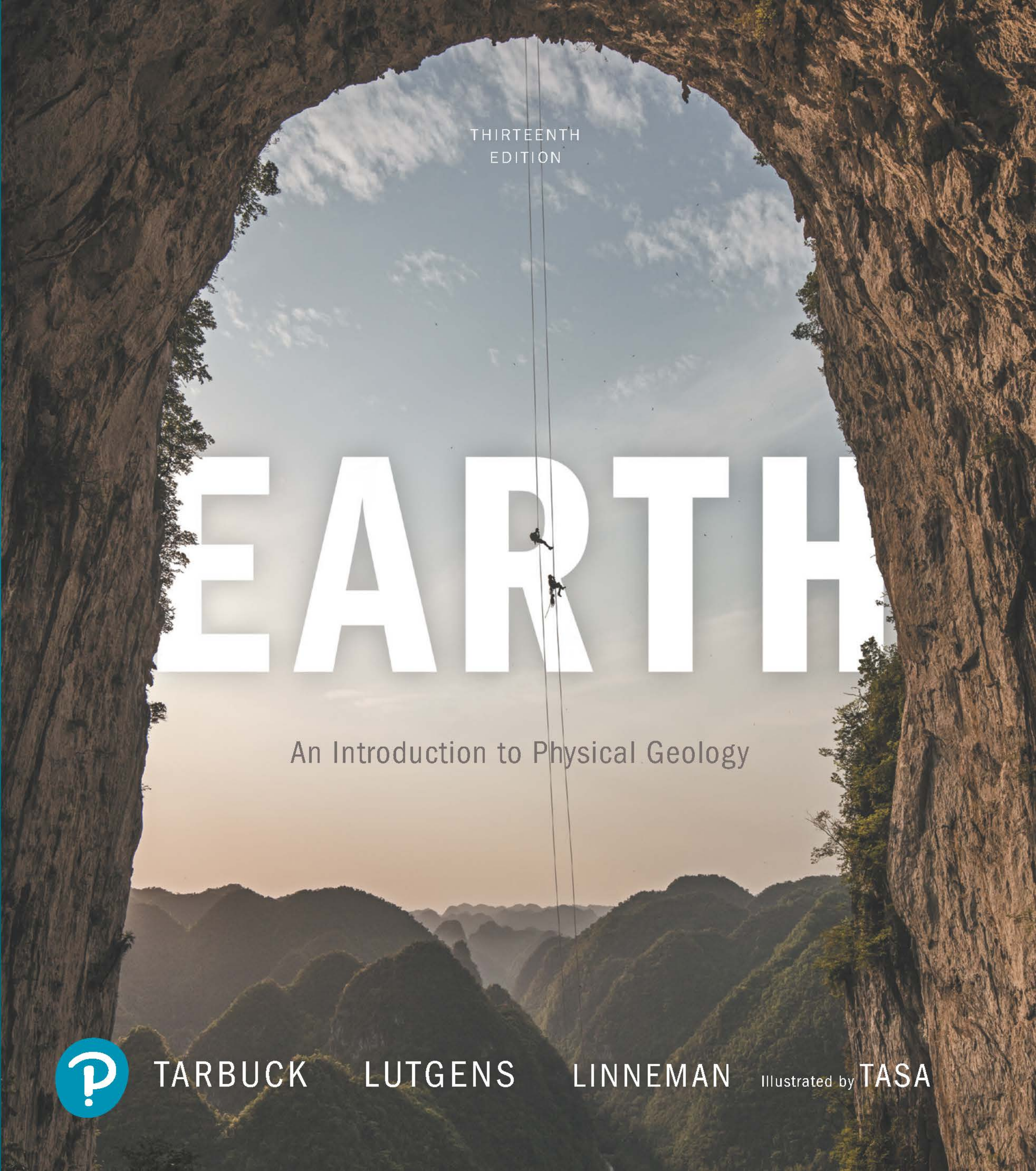


THIRTEENTH EDITION

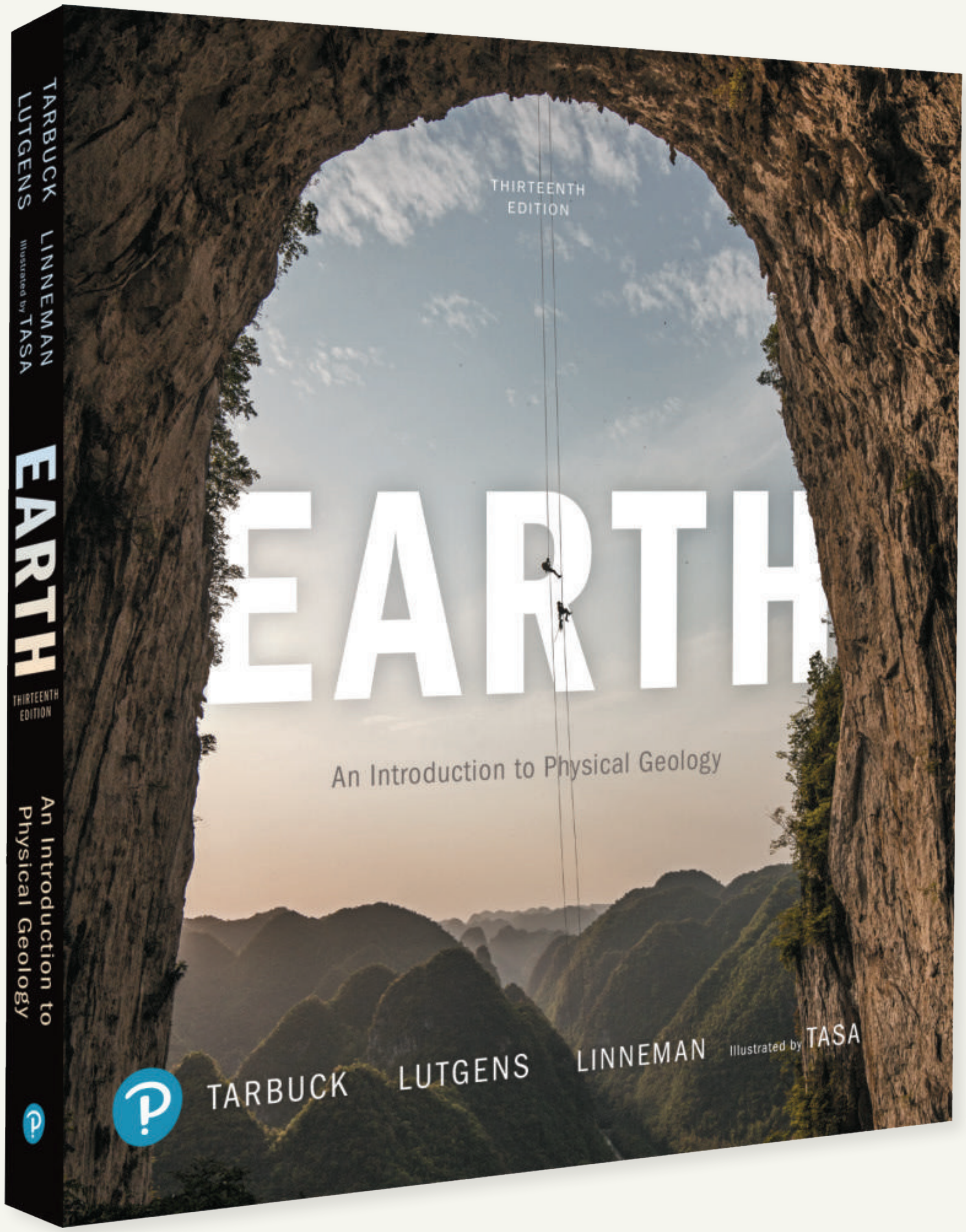
EARTH

An Introduction to Physical Geology

TARBUCK LUTGENS LINNEMAN Illustrated by TASA

BRIEF CONTENTS

Bringing Earth to Life



Earth: An Introduction to Physical Geology is a leading text in the field, characterized by no-nonsense, student-friendly writing, excellent illustrations, and a modular learning path driven by learning objectives. The new edition is the first to integrate 3D technology that brings geology to life. This edition has also been updated with significant content and digital updates—read on to see what's new!

Pearson

Bring Earth to Life with 3D and . . .

NEW! 3D models allow students to get "virtually hands on" with rocks, minerals, and outcrops through guided exploration.

NEW! 3D models are embedded in the eText, available in the Study Area, and assignable with assessment in Mastering Geology.

. . . Other Dynamic Media

SmartFigure Project Condor Videos were created using a quadcopter-mounted GoPro camera. Ten key geological locations and processes were filmed. These process-oriented videos are designed to bring the field to the classroom and improve the learning experience within the text. Available for assignment in Mastering Geology with assessment.

SmartFigure Mobile Field Trips take students to iconic locations with geologist–pilot–photographer Michael Collier in the air and on the ground to learn about iconic landscapes in North America and beyond that relate to discussions in the chapter.

Mobile Field Trips include Formation of a Water Gap, Ice Sculpts Yosemite, Fire and Ice Land, Dendrochronology, and Desert Geomorphology. In Mastering Geology, these videos are accompanied by auto-gradable assessments.

Engage Students with Real-World Connections and Embedded Videos

In The NEWS

Geothermal Energy: Clean Energy to Power the Future?

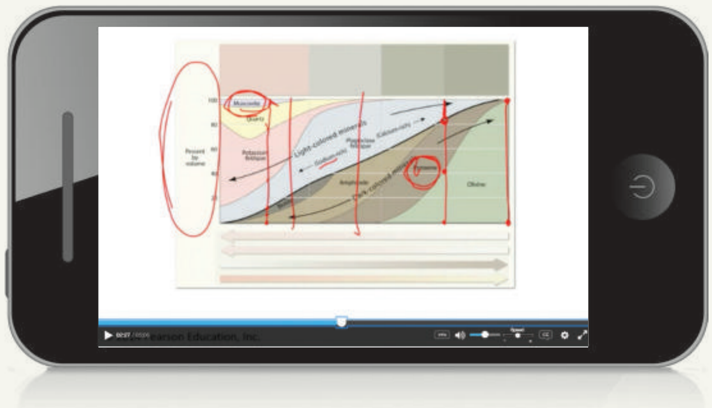
Iceland, a small island country that straddles the Mid-Atlantic Ridge, is a major producer of *geothermal energy*, where heat captured from Earth, in the form of hot water or steam, is used to produce electricity. The source of geothermal energy is hot igneous rocks below the surface of Earth's crust. Unlike fossil fuel–derived electricity, geothermal power is renewable, and it is less polluting.

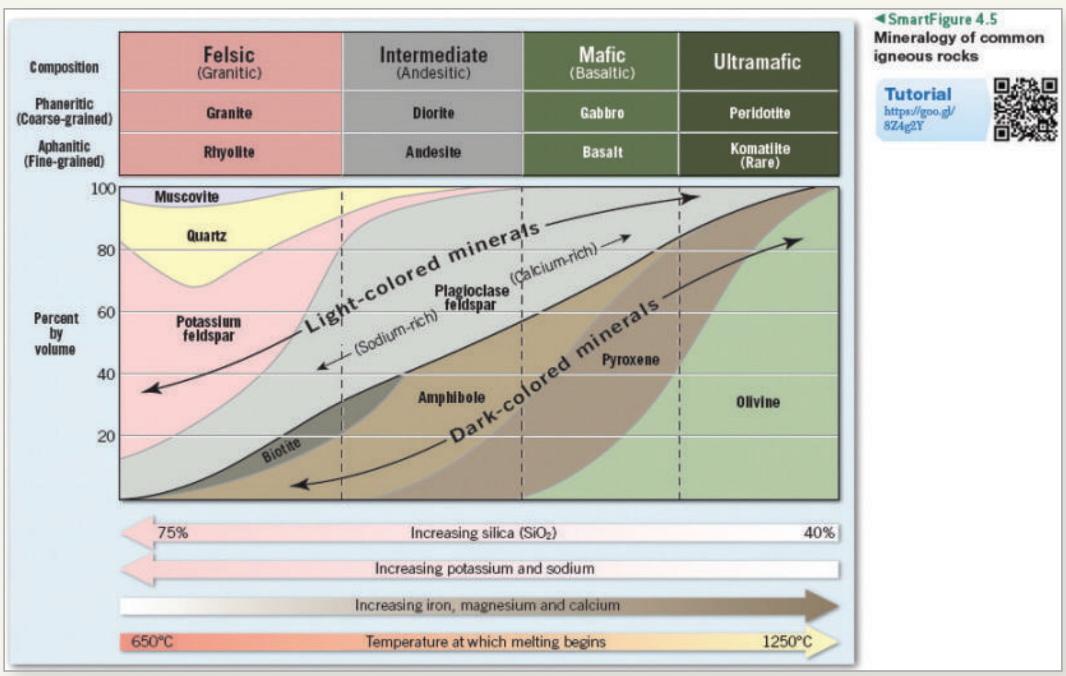
Iceland's abundant volcanic fields allow it easy access to geothermal energy. This surplus of relatively cheap electricity has attracted new industries, including aluminum smelting and processing. New geothermal tapping methods may further expand how much geothermal power generation is possible.

A typical geothermal well in Iceland is now about 2.5 kilometers (1.5 miles) deep and can produce enough electricity to supply roughly 4000 homes. A new government-sponsored study is researching whether drilling twice as deep could tap into a water reservoir hotter than 450°C (about 840°F). This super-heated steam might produce 10 times the electricity of today's typical borehole. If ultimately successful in Iceland, this form of geothermal electricity generation may also be implemented on a wider scale throughout other parts of the world, including the South Pacific, eastern Africa, and the western United States.

▶ Bathers at the Blue Lagoon bath near Reykjanes, Iceland, relax in view of thermal wells used to produce geothermal energy. The Iceland Deep Drilling Project (IDDP) will use a large drilling rig to drill several boreholes to depths of about 5 kilometers (3 miles) in a field of volcanic rock located a short drive from Iceland's capital, Reykjavik.

NEW! In the News features begin each chapter illustrating to students the importance and relevance of the chapter's core topics by providing real-world connections.





◀ SmartFigure 4.5
Mineralogy of common igneous rocks

NEW! Quick Response (QR) codes link to SmartFigures giving readers immediate access to over 200 videos and animations, inlcluding *Project Condor* Videos, Mobile Field Trips, Tutorials, Animations, and Videos to help visualize physical processes and concepts. SmartFigures will be embedded directly in the eText.

Clear Learning Path in Each Chapter

5

Volcanoes and Volcanic Hazards

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:

5.1 Compare and contrast the 1980 eruption of Mount St. Helens with the most recent eruption of Kilauea, which began in 1983.

5.2 Explain why some volcanic eruptions are explosive and others are quiescent.

5.3 List and describe the three categories of materials extruded during volcanic eruptions.

5.4 Draw and label a diagram that illustrates the basic features of a typical volcanic cone.

5.5 Summarize the characteristics of shield volcanoes and provide one example of this type of volcano.

5.6 Describe the formation, size, and composition of cinder cones.

5.7 List the characteristics of composite volcanoes and describe how they form.

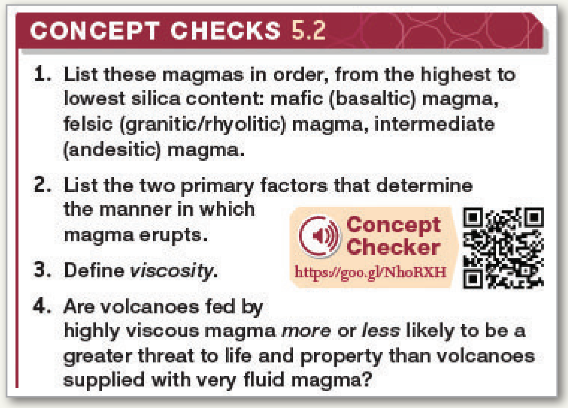
5.8 Describe the major geologic hazards associated with volcanoes.

5.9 List volcanic landforms other than shield, cinder, and composite volcanoes and describe their formation.

5.10 Explain how the global distribution of volcanic activity relates to plate tectonics.

5.11 List and describe the techniques used to monitor potentially dangerous volcanoes.

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

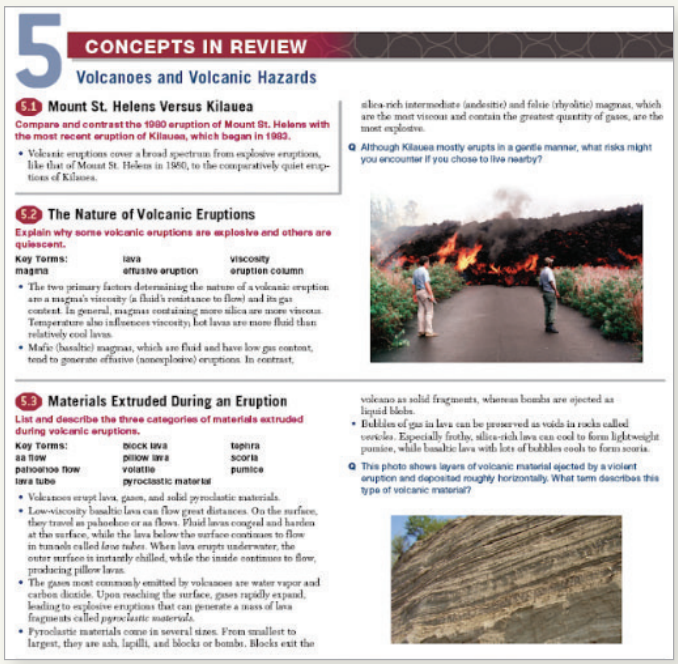


CONCEPT CHECKS 5.2

1. List these magmas in order, from the highest to lowest silica content: mafic (basaltic) magma, felsic (granitic/rhyolitic) magma, intermediate (andesitic) magma.
2. List the two primary factors that determine the manner in which magma erupts.
3. Define *viscosity*.
4. Are volcanoes fed by highly viscous magma *more* or *less* likely to be a greater threat to life and property than volcanoes supplied with very fluid magma?

Concept Checker https://goo.gl/NhoRXH

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. **NEW! Podcast-style Concept Checkers** offer an audio review of the Concept Checks to aid in student self-study.



5 CONCEPTS IN REVIEW

Volcanoes and Volcanic Hazards

5.1 Mount St. Helens Versus Kilauea

Compare and contrast the 1980 eruption of Mount St. Helens with the most recent eruption of Kilauea, which began in 1983.

- Volcanic eruptions cover a broad spectrum from explosive eruptions, like that of Mount St. Helens in 1980, to the comparatively quiet eruptions of Kilauea.

5.2 The Nature of Volcanic Eruptions

Explain why some volcanic eruptions are explosive and others are quiescent.

Key Terms: magma, lava, effusive eruption, viscosity, eruption column

- The two primary factors determining the nature of a volcanic eruption are a magma's viscosity (a fluid's resistance to flow) and its gas content. In general, magmas containing more silica are more viscous. Temperature also influences viscosity; hot lavas are more fluid than relatively cool lavas.
- Mafic (basaltic) magmas, which are fluid and have low gas content, tend to generate effusive (nonexplosive) eruptions. In contrast, silica-rich intermediate (andesitic) and felsic (rhyolitic) magmas, which are the most viscous and contain the greatest quantity of gases, are the most explosive.

Q Although Kilauea mostly erupts in a gentle manner, what risks might you encounter if you chose to live nearby?

5.3 Materials Extruded During an Eruption

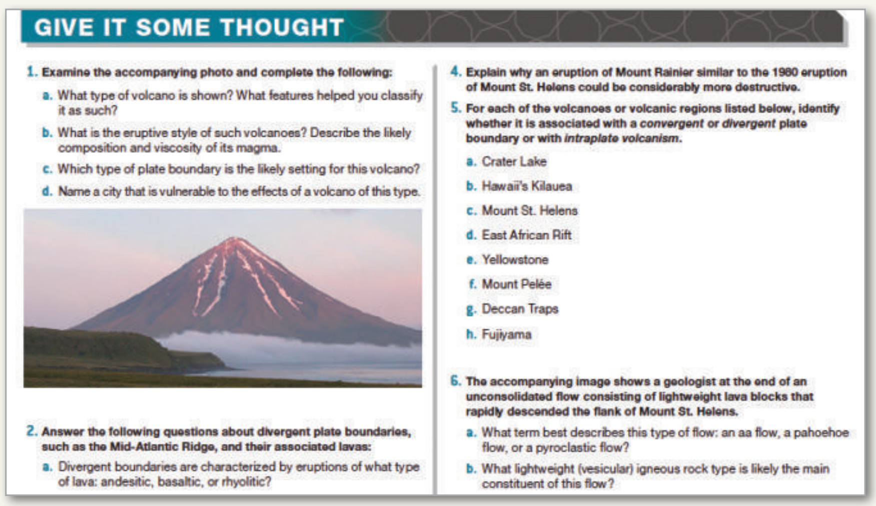
List and describe the three categories of materials extruded during volcanic eruptions.

Key Terms: aa flow, pahoehoe flow, lava tube, block lava, pillow lava, volatile, pyroclastic material, tephra, scoria, pumice

- Volcanoes erupt lava, gases, and solid pyroclastic materials.
- Low-viscosity basaltic lava can flow great distances. On the surface, they travel as pahoehoe or aa flows. Fluid lavas congeal and harden at the surface, while the lava below the surface continues to flow in tunnels called *lava tubes*. When lava erupts underwater, the outer surface is instantly chilled, while the inside continues to flow, producing pillow lavas.
- The gases most commonly emitted by volcanoes are water vapor and carbon dioxide. Upon reaching the surface, gases rapidly expand, leading to explosive eruptions that can generate a mass of lava fragments called *pyroclastic materials*.
- Pyroclastic materials come in several sizes. From smallest to largest, they are ash, lapilli, and blocks or bombs. Blocks exit the volcano as solid fragments, whereas bombs are ejected as liquid blobs.
- Bubbles of gas in lava can be preserved as voids in rocks called vesicles. Especially frothy, silica-rich lava can cool to form lightweight pumice, while basaltic lava with lots of bubbles cools to form scoria.

Q This photo shows layers of volcanic material ejected by a violent eruption and deposited roughly horizontally. What term describes this type of volcanic material?

Concepts in Review provides students with a structured review of the chapter. Consistent with the Focus on Concepts and Concept Checks, Concepts in Review is structured around the learning objective for each section.

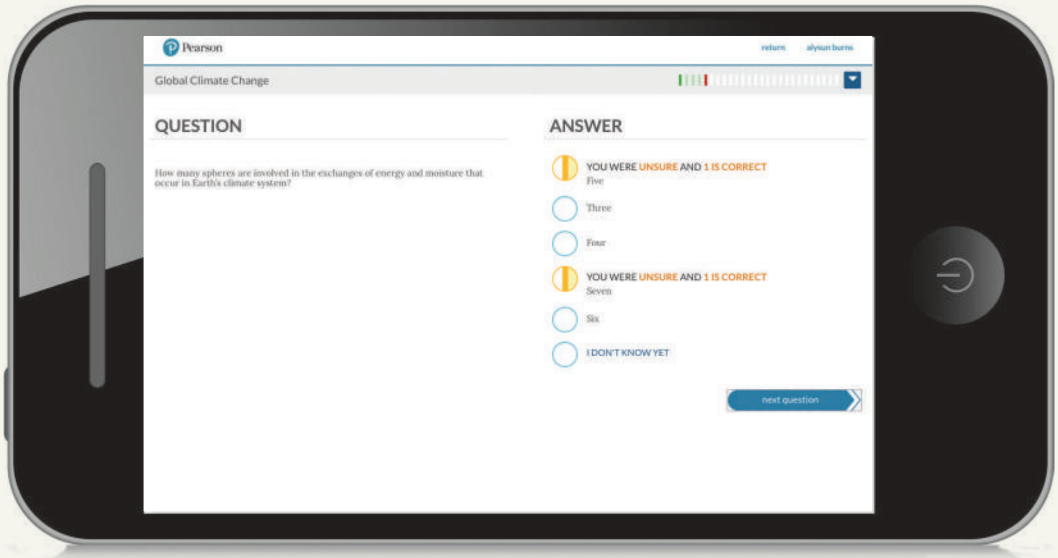


GIVE IT SOME THOUGHT

1. Examine the accompanying photo and complete the following:
   a. What type of volcano is shown? What features helped you classify it as such?
   b. What is the eruptive style of such volcanoes? Describe the likely composition and viscosity of its magma.
   c. Which type of plate boundary is the likely setting for this volcano?
   d. Name a city that is vulnerable to the effects of a volcano of this type.
2. Answer the following questions about divergent plate boundaries, such as the Mid-Atlantic Ridge, and their associated lavas:
   a. Divergent boundaries are characterized by eruptions of what type of lava: andesitic, basaltic, or rhyolitic?
4. Explain why an eruption of Mount Rainier similar to the 1980 eruption of Mount St. Helens could be considerably more destructive.
5. For each of the volcanoes or volcanic regions listed below, identify whether it is associated with a *convergent* or *divergent* plate boundary or with *intraplate volcanism*.
   a. Crater Lake
   b. Hawaii's Kilauea
   c. Mount St. Helens
   d. East African Rift
   e. Yellowstone
   f. Mount Pelée
   g. Deccan Traps
   h. Fujiyama
6. The accompanying image shows a geologist at the end of an unconsolidated flow consisting of lightweight lava blocks that rapidly descended the flank of Mount St. Helens.
   a. What term best describes this type of flow: an aa flow, a pahoehoe flow, or a pyroclastic flow?
   b. What lightweight (vesicular) igneous rock type is likely the main constituent of this flow?

Give It Some Thought activities challenge students to analyze, synthesize, and apply chapter material.

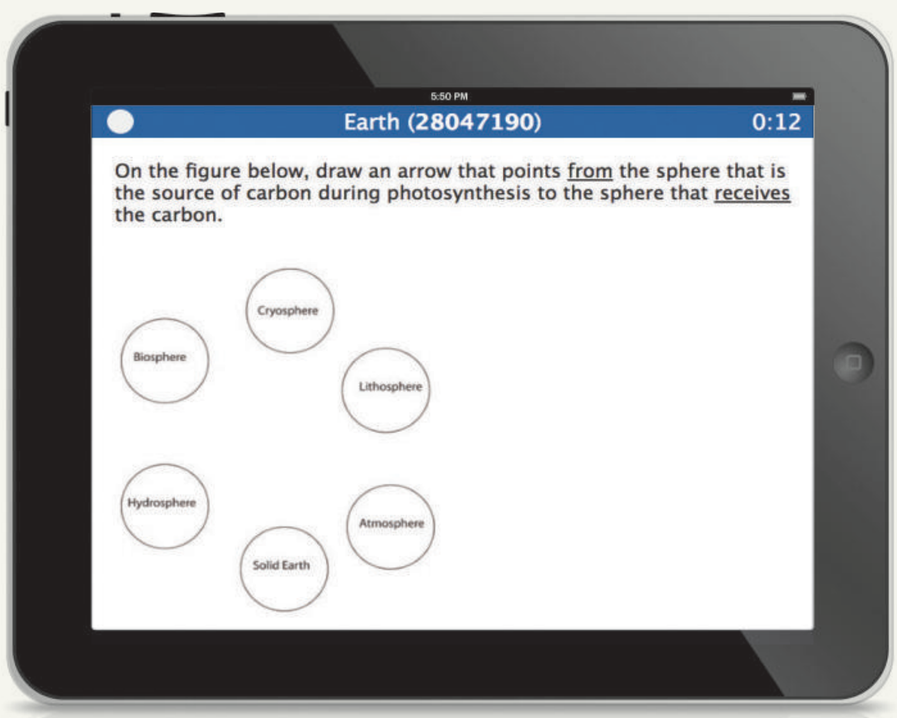
Mastering Geology Delivers Personalized Learning . . .



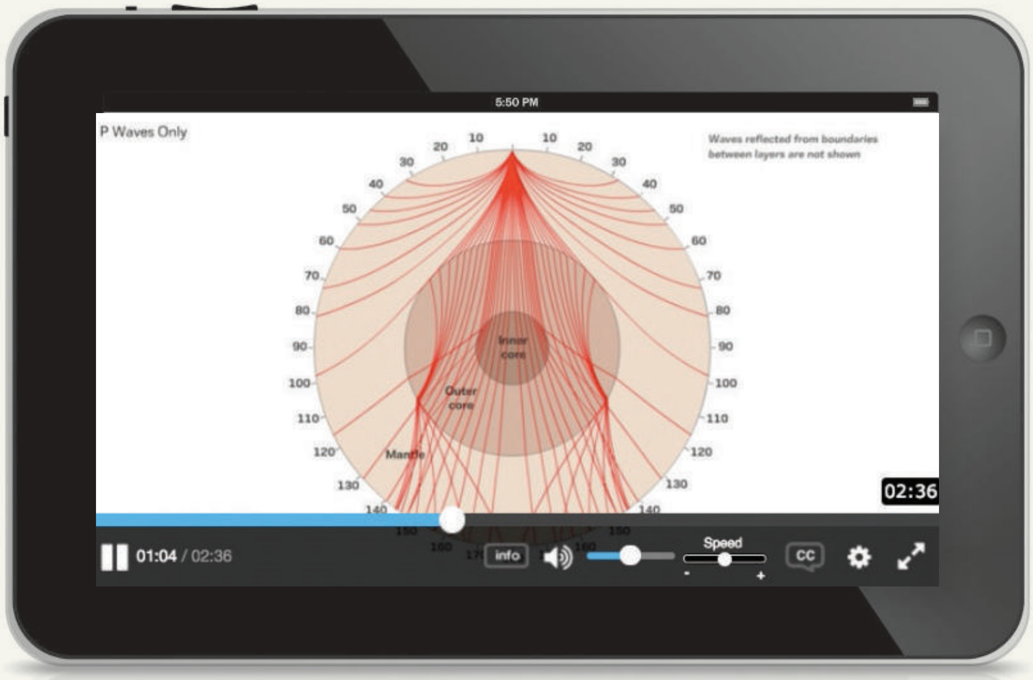
Dynamic Study Modules help students study effectively—and at their own pace. How? By keeping them motivated and engaged. The assignable modules rely on the latest research in cognitive science, using methods—such as adaptivity, gamification, and intermittent rewards—to stimulate learning and improve retention. Each module poses a series of questions about a course topic. These question sets adapt to each student's performance and offer personalized, targeted feedback.

Learning Catalytics™ helps you generate class discussion, customize your lecture, and promote peer-to-peer learning with real-time analytics. As a student response tool, Learning Catalytics uses students' smartphones, tablets, or laptops to engage them in more interactive tasks and thinking.

- **NEW!** Upload a full PowerPoint® deck for easy creation of slide questions.
- Help your students develop critical thinking skills.
- Monitor responses to find out where your students are struggling.
- Rely on real-time data to adjust your teaching strategy.
- Automatically group students for discussion, teamwork, and peer-to-peer learning.



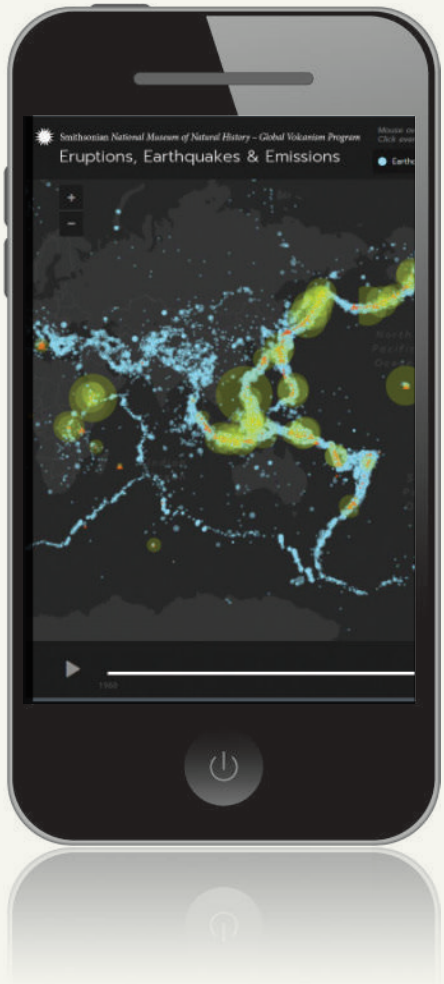
. . . and Interactive Media



SmartFigure Animations are brief videos created by Dennis Tasa that animate a process or concept depicted in the textbook's figures. With QR codes, students are given a view of moving figures rather than static art to depict how geologic processes move throughout time.

GigaPan Activities allow students to take advantage of a virtual field experience with high-resolution picture technology that has been developed by Carnegie Mellon University in conjunction with NASA.

Dig into Data Analysis



NEW! Data Analysis end-of-chapter features send students outside of the book to online science tools and data sets and help develop their data analysis and critical thinking skills.

DATA ANALYSIS

Recent Volcanic Activity

The Smithsonian Institution Global Volcanism Program and the USGS work together to compile a list of new and changing volcanic activity worldwide. NOAA also uses this information to issue Volcanic Ash Advisories to alert aircraft of volcanic ash in the air.

https://goo.gl/eD226M

ACTIVITIES

Go to the Weekly Volcanic Activity Report page at http://volcano.si.edu.

1. **What information is displayed on this page?**
2. **Look at the "New Activity/Unrest" section of the homepage. In what areas is most of the volcanic activity concentrated?**
3. **Under the "Reports tab," click on the "Weekly Volcanic Activity Report." List three ongoing volcanic activity locations shown on the map.**

Click on the name of a volcano under "New Activity Highlights."

4. **Where is this volcano located? Be sure to include the city, country, volcanic region name, latitude and longitude, and type of volcano.**
5. **Do some investigating online and in your text book. What are the key characteristics for this type of volcano?**
6. **Briefly describe the dates of the most recent activity. How was this activity observed?**

Go to the Volcanic Ash Advisory Center (VAAC) page at https://www.ospo.noaa.gov/Products/atmosphere/vaac/.

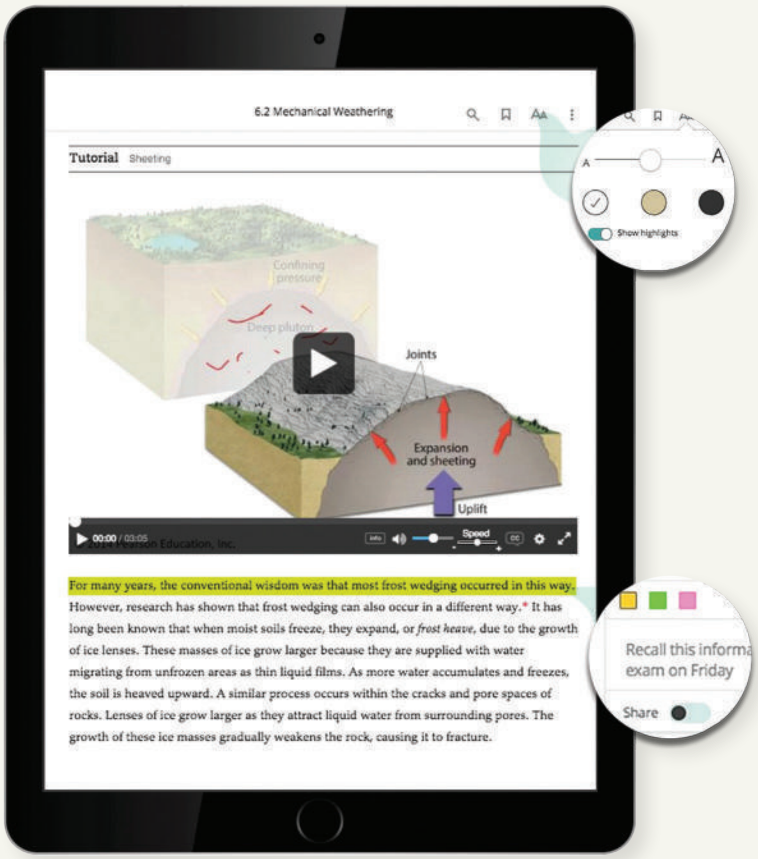
7. **This page shows the Washington VAAC area. Are any active volcanoes listed? Name them.**
8. **Are any advisories listed for eruptions? If so, list the volcano, the date, and the eruption height.**

Give It Some Thought Activities ask students to analyze, synthesize, and think critically about geology to encourage active learning.

Get Hands-On with Maps in MapMaster 2.0

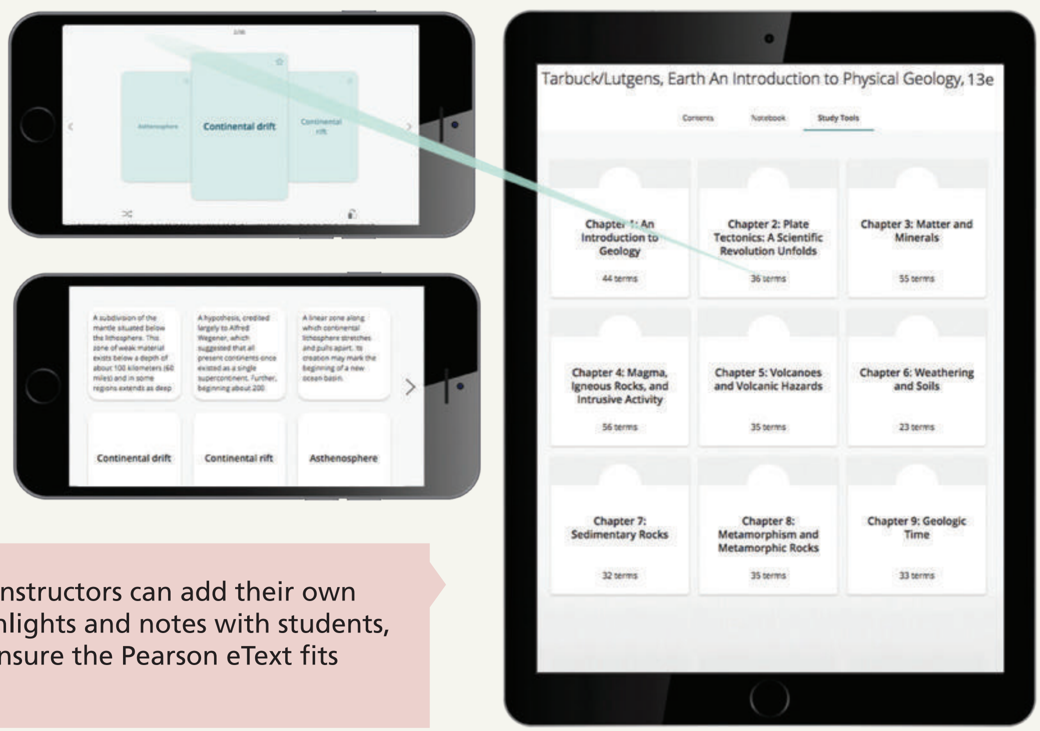
NEW! MapMaster 2.0 Interactive Map Activities Inspired by GIS, these activities allow students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. Now fully mobile, with enhanced analysis tools, the ability for students to geolocate themselves in the data, and the ability for students to upload their own data for advanced map making, this tool includes zoom and annotation functionality with hundreds of map layers leveraging recent data from sources such as the PRB, the World Bank, NOAA, NASA, USGS, United Nations, the CIA, and more.

A Whole New Reading Experience



NEW! Pearson eText is a simple-to-use, mobile-optimized, personalized reading experience available within Mastering. It allows students to easily highlight, take notes, and review key vocabulary all in one place—even when offline. Seamlessly integrated videos, 3D models, and other rich media engage students and give them access to the help they need, when they need it.

"The most interactive, customizable eText I have seen to date."
—Instructor, Ruben Murcia



Customizable for Your Course Instructors can add their own notes, embed videos and links, share highlights and notes with students, and rearrange chapters and sections to ensure the Pearson eText fits every unique course.

THIRTEENTH EDITION

EARTH

An Introduction to Physical Geology

EDWARD J. TARBUCK

FREDERICK K. LUTGENS

SCOTT R. LINNEMAN

Illustrated by

DENNIS TASA

Pearson

Courseware Portfolio Management, Analyst: Cady Owens
Courseware Portfolio Management, Specialist: Christian Botting
Director of Portfolio Management: Beth Wilbur
Content Producer: Heidi Allgair
Managing Producer: Mike Early
Courseware Director, Content Development: Ginnie Simione Jutson
Courseware Sr. Analyst: Erin Strathmann
Courseware Sr. Analyst: Margot Otway
Courseware Editorial Assistant: Sherry Wang
Rich Media Content Producer: Ziki Dekel
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Director of Field Marketing: Tim Galligan
Director of Product Marketing: Allison Rona
Executive Field Marketing Manager: Mary Salzman
Product Marketing Manager: Alysun Estes

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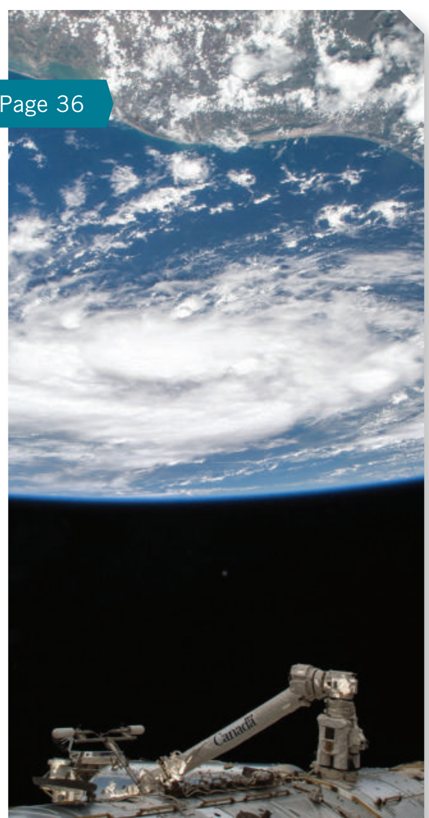

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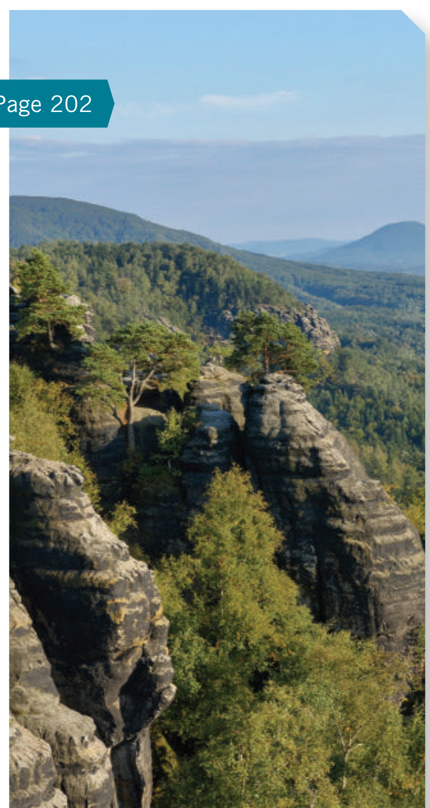
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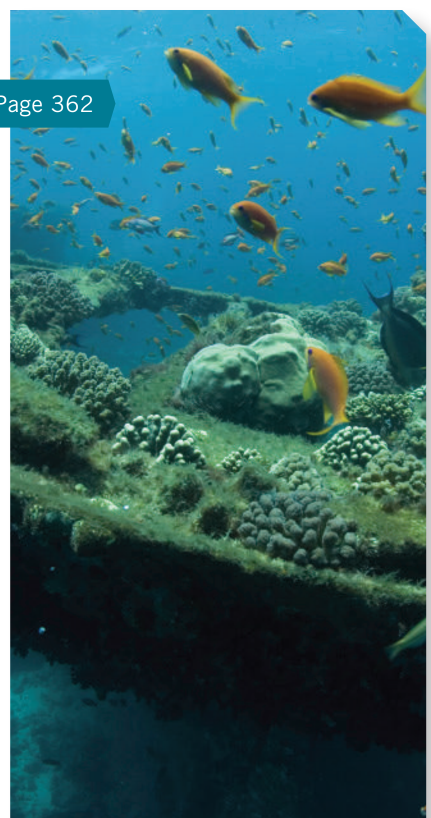

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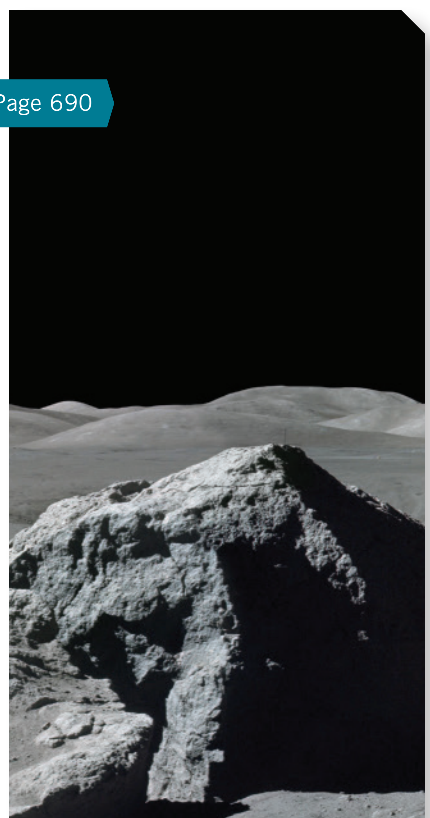

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Appendix

SmartFigures

Use your mobile device and a free Quick Response (QR) code reader app to scan a SmartFigure identified by a QR code, and a video or animation illustrating the SmartFigure's concept launches immediately. No slow websites or hard-to-remember logins required. These mobile media transform textbooks into convenient digital platforms, breathe life into your learning experience, and help you grasp challenging Physical Geology concepts.

PREFACE

Earth: An Introduction to Physical Geology, 13th edition, 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, *Earth* is a readable and user-friendly text that is a valuable tool for learning the basic principles and concepts of geology.

We were fortunate to have Dr. Scott Linneman join the *Earth* team as we prepared the 13th edition. A professor of geology and science education at Western Washington University in Bellingham, Washington, Scott brought an experienced and fresh perspective to this revision. In addition to providing many thoughtful suggestions, he was responsible for revising Chapter 6, *Weathering and Soils*; Chapter 7, *Sedimentary Rocks*; Chapter 9, *Geologic Time*; Chapter 15, *Mass Movement: The Work of Gravity*; and Chapter 16, *Running Water*. Having earned a B.A. from Carleton College in Minnesota and a Ph.D. from the University of Wyoming, Scott's research spans the fields of geomorphology as well as igneous petrology and volcanology. In 2011, he was named the Higher Education Science Teacher of the Year for Washington by the Washington Science Teachers Association, and in 2013 he was chosen the Carnegie Professor of the Year for Washington State. He currently serves as the Director of the Western Washington University Honors Program.

New and Important Features

Extensive revisions and new additions took place in the 13th edition. In addition, integrated textbook and digital resources enhance the learning experience.

- **New: *In the News*** is a chapter-opening current-events story and related two-page photo spread that illustrates real-world connections to the concepts at hand. Topics are fun and engaging; for example, students learn how volcanic ash wreaks havoc on airplanes, why "sand pirates" are stealing whole beaches and islands to manufacture concrete, and that the Sierra Nevada grew taller during a recent California drought.
- **New: *Data Analysis*** end-of-chapter question sets give students practice with data interpretation and problem solving.
- **New: 3D models** are embedded in the eText and can be assigned in Mastering Geology. These activities allow students to get (virtually) hands on with rocks, minerals, and outcrops in guided explorations.
- **New: *Concept Checkers*** are podcast-style audio reviews that can be reached via quick response (QR) codes found in the Concept Check sections that conclude learning objective sections.
- **Significant updating and revision** of book content has occurred in every chapter. In addition to updating data throughout the chapters, the authors have streamlined discussions for easier reading. New photos of recent geologic events—including mass movements, earthquakes, and volcanic eruptions—keep the discussion fresh. The authors added more than two dozen brand new figures and substantially revised many more. (For a chapter-by-chapter summary of important changes, see the "Major Changes to this Edition" section on page xviii.)
- ***SmartFigures*** enhance the student learning experience. QR codes allow you to use your mobile device to link to 200 unique and innovative learning opportunities beyond the printed text. Each *SmartFigure* also displays a short URL to type in instead of using the QR code. *SmartFigures* are truly media that teach! Types include:
  - ***SmartFigure Tutorials*:** These 2- to 4-minute mini-lessons bring key figure topics to life. The Tutorials are prepared and narrated by Professor Callan Bentley.
  - ***SmartFigure Mobile Field Trips*:** More than two dozen video field trips explore classic geologic sites, from Hawaii to Iceland. Each Mobile Field Trip follows geologist/photographer/pilot Michael Collier into the air and onto the ground to learn about landscapes featured in various chapters. New mobile field trips in this edition include formation of a water gap, how ice sculpts Yosemite, and desert geomorphology.
  - ***SmartFigure Condor*:** Ten Project Condor videos take you to mountain sites in America's West. These videos combine footage taken from a quadcopter-mounted GoPro camera with ground-level views, narration, and animation.
  - ***SmartFigure Animations*:** Certain book topics include animations that use static book art as the starting point to clarify difficult-to-visualize processes.
  - ***SmartFigure Videos*:** Brief video clips cement student understanding of topics such as mineral properties and the structure of ice sheets.
- **An objective-driven learning path** guides students through each chapter. The *Focus on Concepts* section lists all chapter learning objectives at the start of each chapter. The main chapter is organized by learning objective, providing an active, modular path through content. At the end of each chapter, a *Concepts in Review* section concisely summarizes the key content once again. *Give It Some Thought, Eye on Earth,* and *Data Analysis* questions allow students to apply chapter information and stretch their understanding.
- **Unparalleled visual program**, including maps, satellite images, photos, and diagrams that are frequently paired to enhance understanding. The visual program was prepared by the gifted and highly respected geoscience illustrator Dennis Tasa.

Digital and Print Resources

Mastering Geology™ with Pearson eText

Used by more than 3 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*, 13th edition, **Mastering Geology™** 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 to class prepared, 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 videos, GigaPan activities, Google Earth Encounter activities, geoscience animations, and much more. Students receive wrong-answer feedback personalized to their answers, to help them get back on track.

The Mastering Geology Student Study Area also provides students with self-study materials including videos, geoscience animations, *In the News* articles, Self-Study Quizzes, Web Links, a Glossary, and Flashcards.

Pearson eText gives students access to the text whenever and wherever they can access the Internet. Features of Pearson eText include:

- Now available on smartphones and tablets using the Pearson eText app
- Seamlessly integrated videos and other rich media, including new 3D models
- Fully accessible (screen-reader ready)
- Configurable reading settings, including resizable type and night reading mode
- Instructor and student note-taking, highlighting, bookmarking, and search

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

For Instructors

All of your resources are now easily available in the Mastering Instructor Resource Area.

Instructor's Resource Materials (Download Only)

- Download all the line art, tables, and photos from the text in JPEG files.
- Three PowerPoint files are available 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 the photos, art, and tables from the text have been loaded into PowerPoint slides, in book order.
  - **Lecture outline:** 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 PowerPoint files allow you to electronically poll your class for responses to questions, pop quizzes, attendance, and more.

Instructor Resource Manual (Download Only)
The *Instructor Resource Manual* has been designed to help seasoned and new instructors alike, offering the following sections in each chapter: an introduction to the chapter, outline, learning objectives/Focus on Concepts; teaching strategies; teacher resources; and answers to *Concept Checks*, *Eye on Earth*, *Give It Some Thought*, and *Data Analysis* 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.

For Students

Laboratory Manual in Physical Geology, 11th edition, by the American Geological Institute and the National Association of Geoscience Teachers, edited by Vincent Cronin, illustrated by Dennis G. Tasa (0134986962)
This user-friendly bestselling lab manual examines the basic processes of geology and their applications to everyday life. Featuring contributions from more than 170 highly regarded geologists and geoscience educators, along with an exceptional illustration program by Dennis Tasa, *Laboratory Manual in Physical Geology*, 11th edition, offers an inquiry- and activities-based approach that builds skills and gives students a more complete learning experience in the lab. Pre-lab videos linked from the print labs introduce students to the content, materials, and techniques they will use in each lab. These teaching videos help TAs prepare for lab setup and learn new teaching skills. The lab manual is available in Mastering Geology with Pearson eText, allowing teachers to use activity-based exercises to build students' lab skills.

***Dire Predictions: Understanding Global Climate Change*, 2nd edition, by Michael Mann and Lee R. Kump (0133909778)**
Periodic reports from the Intergovernmental Panel on Climate Change (IPCC) evaluate the risk of climate change brought on by humans. However, the sheer volume of scientific data remains inscrutable to the general public, particularly to those who may still question the validity of climate change. In just over 200 pages, this practical text presents and expands upon the latest climate change data and scientific consensus of the IPCC's *Fifth Assessment Report* in a visually stunning and undeniably powerful way to the lay reader. Scientific findings that provide validity to the implications of climate change are presented in clear-cut graphic elements, striking images, and understandable analogies. The second edition integrates mobile media links to online media. The text is also available in various eText formats, including an eText upgrade option from Mastering Geology courses.

Acknowledgments

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- **Michael Collier:** 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 remarkable Mobile Field Trips that are scattered throughout the text. Among the many awards he has received 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*, 13th edition. Thanks, Michael.
- **Callan Bentley:** 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 can hear Callen's passion for geology and engaging with students as he explains the concepts illustrated in these features. In addition, Callan was responsible for preparing *Concept Checkers,* the podcast-style audio reviews now available with the Concept Check sections that conclude each learning objective section. We appreciate Callan's contributions to this edition of *Earth*.

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Ed Tarbuck
Fred Lutgens
Scott Linneman

MAJOR CHANGES TO THIS EDITION

Chapter 1: An Introduction to Geology

- Added new *In the News* on why flash floods and mudflows often follow wildfires.
- Added a global climate change head and added updated material to Section 1.1.
- Updated current events references in Section 1.4 so that the California wildfires/mass flows of 2017 are now referenced.
- Reworded solar system formation discussion in Section 1.5.
- Added new Figure 1.3 on world population growth.
- Added new Figure 1.4 on natural hazards, featuring 2016 earthquake in Ecuador.
- Revised Figures 1.7 (geologic time scale) and 1.8 (geologic time) for easier reader comprehension.
- Added new Figure 1.16 on deadly debris flows, featuring Montecito, California, in 2018.
- Added new *Data Analysis* end-of-chapter section on the Swift Creek landslide.

Chapter 2: Plate Tectonics

- Added new *In the News* on the search for plate tectonics and alien life on distant planets.
- Streamlined the introductory section on what drives plate tectonics. Per newer research, this edition also omits mention of the "layer cake model."
- Combined old Sections 2.2 and 2.3 and reworked the section *The Great Debate*.
- Revised Figure 2.4 (fossil evidence of continental drift) to be easier to read and more colorblind accessible.
- Figure 2.10 now combines both spherical and flat views of Earth's lithospheric plates.
- Figures 2.29, 2.30, and 2.31 (all covering magnetic reversals) now have color palettes with more contrasting colors.
- Added new *Data Analysis* end-of-chapter section on tectonic plate movement.

Chapter 3: Matter and Minerals

- Added new *In the News* on the Cave of Crystals in Chihuahua, Mexico.
- Revised Figure 3.17 (hardness scales) to make comparing panels easier.
- Added new *Data Analysis* end-of-chapter section on global mineral resources.

Chapter 4: Igneous Rocks and Intrusive Activity

- Added new *In the News* on research that could greatly leverage how much power can be tapped from geothermal energy.
- Heavily revised Section 4.2 (igneous compositions).
- Revised Figure 4.3 (intrusive and extrusive igneous rocks) so that the magma chamber and eruption column are more realistic.
- Added new Figure 4.11, which shows a photo of an explosive volcanic eruption.
- Revised Figure 4.18 (why the mantle is mainly solid) to include a color key.
- Redrew Figure 4.21 on Bowen's Reaction series to be easier to understand.
- Redrew Figure 4.24 (assimilation of host rock by a magma body) to look more realistic.
- Figure 4.27 (Formation of felsic magma) now includes numbered segments to make it easier to follow.
- Added new *Data Analysis* end-of-chapter section on generating magma from solid rock.

Chapter 5: Volcanoes and Volcanic Hazards

- Added new *In the News* on the perils volcanic eruptions pose to air travel.
- Added new Learning Objective Section 5.1 comparing Mount St. Helens and Kilauea eruptions.
- Redrew Figure 5.11 (anatomy of a volcano) to have a more realistic magma chamber.
- Added information on the 2018 Kilauea eruption.
- Added new Figures 5.33 (InSAR image of ground deformation at Mount Etna), 5.34 (satellite image of an ash plume), and 5.35 (volcano hazard map for Mount Rainier region).
- Added new *Data Analysis* end-of-chapter section on recent volcanic activity.

Chapter 6: Weathering and Soils

- Added new *In the News* on soil erosion as a threat to civilization.
- Added new Figure 6.3 showing a rock crushing plant and quarry.
- Added a soil productivity index rating column to Table 6.2.
- Added new *Data Analysis* end-of-chapter section on soil types.

Chapter 7: Sedimentary Rocks

- Added new *In the News* on how changes in our understanding of when terrestrial plants evolved could change models that explain climate change over time.
- The main terminology in Section 7.2 now refers to "clastic" rather than "detrital" sedimentary rocks.
- Added mention of the simple rock cycle model to Section 7.1.
- Added new separate figures (Figures 7.25 and 7.26) on continental sedimentary environments and marine/transitional sedimentary environments.
- Added new *Data Analysis* end-of-chapter section on sedimentary rocks near you.

Chapter 8: Metamorphism and Metamorphic Rocks

- Added new *In the News* on lapis lazuli mining that funds terrorism groups in Afghanistan.
- Added new *Data Analysis* end-of-chapter section on the formation of metamorphic rocks.

Chapter 9: Geologic Time

- Added new *In the News* on zircons, tiny crystals that give evidence of a lost continent.
- Reordered Sections 9.4 and 9.5 for better concept building and reading flow.
- Figure 9.25 (geologic time scale) has a new color design for easier reading.
- Added new *Data Analysis* end-of-chapter section on fossils and geologic time.

Chapter 10: Crustal Deformation

- Added new *In the News* on the New Madrid seismic zone and its major earthquakes in the past.
- Heavily revised and updated Section 10.1 on how rocks deform.
- Simplified Figure 10.8 (plunging anticline) for easier learning.
- Heavily revised Section 10.4 on mapping geologic structures.
- Added new *Data Analysis* end-of-chapter section on measuring movement of the land.

Chapter 11: Earthquakes and Earthquake Hazards

- Added new *In the News* on earthquake-resistant building and retrofitting.
- Combined old Sections 11.1 and 11.2 into a single Section (11.1).
- Revised Figure 11.7 (fault propagation) to reduce extraneous cognitive load in third panel.
- Added new passage in Section 11.5 on 2015 Nepal earthquake, landslides, and ground subsidence.
- In Section 11.7, included mention of Shanghai Tower and modern skyscraper earthquake-safety building techniques.
- Added new *Data Analysis* end-of-chapter section on earthquakes around the world.

Chapter 12: Earth's Interior

- Added new *In the News* on unusual data sources for studying the historical geomagnetic record.
- Figure 12.1 (Earth's layered structure) has a new layout for easier reading.
- Added new Figure 12.4 on seismic waves providing a way to "see" into Earth.
- Reordered chapter for better concept building and learning progression.
- Added new *Data Analysis* end-of-chapter section on seismic tomography.

Chapter 13: Origin and Evolution of the Ocean Floor

- Added new *In the News* on searching for a missing jet and finding shipwrecks through mapping the uncharted ocean floor.
- In Section 13.1, added information on the latest bathymetric technologies used to create maps.
- In Section 13.2, expanded information on turbidity currents and submarine canyons.
- Added new Figure 13.10 on Challenger Deep.
- Added new *Data Analysis* end-of-chapter section on exploring the ocean surface.

Chapter 14: Mountain Building

- Added new *In the News* on how drought made the Sierra Nevada mountains grow taller.
- Revised Figure 14.12 (collision and accretion of small crustal fragments to a continental margin) so asthenosphere is easier to see.
- Added new *Data Analysis* end-of-chapter section on isostasy at work.

Chapter 15: Mass Movement: The Work of Gravity

- Added new *In the News* on air pollution possibly triggering landslides.
- Changed the term *mass wasting* to *mass movement* throughout the chapter to reflect more current terminology.
- Clarified the terms *slump* and *rockfall* to reflect more current terminology.
- Added new section on detecting, monitoring, and mitigating landslides.
- Added new Figures 15.23 (landslide monitoring) and 15.24 (slide displacement map).
- Added new *Data Analysis* end-of chapter section on landslides in Oregon.

Chapter 16: Running Water

- Added new *In the News* on predicting and monitoring floods with social media.
- Added new SmartFigure about water gaps in Section 16.2.
- Updated examples of floods throughout chapter.
- Completely rewrote content on the hydrologic cycle for Section 16.1.
- Added new *Data Analysis* end-of-chapter section on streamflow rates.

Chapter 17: Groundwater

- Added new *In the News* on a giant sinkhole that swallowed three homes in Florida.
- In Section 17.1, under “Groundwater: A Basic Resource,” updated statistics to the most recently available, and added the new section “Trends in Water Use.”
- In Section 17.6, updated the text on environmental problems and added a new passage on the impact of prolonged drought and groundwater pumping in California.
- In Section 17.7, added a paragraph and illustration on flowstone and augmented Figure 17.33 with diagrams showing how stalactites and stalagmites grow and may join to form a column.
- In *Give It Some Thought*, removed four questions and added two new ones.
- Added new *Data Analysis* end-of-chapter section on sinkholes in Tennessee.

Chapter 18: Glaciers and Glaciation

- Added new *In the News* on the impending loss of glaciers in Glacier National Park.
- Updated the discussion of ice shelves and the Larsen C shelf in Section 18.1.
- In Section 18.2, revised and improved the description of glacial ice formation.
- Updated the Section 18.2 information on glacier retreat.
- Expanded the Section 18.5 passage on crustal subsidence and rebound to include interactions between crustal movements and sea-level rise.
- Substantially revised or updated Figures 18.3, 18.4, 18.6, 18.8, 18.14, 18.23, and 18.25.
- Added new SmartFigure 18.15 on declining ice mass in Greenland.
- Added new *Data Analysis* end-of-chapter section on glacial flow patterns.

Chapter 19: Deserts and Wind

- Added new *In the News* on the world’s sand shortage.
- Revised the Section 19.2 passage on desert varnish to reflect new science, with a new illustration.
- Added new Figure 19.5 on petroglyphs.
- Rewrote Section 19.3 to contrast the desert landforms of the Basin and Range with those of the Colorado Plateau. Three new figures (Figures 19.10, 19.11, and 19.12) now illustrate the Colorado Plateau, buttes and mesas, and Monument Valley.
- Combined old Sections 19.4 and 19.5 into a single Section 19.4, on wind erosion.
- Revised the section “Armoring the Desert Surface” to discuss lag deposits and desert pavement as phenomena with distinct mechanistic explanations.
- Substantively altered or updated Figures 19.2, 19.3, 19.9, 19.13, 19.18, and 19.22.
- Added two new *Give It Some Thought* questions and removed one old question.
- Added new *Data Analysis* end-of-chapter section on the Aral Sea.

Chapter 20: Shorelines

- Added new *In the News* on erosion threatening the Alaska coast now that protective sea ice has melted.
- Reorganized Sections 20.1–20.3. After introducing the shoreline as a dynamic interface, the text now covers the generation and characteristics of ocean waves, then beaches and shoreline processes, and finally the features found on shorelines.
- Added information on lagoon filling to Section 20.3.
- Section 20.5 now covers the 2017 hurricanes Harvey, Maria, and Irma, and the subsection “Heavy Rain and Inland Flooding” has been rewritten.
- Thoroughly updated and revised the section “Monitoring Hurricanes.”

- Added four new figures on bluff failure (Figure 20.1), hurricane categories (Figure 20.25), Hurricane Harvey (Figure 20.28), and hurricane track forecasts (Figure 20.31).
- Substantially updated or revised Figures 20.9, 20.18, 20.23, 20.27, and 20.34.
- Added one new *Give It Some Thought* question, deleted two old questions, and modified one question.
- Added new *Data Analysis* end-of-chapter section on tides and sea level rise.

Chapter 21: Global Climate Change

- Added new *In the News* on the effect on roads and buildings when sea ice melts.
- Updated numbers and statistics throughout the chapter to the most recent available.
- Broadly revised and updated Section 21.2, including an improved treatment of oxygen isotope analysis.
- Broadly revised the Section 21.5 passage on volcanic activity and climate change.
- Generally revised the Section 21.6 passage on the role of trace gases.
- Retitled Section 21.7 "Predicting Future Climate Change" and revised to give more thorough discussion on computer models and their use in predicting future changes.
- Provided more detail on Arctic sea ice in Section 21.8.
- Added new figures on ocean floor sediment core studies (Figure 21.5), concentration of oxygen isotopes in seawater by climate (Figure 21.6), sulfur dioxide from Kilauea Volcano (21.18), methane (21.24), projected global temperature changes based on two emission scenarios (Figure 21.30), and a graph on sea level rise from 1993 to 2017 (Figure 21.32).
- Substantively altered Figures 21.4, 21.9, 21.13, 21.17, 21.19, 21.25, 21.26, and 21.34.
- Replaced one *Give It Some Thought* question.
- Added new *Data Analysis* end-of-chapter section on Arctic sea ice.

Chapter 22: Earth's Evolution Through Geologic Time

- Added new *In the News* on Earth's first known animal.
- Expanded Section 22.1 to discuss exoplanets, the Kepler mission, and what is meant by a habitable zone.
- Updated Section 22.2 to reflect additional modes of nucleosynthesis, including neutron-star mergers.
- Updated the Section 22.3 passage on oxygen in the atmosphere.
- Reorganized the Section 22.7 passage on mid-Paleozoic life passage and made it into a separate subsection.
- Expanded the Section 22.7 passage on reptiles to include a discussion of amniotic eggs and their importance from an evolutionary point of view.
- Updated the Section 22.9 information on mammal groups and the demise of dinosaurs and expansion of mammals.
- Added four new figures on the Laramide Rockies (Figure 22.18), placoderms (Figure 22.24), anatomy of a reptile egg (Figure 22.28), and giant sequoia trees (Figure 22.29).
- Substantively altered Figures 22.2, 22.3, 22.12, 22.26, and 22.33.
- Added new *Data Analysis* end-of-chapter section on fossils in your area.

Chapter 23: Energy and Mineral Resources

- Added new *In the News* on sand pirates getting rich by stealing beaches, riverbeds, and islands.
- Added new statistics on coal energy usage and oil sands in Section 23.1.
- Expanded information on solar energy and updated information on geothermal energy.
- Added new *Data Analysis* end-of-chapter section on global mineral resources.

Chapter 24: Touring Our Solar System

- Added new *In the News* on potentially using a giant cavern as a future moonbase.
- Expanded information on the formation of gas giants in Section 24.1.
- Added discussion of issues the nebular theory of solar system formation does not address in Section 24.1.
- Added new Figure 24.10 on the lobate scarps of Mercury.
- Updated and expanded discussion of possible existence of liquid water on Mars in Section 24.3.
- Updated Section 24.4 on Jupiter, including revised Figure 24.18.
- Section 24.5 now mentions *Hayabusa-2*, an unstaffed spacecraft currently studying the asteroid Ryugu.
- Added to Section 24.5 mention of carbonaceous chondrite, a subcategory of stony meteorite.
- Added new *Data Analysis* end-of-chapter section exploring the topography of Venus.

In The NEWS

Why Do Flash Floods and Mud Flows Often Follow Wildfires?

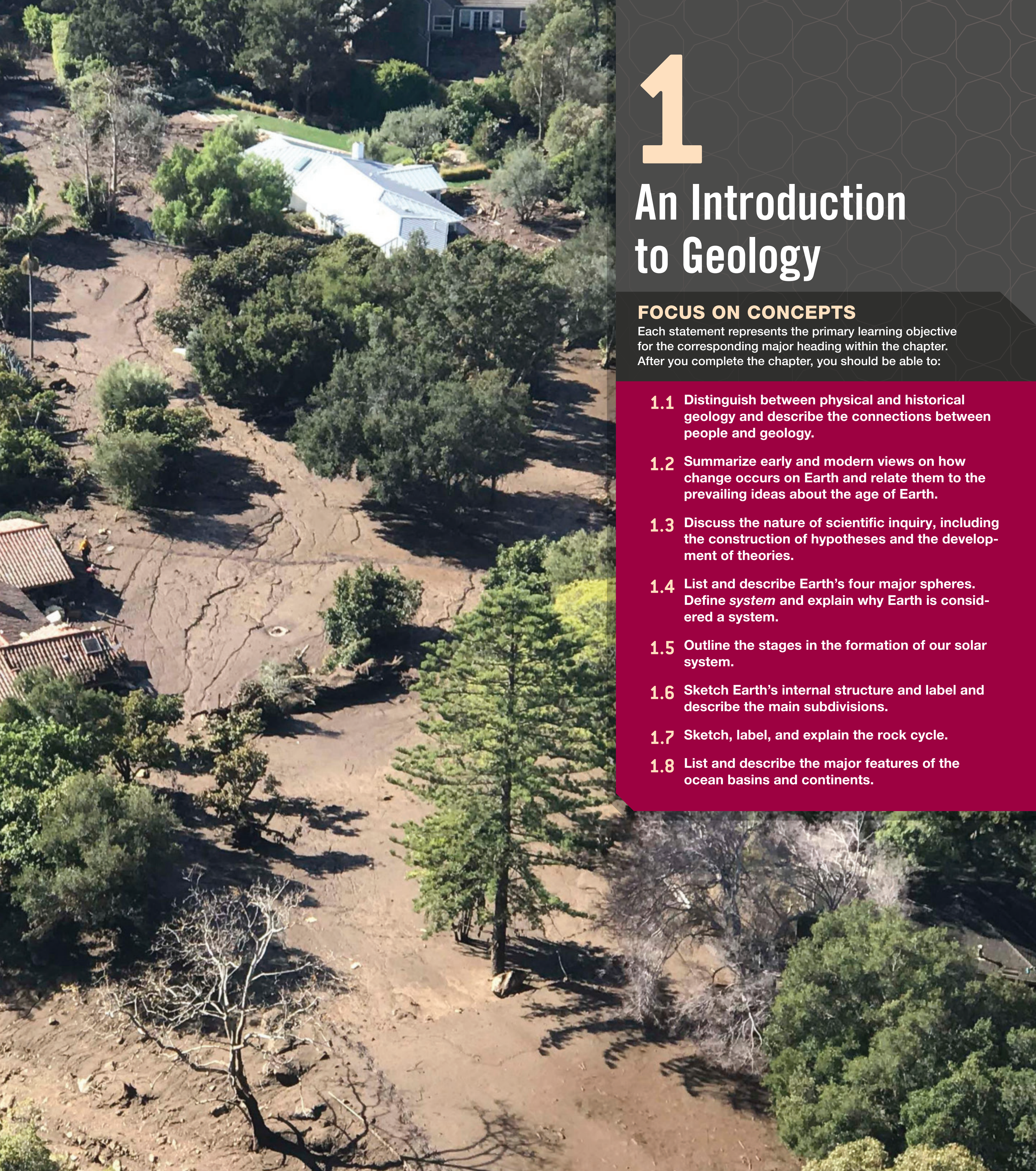
▲ Raging wildfire in southern California.

In December 2017, wildfires burned large areas in the rugged hills of southern California. The fires were especially fierce because the weather had been unusually dry, and strong, hot seasonal Santa Ana winds fanned the flames.

Then, in early January 2018, this same area experienced extraordinarily heavy rains. One might think rain would be welcomed by fire-weary locals, but people immediately went on alert because they knew from experience that in California, flash floods and mudflows often follow fires. As much as 10 centimeters (4 inches) of rain fell in 2 days in the areas around Santa Barbara and Montecito, California. With vegetation that normally anchors steep hillsides burned away, the rain-soaked slopes became unstable. This paved the way for large debris flows and flash floods to destroy property and take lives.

As this example illustrates, atmospheric conditions such as drought and the processes that move water from the hydrosphere to the atmosphere and then to the solid Earth can have a profound impact on plants and animals (including humans). As you will learn in this chapter, Earth is a complex system, and geology gives us a way to study how parts of the system influence and interact with each other.

► Wildfires swept through the Montecito, California, area in December 2017, burning away much of the hillside vegetation. When heavy rains fell in January 2018, massive mudflows inundated the town.



1

An Introduction to Geology

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 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 ocean basins and continents.**

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 it 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.

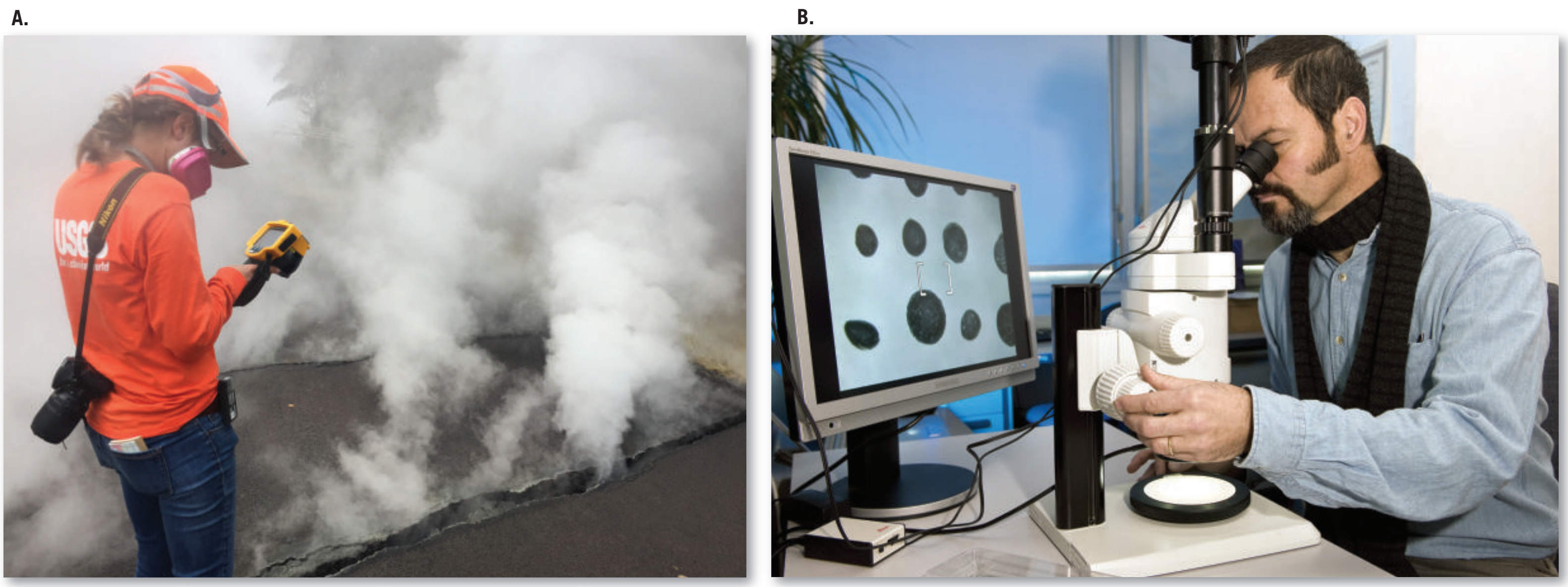
Physical and Historical Geology

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

▼ Figure 1.1
Internal and external processes The processes that operate upon and beneath Earth's surface are an important focus of physical geology.

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 geologist from the U.S. Geological Survey's Hawaiian Volcano Observatory is taking measurements near Kilauea Volcano during activity in May 2018. **B.** This researcher is studying micrometeorites, microscopic particles of rocks that fell to Earth from space.

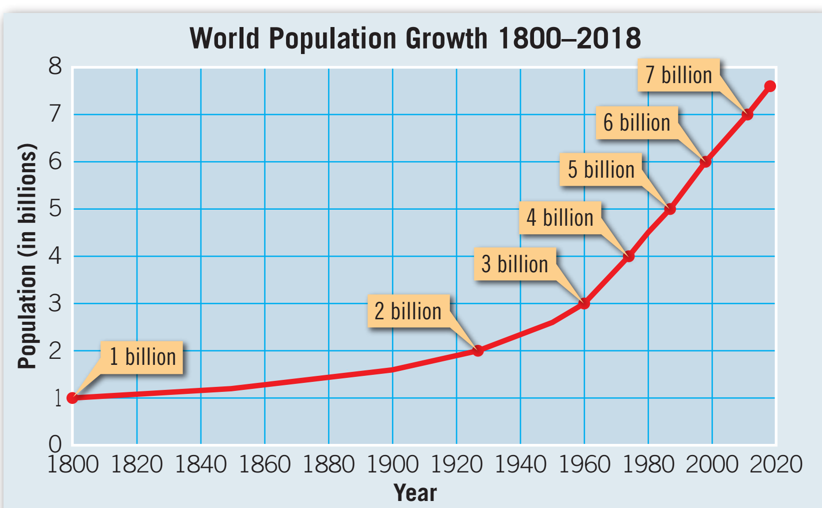
physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of Earth history because we must first understand how Earth works before we attempt to unravel its past. It should also be pointed out that physical and historical geology 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.

Geology, People, and the Environment

Geology is a science that explores many important relationships between people and the natural environment. Complicating all environmental issues is the rapid growth of world population and everyone's aspiration to a better standard of living (Figure 1.3).

Natural Hazards Natural hazards are a part of living on Earth. Every day they adversely affect millions of people worldwide and are responsible for staggering



◄ Figure 1.3
World population growth Our planet is currently adding an estimated 83 million people per year. The demand for resources is ballooning, and there is growing pressure for people to live in environments facing significant geologic hazards.
(Data from *World Population Prospects, 2017 Revision*, from the United Nations Department of Economics and Social Affairs)

▶ **Figure 1.4**
Earthquake in Ecuador On April 16, 2016, a magnitude 7.8 earthquake struck coastal Ecuador. It was the strongest quake in that region in 40 years. There were nearly 700 fatalities and more than 7000 people injured. Natural hazards are *natural processes*. They become hazards only when people try to live where the processes occur.

damages. Geologists study volcanoes, floods, tsunamis, earthquakes, and landslides. Of course, these geologic hazards are *natural* processes. They become hazards only when people try to live where these processes occur (**Figure 1.4**).

According to the United Nations, more people live in cities than in rural areas. This global trend toward urbanization concentrates millions of people into megacities, many of which are susceptible to natural hazards. Coastal sites are especially vulnerable because development often destroys natural storm defenses such as wetlands and sand dunes. Some megacities are exposed to seismic (earthquake) and volcanic hazards, and inappropriate land use and poor construction practices, coupled with rapid population growth, increase the risk of death and damage.

Global Climate Change Among the most important environmental issues linked to human activities is global climate change. As you will learn in Chapter 21, climate is naturally variable. However, when recent and future climate changes are considered,

▶ **Figure 1.5**
Mineral resources represent an important link between people and geology Each year an average American requires huge quantities of Earth materials. According to the USGS, each person in the country uses 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.

natural variability is overshadowed by the influence of humans. Human activities, especially those associated with burning fossil fuels (coal, oil, and natural gas), cause changes in the composition of the atmosphere, which in turn cause global temperatures to rise. Among the many potential impacts of global warming are a rise in sea level, more extreme weather events, and the extinction of many plant and animal species (see Figure 21.26, page 611).

Resources Resources are an important focus of geology that is of great practical value to people. Resources include water and soil, a great variety of metallic and nonmetallic minerals, and energy (**Figure 1.5**). Together resources 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. Chapter 23 focuses on this aspect of geology.

People Influence Geologic Processes At the same time that geologic processes have impacts on people, we humans dramatically influence geologic processes as well. For example, landslides and river flooding occur naturally, but the magnitude and frequency of these events 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 many 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.

CONCEPT CHECKS 1.1

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.**

Concept Checker https://goo.gl/b13P5t

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 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 form only over great spans of time, 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 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 many geologic processes must 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, 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 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 1.6**).

▶ **SmartFigure 1.6**
Earth history—Written in the rocks The erosional work of the Colorado River along with other external processes created this natural wonder. For someone studying historical geology, hiking down the South Kaibab Trail in Grand Canyon National Park is a trip through time. The canyon's rock layers hold clues to more than 1.5 billion years of Earth history.

Mobile Field Trip
https://goo.gl/e225rn

The rock record contains evidence showing that Earth has experienced many cycles of mountain building and erosion (**Figure 1.7**). Concerning the ever-changing nature of Earth through great expanses of geologic time, Hutton famously stated in 1788, "The results, therefore, 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.

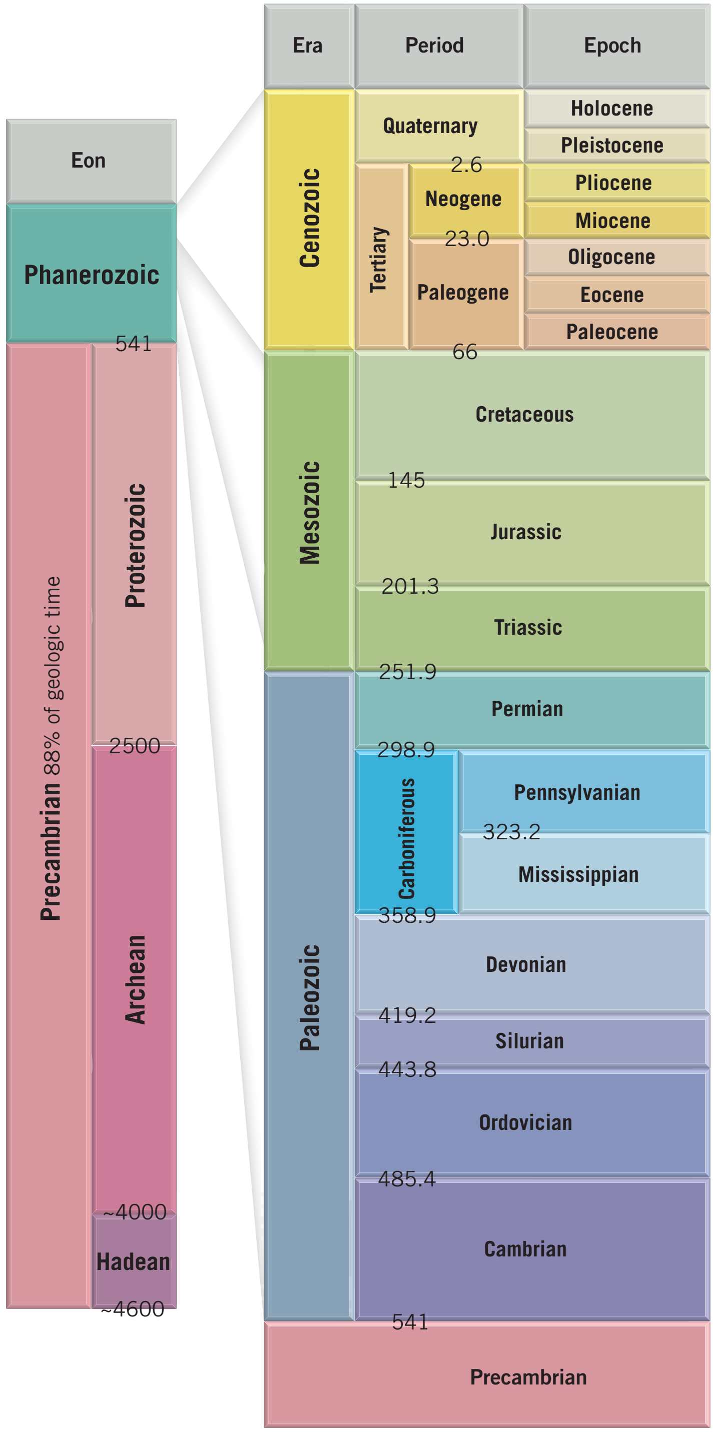
The Magnitude of Geologic Time

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 indicating 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 (see Figure 1.7). 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.

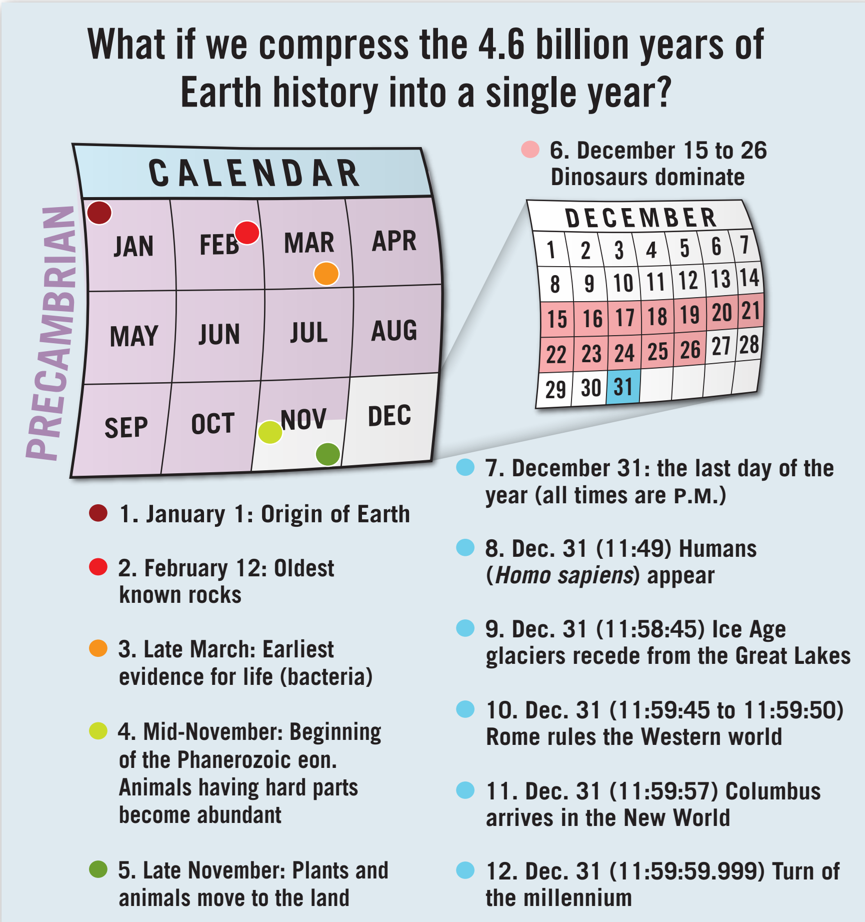
The concept of geologic time is new to many non-geologists. People are accustomed to dealing with increments of time measured in hours, days, weeks, and years. History books often examine events over spans of centuries, but even a century is difficult to appreciate fully. For most of us, someone or something 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 50 million years ago may be characterized as "recent" by a geologist, and a rock sample that has been dated at 5 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,



▲ **Figure 1.7**

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 2018. The ICS is responsible for establishing global standards for the time scale.



◀ **SmartFigure 1.8**
Magnitude of geologic time

Tutorial https://goo.gl/t6HKxU

it would take about two lifetimes (150 years) to reach 4.6 billion! **Figure 1.8** 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. Nevertheless, they help us shift from thinking a million years is impossibly long ("never in a million years") to thinking that a million years is a "blink of an eye" in the history of Earth.

CONCEPT CHECKS 1.2

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 1.7 and list the eon, era, period, and epoch in which we live.

Concept Checker https://goo.gl/5ZGw7Q

1.3 The Nature of Scientific Inquiry

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

Developing an understanding of how science is done and how scientists work is an important theme in this book. As members of a 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. The process depends both on making careful observations and on creating explanations that make sense of the observations. The types of data collected often help to answer well-defined questions about the natural world. In this book you will explore the difficulties in gathering data and some of the ingenious methods that have been developed to overcome these difficulties (**Figure 1.9**). 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 to use the 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.

Hypothesis

A scientific **hypothesis** is a proposed explanation for a certain phenomenon that occurs in the natural world. Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. Therefore, a hypothesis must be *testable*, and it must be possible to make *predictions* based on the hypothesis being considered. 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. More detailed astronomical observations disproved this hypothesis.

◄ **Figure 1.9**
Observation and measurement Scientific data are gathered in many ways. This piece of equipment produces artificial earthquake waves, which are used to probe the underlying rock structures. Vibrations from the 26-ton truck are transmitted to the ground by way of a baseplate (visible between the wheels). The waves reflect from rock layers and structures and are recorded by a network of seismographs.

Theory

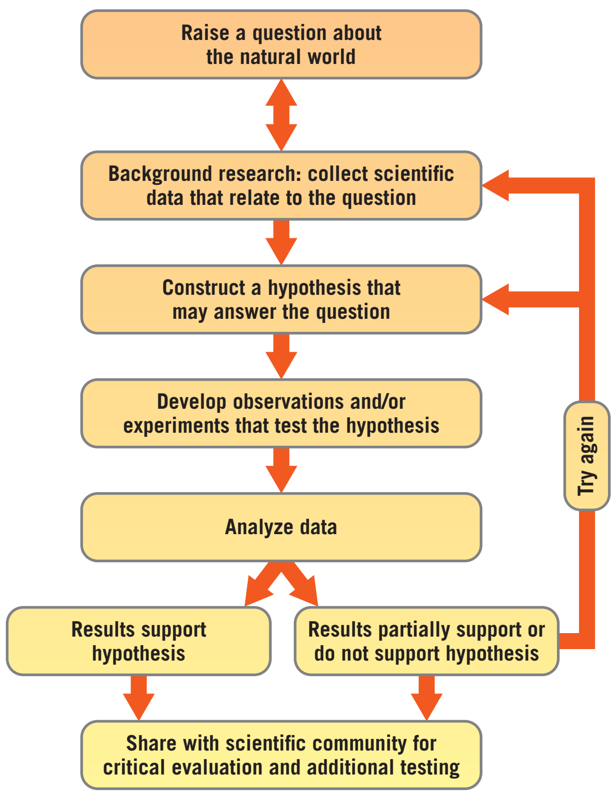
When a hypothesis has survived extensive scrutiny and when competing hypotheses have been eliminated, it may be elevated to the status of a scientific **theory**. In everyday language, we may say that something is "only a theory." But among the scientific community, a theory is a well-tested and widely 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. It also explains the evolution of continents and ocean basins through time—ideas that are explored in detail in Chapters 2, 13, and 14. As you will see in Chapter 21, this theory also helps us understand some important aspects of climate change through long spans of geologic time.

Scientific Methods

The process just described, in which scientists 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."*

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 1.10**. 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



◄ **Figure 1.10**
Steps frequently followed in scientific investigations The diagram depicts the steps involved in the process many refer to as the *scientific method*.

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

unexpected happening occurs during an experiment. These serendipitous discoveries are more than pure luck.

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.

Plate Tectonics and Scientific Inquiry

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

During the past several decades, we have learned a great deal about the workings of our dynamic planet. The revolution in our understanding 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. What finally emerged—called the *theory of plate tectonics*—provided geologists with the first comprehensive model of Earth's internal workings.

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

CONCEPT CHECKS 1.3

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

Concept Checker https://goo.gl/S2StjP

1.4 Earth as a System

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

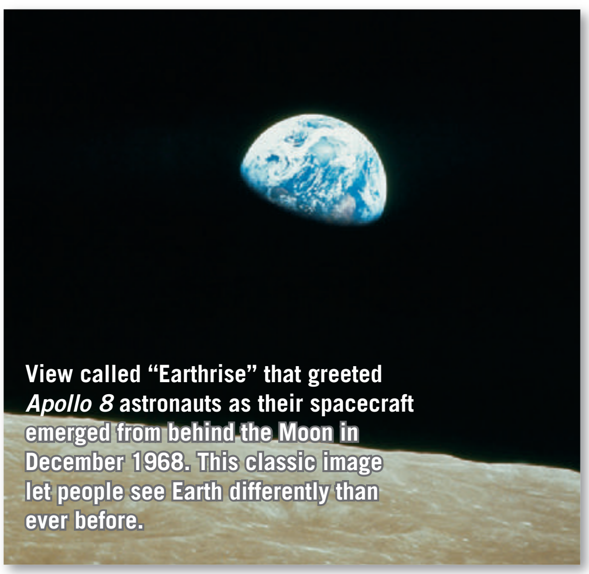
Anyone who studies Earth soon learns that our planet is a dynamic body with many separate but interacting parts, or *spheres*. The hydrosphere, atmosphere, biosphere, and geosphere and all of their components can be studied separately. However, the parts are *not* isolated. Each is related in many ways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

Earth's Spheres

The images in **Figure 1.11** are important because they let humanity see Earth differently than ever before. These early views from the NASA Moon missions of the late 1960s and early 1970s profoundly altered our conceptualizations of Earth. Seen from space, Earth is breathtaking in its beauty

▼ SmartFigure 1.11
Two classic views of Earth from space The accompanying video commemorates the *Apollo 8 mission*, which occurred over 50 years ago, and was the first time a spacecraft carrying humans reached the Moon's orbit. The video re-creates the moment when the crew first saw and photographed Earth rising from behind the Moon.

Video https://goo.gl/uiYNAe



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.

A.

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.

B.

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. Bill Anders, the *Apollo 8* astronaut who took the "Earthrise" photo, expressed it this way: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

The closer view of Earth from space shown in Figure 1.11 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.

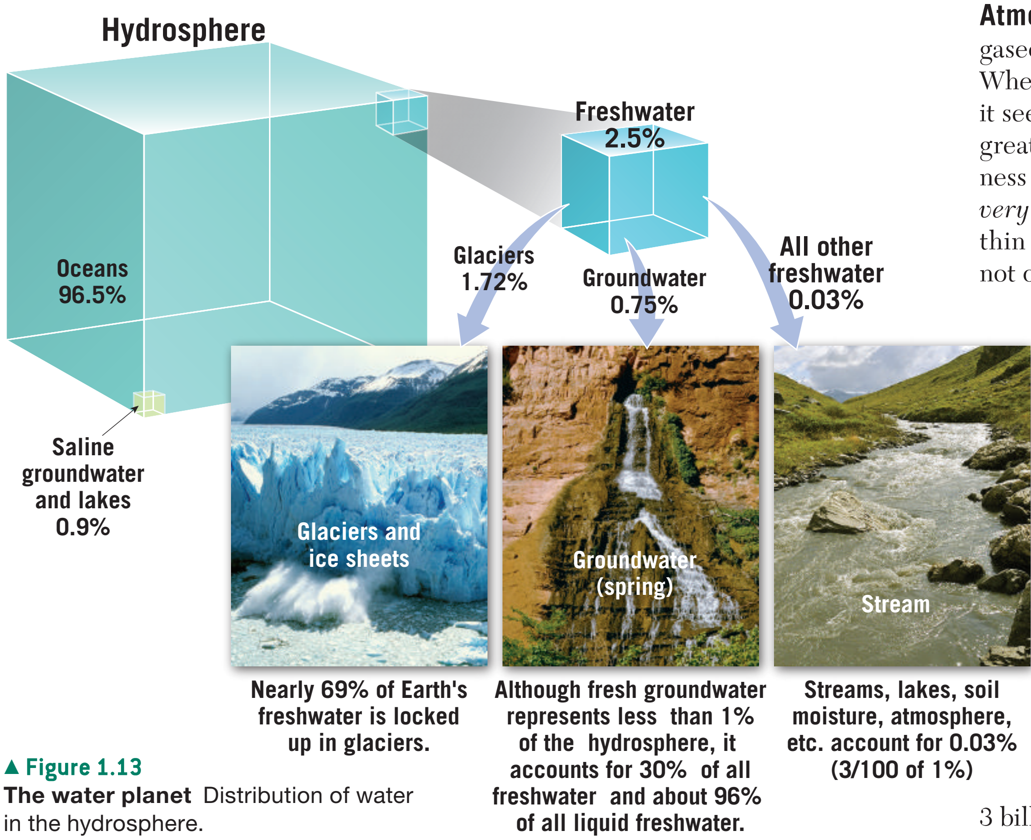
"We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."—Bill Anders, Apollo 8 astronaut

The interactions among Earth's spheres are incalculable. **Figure 1.12** provides us with one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air, and these spheres in turn support life-forms in and near the water. In this scene, ocean waves created by the drag of air moving across the water are breaking against the rocky shore. The force of water, in turn, erodes the shoreline.

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 more than 96 percent of Earth's water (**Figure 1.13**). The hydrosphere also includes the freshwater found underground and in streams, lakes, glaciers, and clouds. Moreover, water is an important component of all living things.

Although freshwater constitutes just a tiny fraction of the total, it is much more important than its meager percentage indicates. Clouds play a vital role in many weather and climate processes, and streams, glaciers, and groundwater are responsible for sculpting and creating many of our planet's varied landforms.

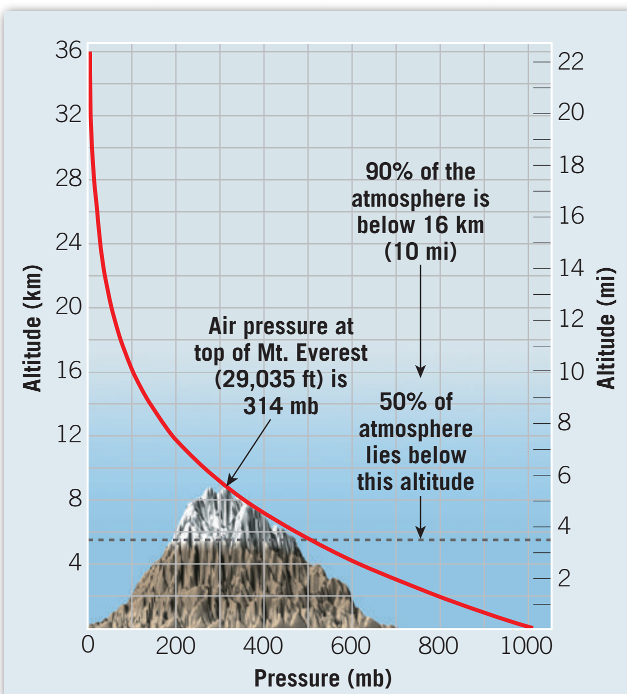
◄ **Figure 1.12**
Interactions among Earth's spheres The shoreline is one obvious interface—a common boundary where different parts of a system interact. In this scene, ocean waves (hydrosphere) that were created by the force of moving air (atmosphere) break against a rocky shore (geosphere). The force of the water can be powerful, and the erosional work that is accomplished can be great.



▲ **Figure 1.13**
The water planet Distribution of water in the hydrosphere.

Atmosphere Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (**Figure 1.14**). 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, the atmosphere is a *very* shallow layer. Despite its modest dimensions, this thin blanket of 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.



► **Figure 1.14**
The atmosphere Earth's shallow envelope of air is an integral part of the planet. Average sea-level pressure is slightly more than 1000 millibars (about 14.7 lb/in^2). There is no sharp upper boundary, but the atmosphere thins rapidly as you travel to greater heights.

Biosphere The **biosphere** includes all life on Earth (**Figure 1.15**). 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.

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 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.

◄ **Figure 1.15**
The biosphere The biosphere, one of Earth's four spheres, includes all life.

Earth System Science

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 *In the News* feature on the opening page of the chapter and **Figure 1.16** provide examples of the interactions among different parts of the Earth system.

The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over. One familiar loop, or subsystem, is the *hydrologic cycle* (see Figure 16.2, page 441). 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.

▲ **Figure 1.16**
Deadly debris flow This image provides an example of interactions among different parts of the Earth system. Extraordinary rains triggered the debris flow (popularly called a mudslide) that buried this house in Montecito, California, in January 2018.

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 is discussed at some length later in the chapter. The cycles of the Earth system are not independent of one another. To the contrary, there are many places where the cycles come in contact and interact.

The Parts Are Linked 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 1.17**). 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.

Time and Space Scales 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.

Energy for the Earth System The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, in

▲ **Figure 1.17**

Change is a geologic constant Mount St. Helens erupted in May 1980. **A.** The eruption. **B.** The immediate aftermath. **C.** The recovery that followed.

the hydrosphere, and at Earth's surface. Weather and climate, ocean circulation, and erosional processes are also 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.

People and the Earth System 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.

CONCEPT CHECKS 1.4

1. **List and briefly contrast the four spheres that constitute the Earth system.**
2. **How much of Earth's surface do oceans cover? What percentage of Earth's water supply do oceans represent?**
3. **What is a system? List three examples.**
4. **What are the two sources of energy for the Earth system?**

Concept Checker https://goo.gl/KL6CSh

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 are 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 Planet Earth

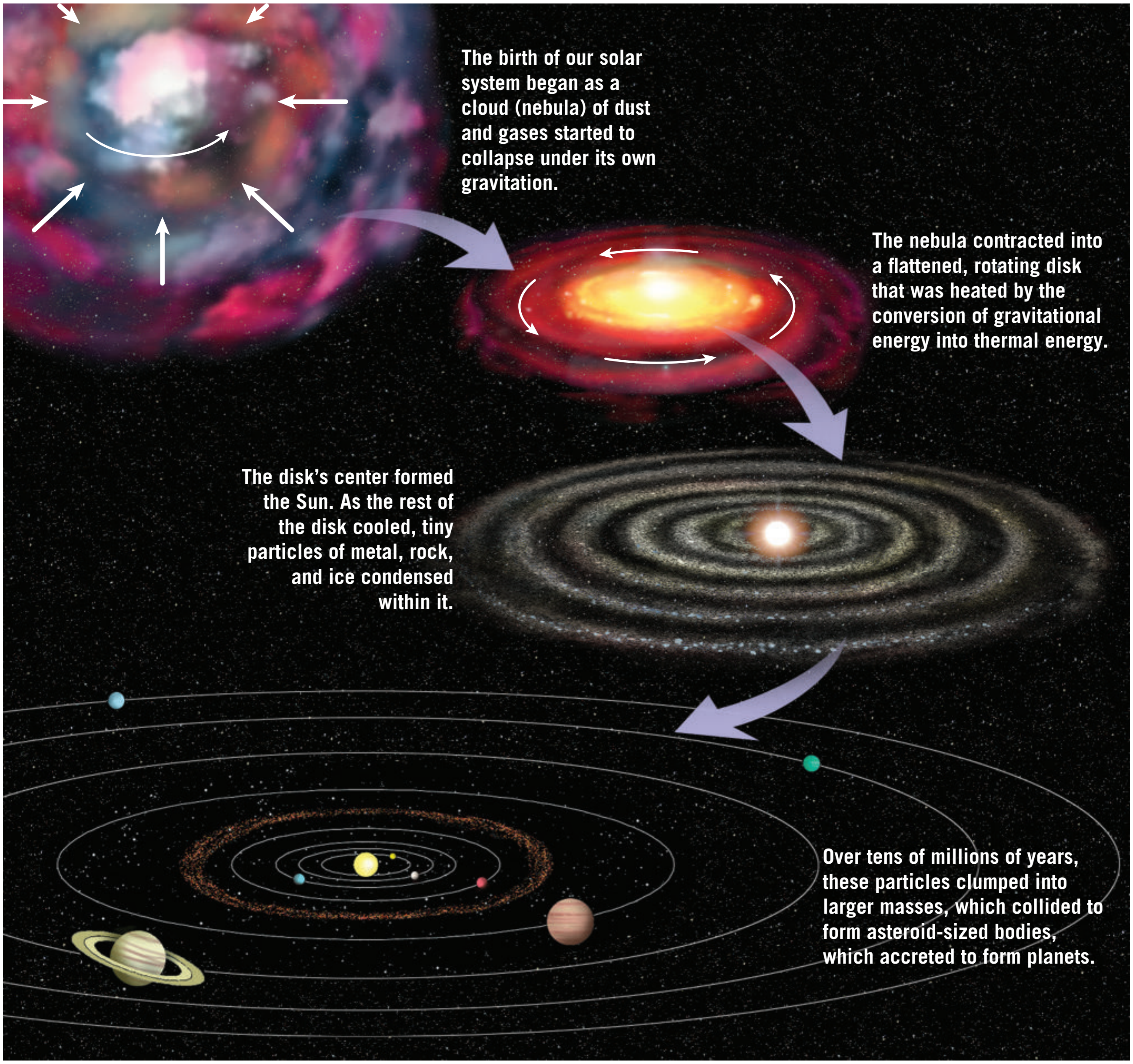
This section describes the most widely accepted views on the origin of our solar system. The theory described here represents the most consistent set of ideas we have to explain what we know about our solar system today. **GEOgraphics 1.1** provides a useful perspective on size and scale in our solar system. In addition, the origins of Earth and other bodies of our solar system are discussed in more detail in Chapters 22 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 1.18**). 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, something—perhaps a shock wave from an exploding star (*supernova*)—caused this nebula to start collapsing in response to its own gravitation. As it collapsed, it evolved from a huge, vaguely rotating cloud to a much smaller, faster-spinning disk. Gradually, through collisions and other interactions, gases and particles began to orbit in one plane. The disk spun faster as it shrank, and most of the cloud's matter ended up in the center of the disk, where it formed the *protosun* (pre-Sun). Astronomers have observed many such disks around newborn stars in neighboring regions of our galaxy.

The protosun and inner disk were heated by the gravitational energy of infalling matter. In the inner disk, temperatures became high enough to cause the dust grains to evaporate. However, at distances beyond the orbit of Mars, temperatures probably remained quite low. At −200°C (−328°F), the tiny particles in the



◀ SmartFigure 1.18
Nebular theory The nebular theory explains the formation of the solar system.

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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.

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 1.18). 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 1.19**). Not all of these clumps of matter were incorporated into the planetesimals. The 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 these growing planetary bodies, the high-velocity impact of nebular debris caused their temperatures 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.

▶ **Figure 1.19**
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.

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 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.

CONCEPT CHECKS 1.5

1. Name and briefly outline the theory that describes the formation of our solar system and then describe the steps in the formation of Earth's layered structure.
2. List the inner planets and outer planets. Describe basic differences in size and composition.

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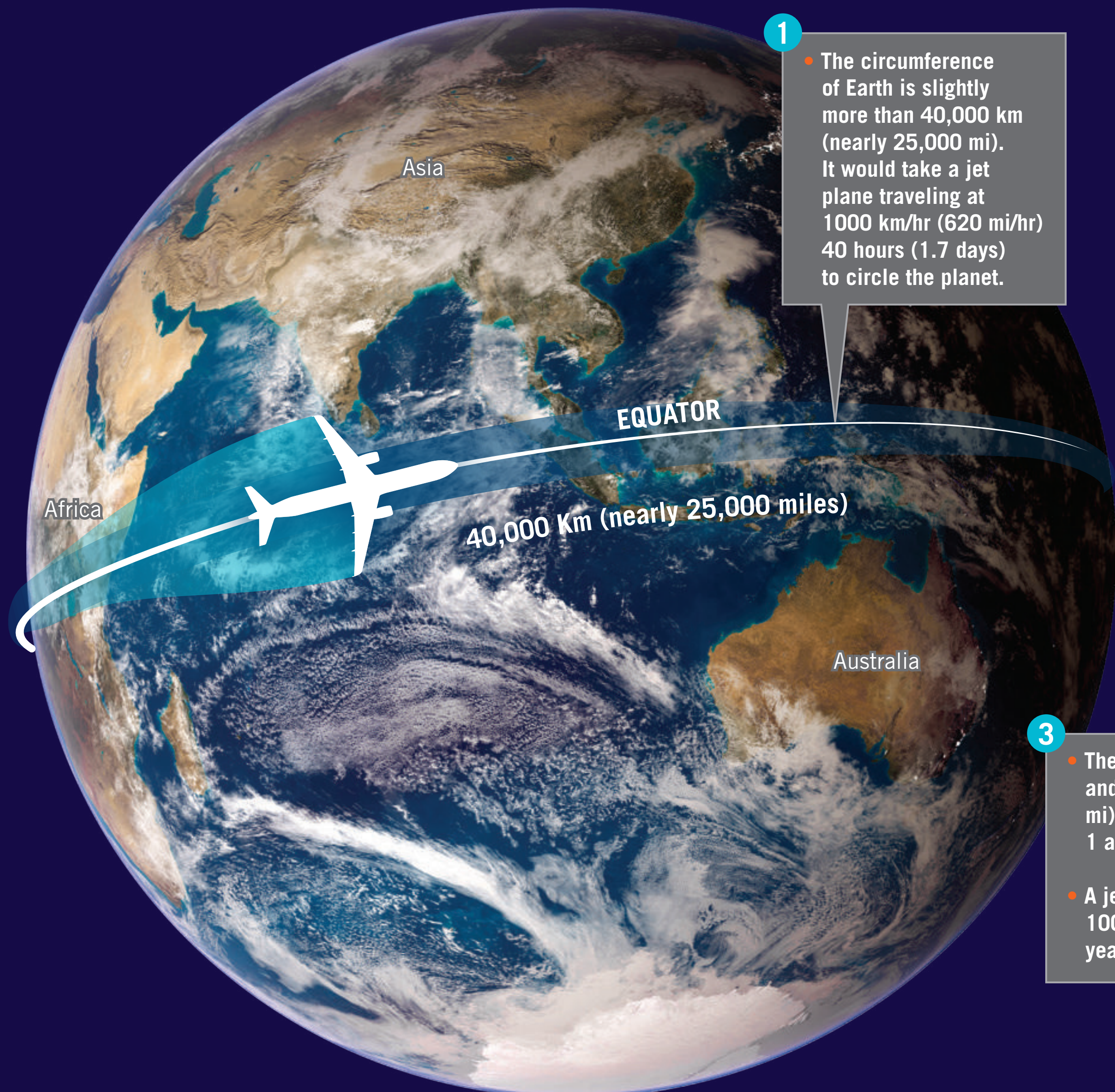
3. Explain why density and buoyancy were important in the development of Earth's layered structure.

GEOGRAPHICS 1.1

Solar System: Size and Scale

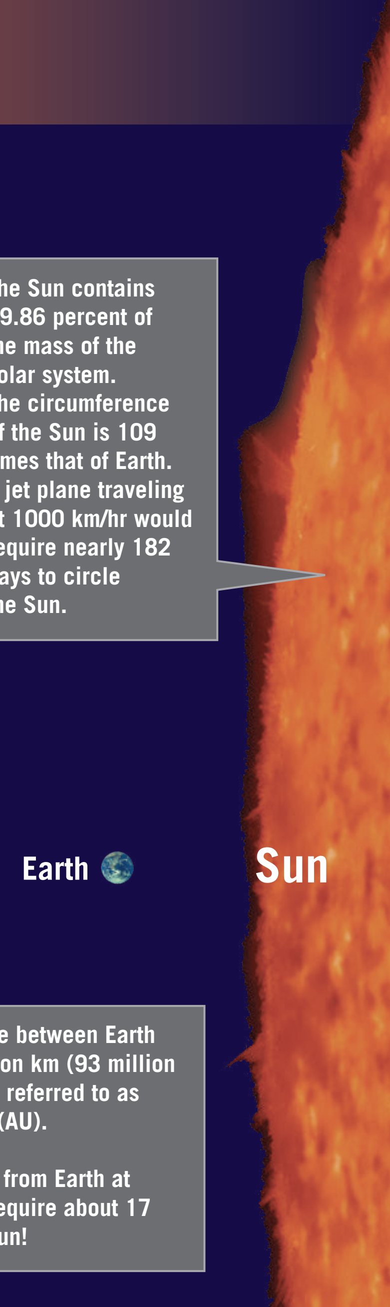


1

- The circumference of Earth is slightly more than 40,000 km (nearly 25,000 mi). It would take a jet plane traveling at 1000 km/hr (620 mi/hr) 40 hours (1.7 days) to circle the planet.

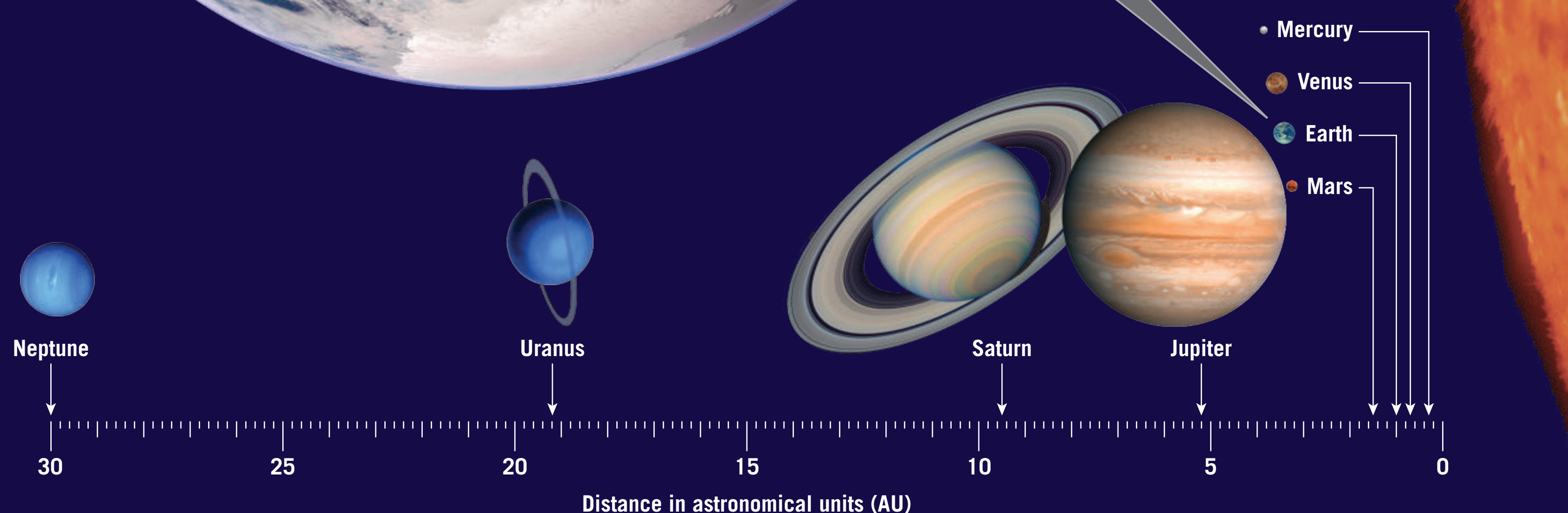
2

- The Sun contains 99.86 percent of the mass of the solar system.
- The circumference of the Sun is 109 times that of Earth.
- A jet plane traveling at 1000 km/hr would require nearly 182 days to circle the Sun.



3

- The average distance between Earth and Sun is 150 million km (93 million mi). This distance is referred to as 1 astronomical unit (AU).
- A jet plane traveling from Earth at 1000 km/hr would require about 17 years to reach the Sun!

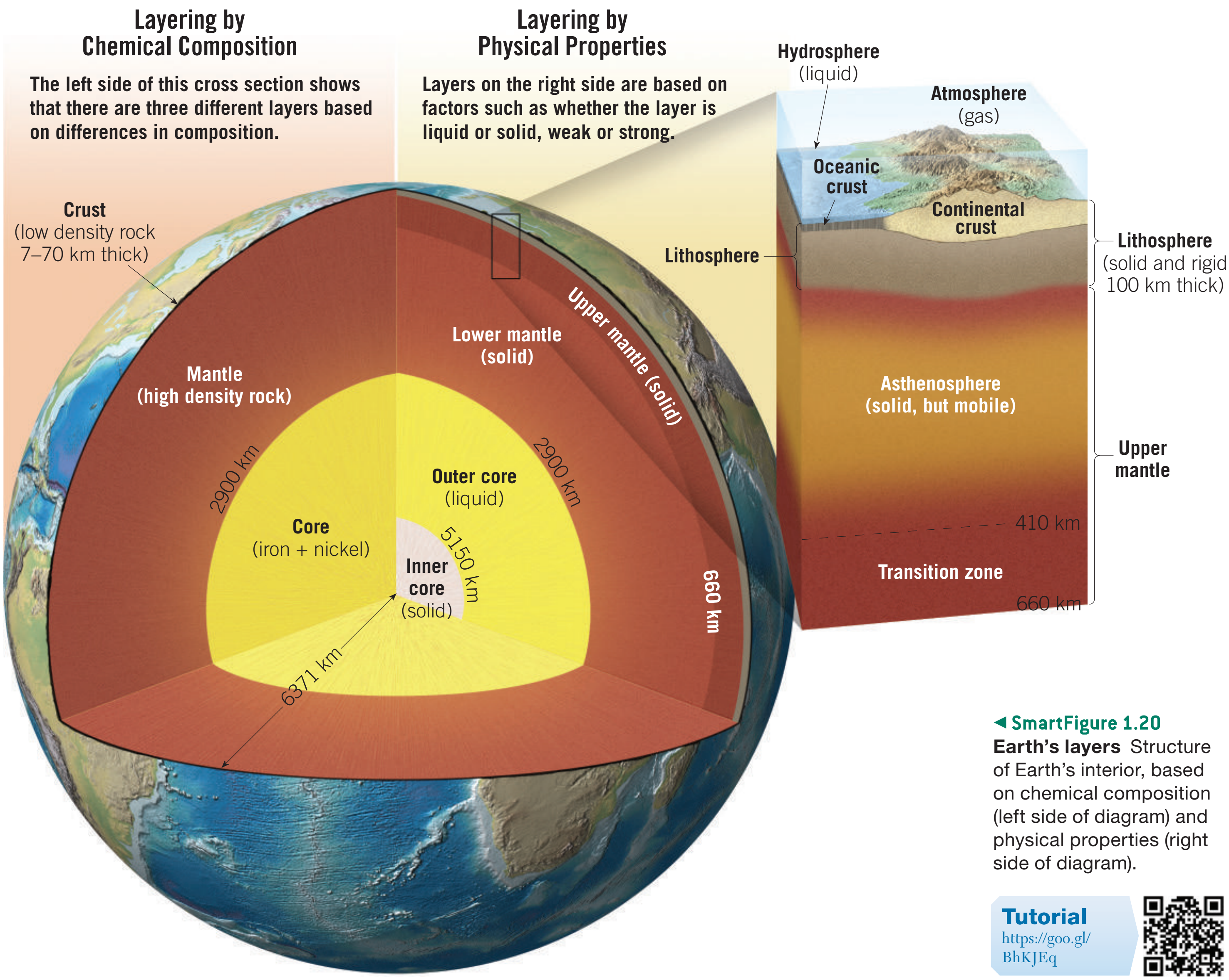


1.6 Earth's Internal Structure

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 1.20** 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 much more about this in Chapter 12.



◄ SmartFigure 1.20
Earth's layers Structure of Earth's interior, based on chemical composition (left side of diagram) and physical properties (right side of diagram).

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Earth's Crust

The **crust**, Earth's relatively thin, rocky outer skin, consists of continental crust and oceanic crust. 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 found to be 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 is part of the stronger *lithosphere*, and beneath it 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 1.20). Averaging about 100 kilometers (60 miles) thick, the lithosphere can be as much as two and a half times this 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 Chapter 2, when we discuss plate tectonics.

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** (see Figure 1.20). 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 The **lower mantle** is a zone that exists from a depth of 660 kilometers (410 miles) to 2900 kilometers (1800 miles). The lower mantle ends at the top of the core. 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″ (pronounced "dee double-prime") layer. 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, as the name implies, the region at the center of Earth's interior. It 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 the higher temperature, the iron in the inner core is *solid* due to the immense pressures that exist in the center of the planet.

CONCEPT CHECKS 1.6

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?

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