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# Earth

## *An Introduction to Physical Geology*

TWELFTH EDITION

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**Earth**

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# Earth

An Introduction to Physical Geology

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**EDWARD J. TARBUCK**

**FREDERICK K. LUTGENS**

*Illustrated by*  
**DENNIS TASA**



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To Our Grandchildren

Shannon, Amy, Andy, Ali, and Michael

Allison and Lauren

*Each is a bright promise for the future.*

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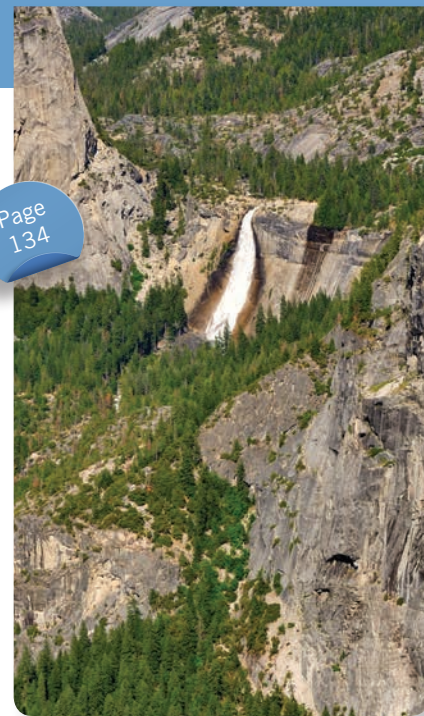
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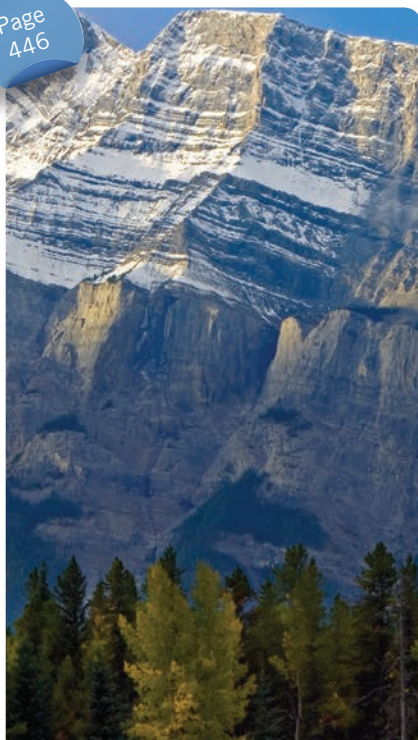
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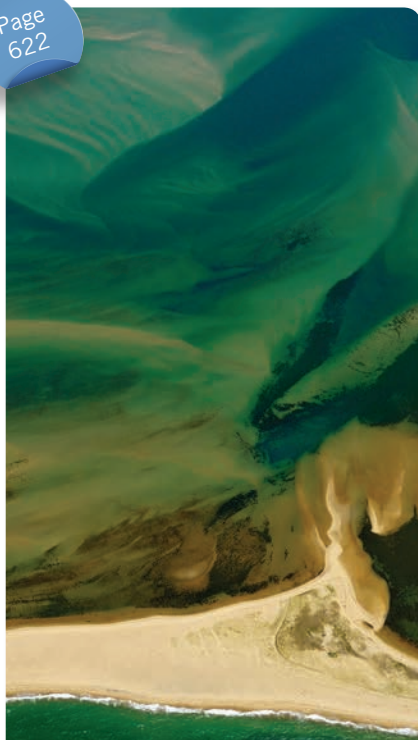
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# Preface

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

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

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

## New and Important Features

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

- **Significant updating and revision of content.** A basic function of a college science textbook is to present material in a clear, understandable way that is accurate, engaging, and up-to-date. In the long history of this textbook, our number-one goal has always been to keep *Earth* current, relevant, and highly readable for beginning students. To that end, every part of this text has been examined carefully. Many discussions, case studies, examples, and illustrations have been updated and revised.
- **SmartFigures that make *Earth* much more than a traditional textbook.** Through its many editions, an important strength of *Earth* has always been clear, logically organized, and well-illustrated explanations. Now, complementing and reinforcing this strength are a series of SmartFigures. Simply by scanning a SmartFigure with a mobile device and **Pearson's BouncePages Augmented Reality app** (FREE and available for iOS and Android),

students can link to hundreds of unique and innovative digital learning opportunities that will increase their insight and understanding of important ideas and concepts. We have also placed short URLs in the caption for every SmartFigure. This will ensure that students who may not have a smart phone, will have the ability to access these videos easily. SmartFigures are truly art that teaches! This 12th edition of *Earth* has more than 200 SmartFigures, of five different types:

1. **SmartFigure Tutorials.** Each of these 2- to 4-minute tutorials, prepared and narrated by Professor Callan Bentley, is a mini-lesson that examines and explains the concepts illustrated by the figure.
2. **SmartFigure Mobile Field Trips.** Scattered throughout this new edition are 24 video field trips that explore classic geologic sites from Iceland to Hawaii. On each trip you will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to see and learn about landscapes that relate to discussions in the chapter.
3. **SmartFigure Condor Videos.** The 10 *Condor* videos take you to sites in the American West. By coupling aerial footage acquired by a quadcopter aircraft with ground-level views, effective narratives, and helpful animations, these videos will engage you in real-life case studies.
4. **SmartFigure Animations.** Scanning the many figures with this designation brings art to life. These animations and accompanying narrations illustrate and explain many difficult-to-visualize topics and ideas more effectively than static art alone.
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- **Enhanced Modular, learning objective-driven, active learning path.** *Earth* is designed for learning. Every chapter begins with *Focus on Concepts*. Each numbered learning objective corresponds to a major section in the chapter. The statements identify the knowledge and skills students should master by the end of the chapter and help students prioritize key concepts. Within the chapter, each major section concludes with *Concept Checks* that allow students to check their understanding and comprehension of important ideas and terms before moving on to the next section. Two end-of-chapter features complete the learning path. *Concepts in Review* coordinates with the *Focus on Concepts* at the start of the chapter

and with the numbered sections within the chapter. It is a concise overview of key ideas, with photos, diagrams, and questions that help students focus on important ideas and test their understanding of key concepts. Chapters conclude with *Give It Some Thought* questions that challenge learners by involving them in activities that require higher-order thinking skills, such as application, analysis, and synthesis of chapter material.

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

## The Teaching and Learning Package

### MasteringGeology™ with Pearson eText

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

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

feedback personalized to their answers, which will help them get back on track.

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

For more information or access to MasteringGeology, please visit [www.masteringgeology.com](http://www.masteringgeology.com).

## Instructor's Resource Materials (Download Only)

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

### Instructor's Resource Materials (IRM)

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

- All of the line art, tables, and photos from the text in .jpg files
- PowerPoint presentations
  - The IRM provides three PowerPoint files for each chapter. Cut down on your preparation time, no matter what your lecture needs, by taking advantage of these components of the PowerPoint files:
- **Exclusive art.** All of the photos, art, and tables from the text, in order, loaded into PowerPoint slides.
- **Lecture outlines.** This set averages 50 slides per chapter and includes customizable lecture outlines with supporting art.

## Instructor Manual (Download Only)

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

## TestGen Computerized Test Bank (Download Only)

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

## Acknowledgments

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

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

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

responsible for preparing the SmartFigure Tutorials that appear throughout the text. As you take advantage of these outstanding learning aids, you will hear his voice explaining the ideas. We appreciate Callan's contributions to this new edition of *Earth*.

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

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**Ed Tarbuck**  
**Fred Lutgens**

Pearson would like to thank and acknowledge Supriyo Das, Presidency University, and Julien Moreau, University of Copenhagen, for contributing to the Global Edition, and Prosenjit Ghosh, Indian Institute of Science, Ashima Saikia, University of Delhi, and Vikram Vishal, Indian Institute of Technology, Bombay, for reviewing the Global Edition.

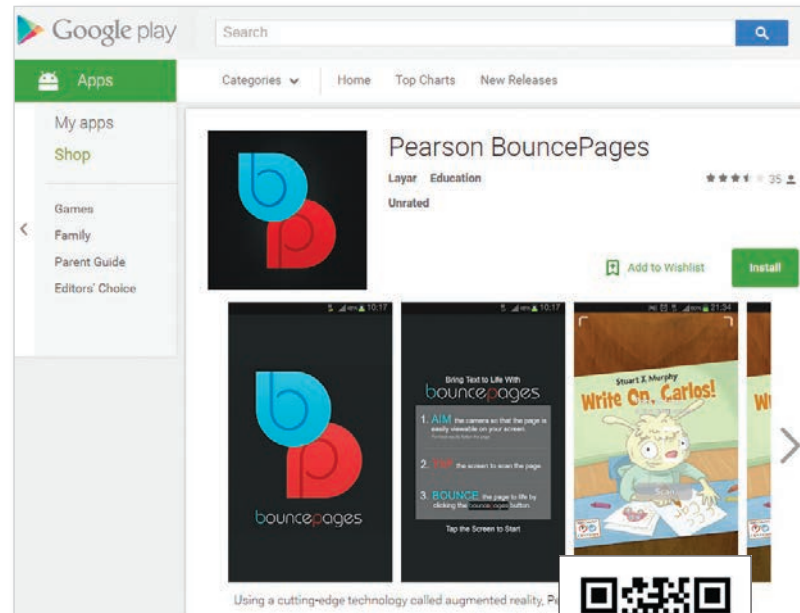
# Augmented Reality Enhances the Reading Experience, Bringing the Textbook to Life



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

BouncePages' augmented reality technology transforms textbooks into convenient digital platforms, breathes life into your learning experience, and helps you grasp difficult academic concepts. Learning geology from a textbook will never be the same.

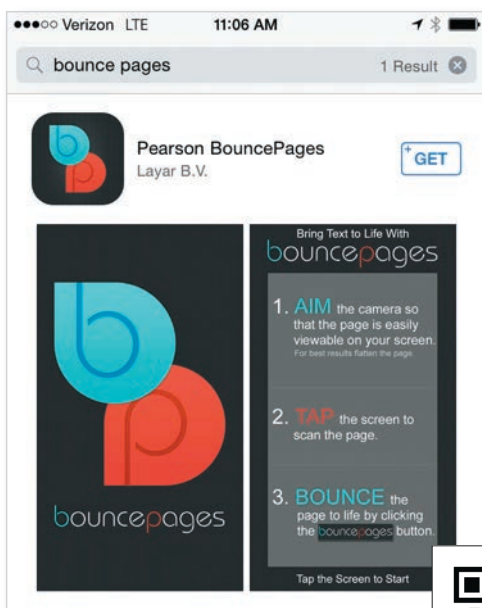
## Download the FREE BP App for Android



<https://play.google.com/store/apps/details?id=com.layar.bouncepages&hl=en>



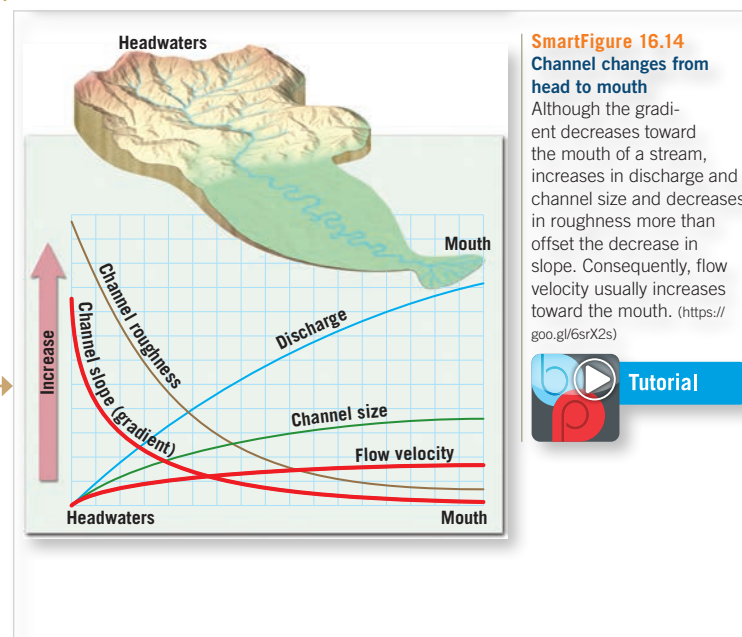
## Download the FREE BP App for iOS



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



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



# Bring the Field to YOUR Teaching and Learning Experience



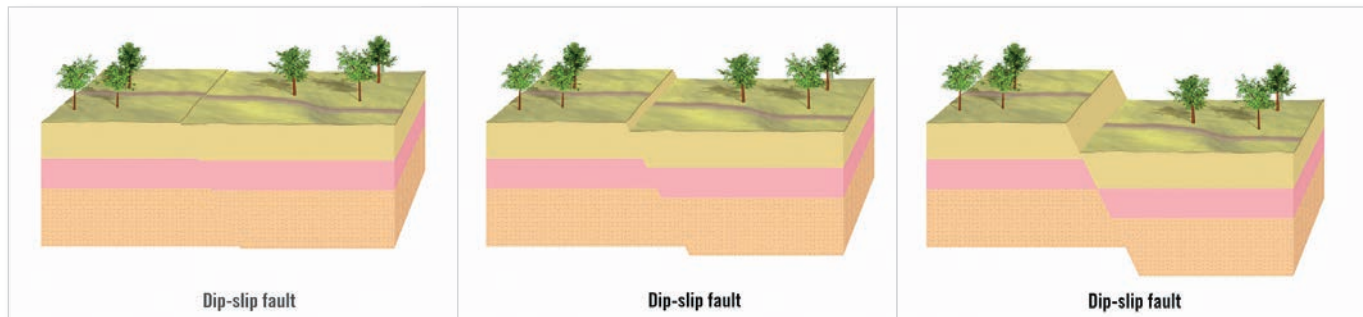
**NEW! SmartFigure: Condor Videos.** Bringing Physical Geology to life for GenEd students, three geologists, using a quadcopter with a GoPro camera mounted to it, have ventured out into the field to film 10 key geologic locations. These process-oriented videos, accessed through BouncePages technology,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



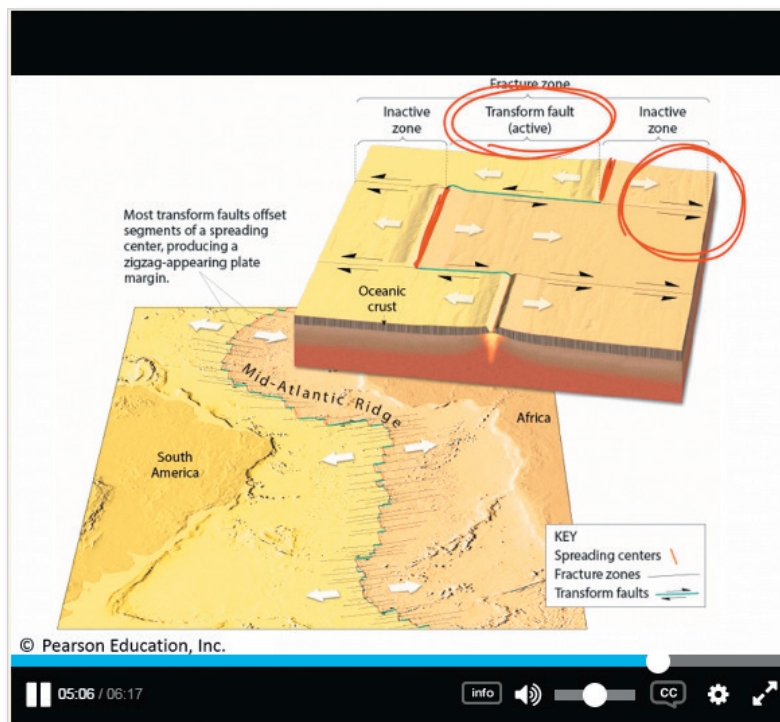
**NEW! SmartFigure: Mobile Field Trips.** Scattered throughout this new edition of Earth are **24 video field trips**. On each trip, you will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to see and learn about iconic landscapes that relate to discussions in the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



# Visualize Processes and Tough Topics



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



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



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



# Improved Geospatial and Data Visualizations

**GEO GRAPHICS 15.2** **Landslide Risks: United States and Worldwide**

According to the U. S. Geological Survey, each year in the United States, landslides cost nearly \$4 billion (2010 dollars) in damage repair and cause between 25 and 50 deaths. All states experience rapid mass-wasting processes, but not all areas have the same landslide potential. What's the risk where you live?

**U.S. LANDSLIDE POTENTIAL**

**KEY**  
 VERY HIGH POTENTIAL  
 HIGH POTENTIAL  
 MODERATE POTENTIAL  
 LOW POTENTIAL

- In parts of the Seattle area, volcanic mudflows called lahars are a potential threat.
- In the mountainous parts of the Pacific Northwest, heavy rains and melting snow often trigger rapid forms of mass wasting.
- Coastal California's steep slopes have a high landslide potential often triggered by winter storms or ground shaking associated with earthquakes.
- Strong wave activity undercuts and oversteepens coastal cliffs.
- In the center of the country, the plains states are relatively flat, so landslide potential is mostly low-to-moderate.
- High potential occurs along steep bluffs that flank river valleys.
- Florida and the adjacent Atlantic and Gulf coastal plains have some of the lowest potential because steep slopes are largely absent.
- In the East, landslides are most common in the Appalachian Mountains.

**GLOBAL LANDSLIDE RISKS**

**Question:** What do areas with the highest landslide potential have in common?

NASA scientists compiled this risk map based on topographic data, land cover classifications and soil types.

Purple and dark red indicate areas at highest risk.

Black dots identify locations of major landslides over a four-year span (2003-2006).

**LANDSLIDE RISK**  
 SLIGHT → MODERATE → SEVERE

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

**GEO GRAPHICS 1.1** **World Population Passes 7 Billion**

This composite satellite image of Earth's city lights helps us appreciate the intensity of human occupation in many parts of the world. In the year 1900, only about 3 percent of the world's people were urban. Today about 61 percent are classified as urban.

Complicating all environmental issues is rapid world population growth and everyone's aspiration to a better standard of living. There is a ballooning demand for resources and a growing pressure for people to live in environments having significant geologic hazards.

**WORLD'S 10 LARGEST METRO AREAS IN 2010**  
 MILLIONS OF CITIZENS

- NEW YORK, USA: 18,490,000
- MEXICO CITY, MEXICO: 16,400,000
- SÃO PAULO, BRAZIL: 20,200,000

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

**EYE ON EARTH 2.1**

In December 2011 a new volcanic island formed near the southern end of the Red Sea. Less than 2 years later, in late October 2013, another volcanic island emerged in the same area. These volcanic islands are part of several small islands in the Zubair Group located off the west coast of Yemen, along the Red Sea Rift.

**QUESTION 1** What type of plate boundary produced these new volcanic islands?

**QUESTION 2** What two plates border the Red Sea Rift?

**QUESTION 3** Are these two plates moving *toward* or *away* from each other?

**Red Sea**

Haycock

New volcanic island, 2013

Rugged

Arabian plate

New island

African plate

Eritrea

Yemen

Ethiopia

Djibouti

Somalia

NASA

# Modular Approach Driven by Learning Objectives

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

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

## 10 Crustal Deformation



**FOCUS ON CONCEPTS**

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

- 10.1 Describe the three types of differential stress and name the type of plate boundary most commonly associated with each.
- 10.2 Compare and contrast brittle and ductile deformation.
- 10.3 List and describe five common folded structures.
- 10.4 Sketch and briefly describe the relative motion of rock bodies located on opposite sides of normal, reverse, and thrust faults as well as both types of strike-slip faults.
- 10.5 Explain how strike and dip are measured and how these measurements tell geologists about the orientations of rock structures located mainly below Earth's surface.

Wyoming's Grand Teton are the result of crustal deformation created by tectonic forces that operate in Earth's interior.

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

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

## 10.5 Concept Checks

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

### 10 Concepts in Review Crustal Deformation

#### 10.1 What Causes Rock to Deform?

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

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

- Rock structures are generated when rocks are deformed by bending or breaking due to differential stress. Crustal deformation produces geologic structures that include folds, faults, joints, foliation, and rock cleavage.

- Stress is the force that drives rock deformation. When stress has the same magnitude in every direction, it is called confining pressure. Alternatively, when the amount of stress coming from one direction is greater in magnitude than the stress coming from another direction, we call it differential stress. There are three main types of differential stress: compressional, tensional, and shear stress.
- Strain is the change in the shape of a rock body caused by stress.

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

#### 10.2 How Do Rocks Deform?

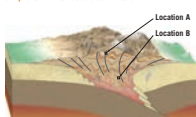
Compare and contrast brittle and ductile deformation.

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

- There are several types of deformation. Elastic deformation is a temporary stretching of the chemical bonds in a rock. When the stress is released, the bonds snap back to their original lengths. When stress is greater than the strength of the bonds, the rock deforms in either a brittle or ductile fashion. Brittle deformation occurs when rocks break into smaller pieces, whereas ductile deformation is a solid-state flow that allows a rock to bend without fracturing.

- The rate at which differential stress is applied also affects how rocks deform. Silly Putty provides a good analogy: If pulled apart quickly, silly Putty tends to break, whereas if pulled apart slowly, it tends to stretch (ductile flow) without breaking.

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



- The type of deformation (brittle or ductile) that occurs depends mainly on temperature, confining pressure, rock type, and time. In Earth's upper crust where temperature and pressure are low, rocks tend to exhibit brittle behavior and break or fracture. At depth rocks tend to deform by flowing or bending.
- Igneous rocks tend to be strong and are more likely to deform in a brittle fashion, whereas sedimentary rocks are weaker and usually deform in a ductile fashion.

#### 10.3 Folds: Rock Structures Formed by Ductile Deformation

List and describe five common folded structures.

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

- Folds are wavelike undulations in layered rocks that develop through ductile deformation in rocks undergoing compressional stress.
- Folds may be described in terms of their geometric configuration. If the limbs of a fold dip down from the hinge, the fold has an arch-like structure and is called an anticline. If the limbs of a fold dip upward, the fold has a trough-like structure and is called a syncline. Anticlines and synclines may be symmetrical, asymmetrical, overturned, or recumbent.

- The shape of a fold does not necessarily correlate to the shape of the landscape above it. Rather, surface topography usually reflects patterns of differential weathering.
- A fold is said to plunge when its axis penetrates the ground at an angle. This results in a V-shaped outcrop pattern of the folded layers.
- Domes and basins are large folds that produce nearly circular-shaped outcrop patterns. The overall shape of a dome or basin is like a saucer or a bowl, either right-side-up (basin) or inverted (dome).
- Monoclines are large step-like folds in otherwise horizontal strata that result from subsurface faulting. Imagine a carpet draped over a short staircase to envision how the strata can go from horizontal to tilted and back to horizontal again.

#### 10.4 Faults and Joints: Structures Formed by Brittle Deformation

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

**KEY TERMS:** fault, slip-slip fault, hanging wall block, footwall block, normal fault, fault-block mountain, horst, graben, half-graben, detachment

**fault, reverse fault, thrust fault, kippe, strike-slip fault, transform fault, oblique-slip fault, megathrust fault, fault scars, slickenside, joint**

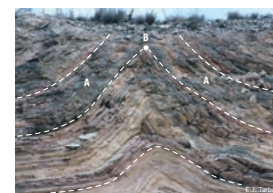
- Faults are fractures along which one rock body slides past another.
- The direction of offset on a fault may be determined by comparing the blocks of rock on either side of the fault surface. Faults in which movement is primarily parallel to the dip of the fault surface are called dip-slip faults.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

### Give It Some Thought

1. Is limestone or shale more likely to fold or flow rather than fracture when subjected to differential stress? Explain.
2. This coin has been run over by a passing train. What is its current shape telling us about the strain that the coin underwent? In what direction was the train going?



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



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

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



## After Class

Easy-to-Assign, Customizable, and Automatically Graded Assignments

10 Crustal Deformation and Mountain B... Condor Videos: Monoclines of the Colorado Plateau

Item Type: Coaching Activities | Difficulty: 2 | Time: 6m

Condor Videos: Monoclines of the Colorado Plateau

Launch the video on monoclines

When you have finished, answer the questions.

**Part D - Structure of a Monocline**

A cross-section of a monocline is shown below. Use what you learned in the video to label the parts of the monocline and the directional forces that created it.

Drag the appropriate labels to their respective targets. Not all labels will be used.

Labels: crystalline basement rocks

Diagram labels: uplifted sedimentary rocks, lowered sedimentary rocks

Submit | Hints | My Answers | Give Up | Review Part

**Incorrect; Try Again**

You labeled 1 of 4 targets incorrectly. Think about where the basement rocks would be located relative to the sedimentary layers.

Part E - The San Rafael Swell

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

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

2015 Geology Demo Assessment Mobile Field Trip Video Quiz - The San Andreas Fault

Item Type: Coaching Activities | Difficulty: 2 | Time: 3m | Learning Outcomes | Contact the Publisher

Mobile Field Trip Video Quiz - The San Andreas Fault

Launch the Mobile Field Trip Video

**Part A**

Earth's outer layer is composed of seven dominant plates. What is the name of this rigid outer layer?

Options: hydrosphere, asthenosphere, mantle, mesosphere, lithosphere

Submit | Hints | My Answers | Give Up | Review Part

**Part B**

What type of plate interaction produces the San Andreas Fault?

Options: Diverging plates, converging plates, plates sliding past one another

Submit | Hints | My Answers | Give Up | Review Part

**Part C**

The bend in the stone walls in the town of Hollister, California are a result of \_\_\_\_\_

Options: extensive igneous activity whereby magma rose towards the surface, causing structural damage; a large earthquake that caused major loss of life and property damage

**Part B - Materials associated with each type of mass movement**

The various types of mass movements are different in terms of the materials they constitute, and this difference results in a unique mark on the landscape for each type.

You will label the five type of mass wasting in terms of the materials they carry.

Drag the appropriate labels to their respective targets.

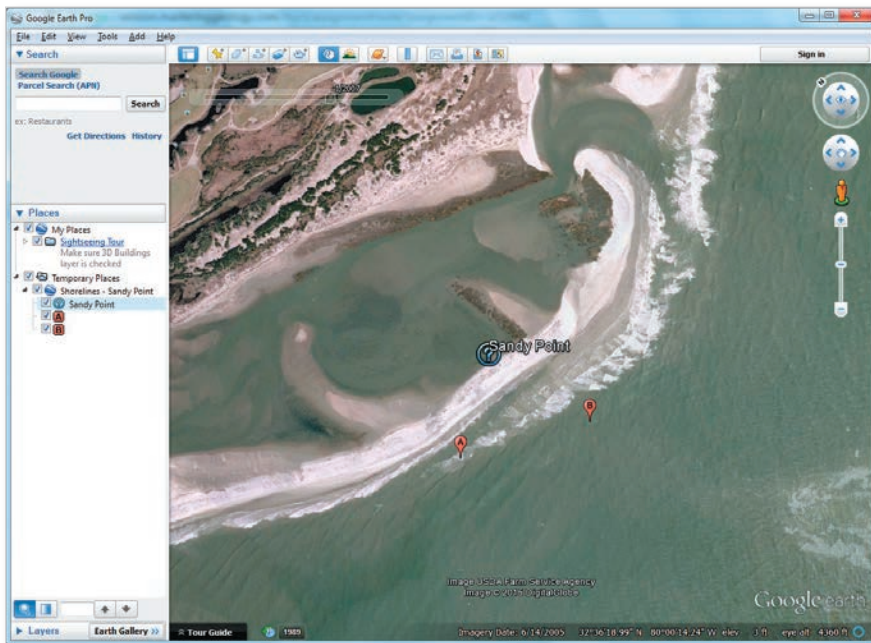
Slump	Slide	Flow	Creep	Fall
Material	Material	Material	Material	Material
Unconsolidated sediments along a curved surface	Loose sediments gradually transported downhill	Sometimes ash	Blocks of bedrock broken loose and sliding downhill	Boulders on a rocky cliff

Submit | Hints | My Answers | Give Up | Review Part

**Incorrect; Try Again**

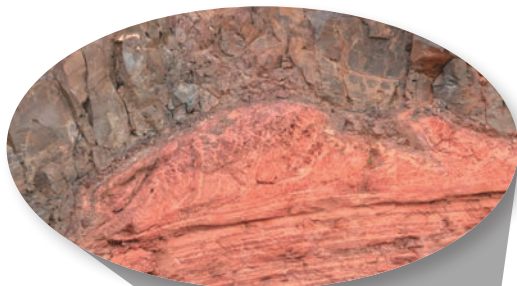
You labeled 2 of 5 targets incorrectly. Which type of mass movement involves the movement of consolidated blocks of detached bedrock and has a distinct zone of weakness separating the slide material from the more stable underlying material?

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



**Encounter Activities** provide rich, interactive explorations of geology and earth science concepts using the dynamic features of Google Earth™ to visualize and explore earth's physical landscape. Dynamic assessment includes questions related to core geology concepts. All explorations include corresponding Google Earth KML media files, and questions include hints and specific wrong-answer feedback to help coach students towards mastery of the concepts while improving students geospatial skills.

**NEW! 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.



**Part D - Making Observations**

After exploring the Gigapan field site, arrange the following observations/inferences by their respective rock unit. These observations/inferences describe the material, appearance and weathering pattern of the respective rock units.

Drag the appropriate items into their respective bins. Each item may be used only once.

**Rock Unit 1**

Red and white in color

Appears to be made up of many thin layers

Weathers in small irregular shapes

Weathers in large blocks

Appears to be massive (no layers)

Sediments too small to see

**Rock Unit 2**

Black and dark gray in color

Crystals too small to see

[reset](#) [help](#)

[Submit](#) [Hints](#) [My Answers](#) [Give Up](#) [Review Part](#)

**Incorrect; Try Again**

You sorted 2 out of 8 items incorrectly. Compare the weathering pattern of rock unit #2 to the weathering pattern of rock unit #1. Which rock unit produces large blocks?

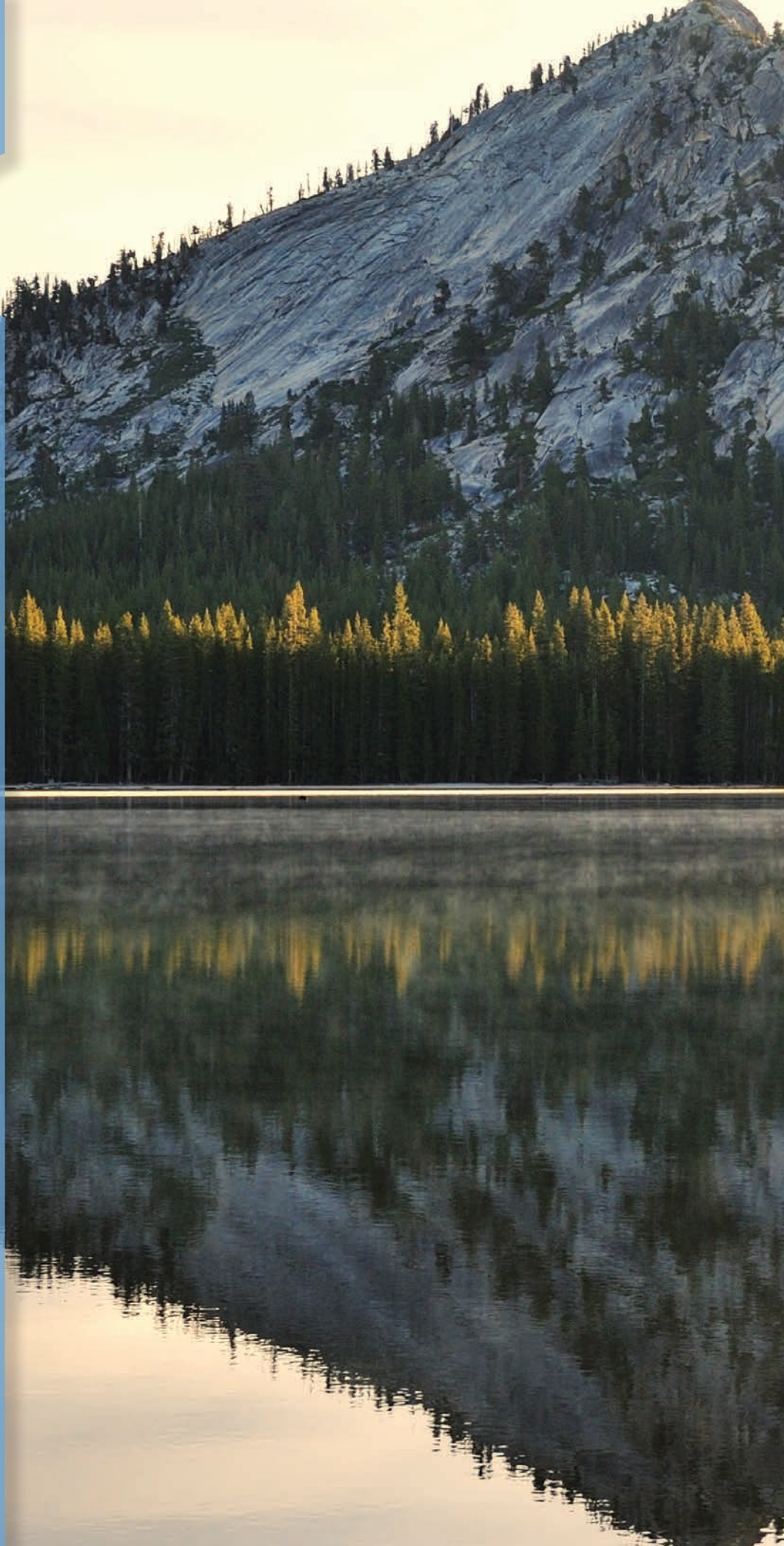
**Additional MasteringGeology assignments available:**

- SmartFigures
- Interactive Animations
- Give It Some Thought Activities
- Reading Quizzes
- MapMaster Interactive Maps

# 1

## An Introduction to Geology

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





**FOCUS ON  
CONCEPTS**

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

- 1.1 Distinguish between physical and historical geology and describe the connections between people and geology.**
- 1.2 Summarize early and modern views on how change occurs on Earth and relate them to the prevailing ideas about the age of Earth.**
- 1.3 Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.**
- 1.4 List and describe Earth's four major spheres. Define *system* and explain why Earth is considered to be a system.**
- 1.5 Outline the stages in the formation of our solar system.**
- 1.6 Sketch Earth's internal structure and label and describe the main subdivisions.**
- 1.7 Sketch, label, and explain the rock cycle.**
- 1.8 List and describe the major features of the continents and ocean basins.**

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

## 1.1 Geology: The Science of Earth

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

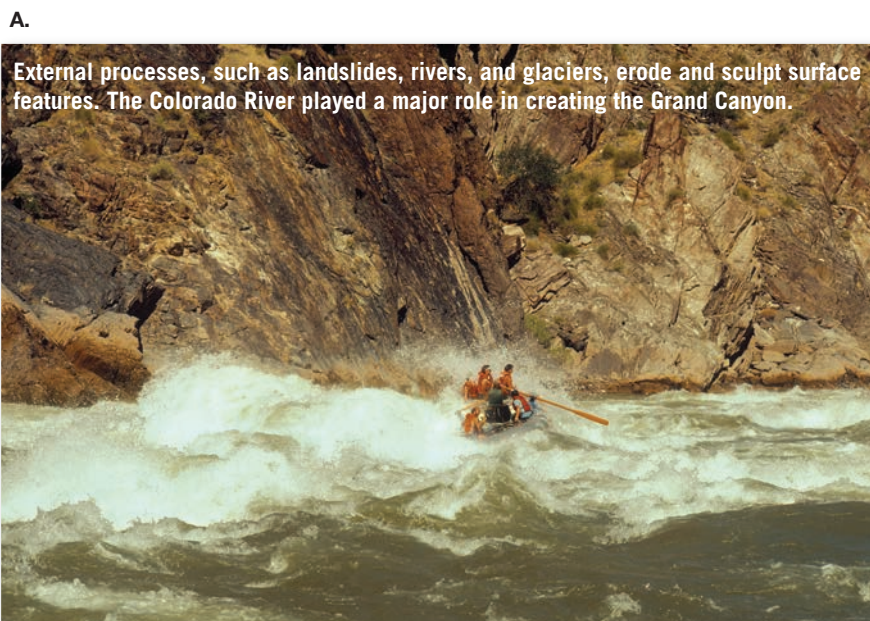
The subject of this text is **geology**, from the Greek *geo* (Earth) and *logos* (discourse). Geology is the science that pursues an understanding of planet Earth. Understanding Earth is challenging because our planet is a dynamic body with many interacting parts and a complex history. Throughout its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

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

### Physical and Historical Geology

Geology is traditionally divided into two broad areas—physical and historical. **Physical geology**, which is the primary focus of this book, examines the materials composing Earth and seeks to understand the many processes that operate beneath and upon its surface (Figure 1.1). The aim of **historical geology**, on the other

hand, is to understand Earth's origins and its development through time. Thus, it strives to establish an orderly chronological arrangement of the multitude of physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of Earth history because we must first understand how Earth works before we attempt to unravel its past. It should also be pointed out that physical and historical



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

The primary focus of this book is to develop your understanding of basic geologic principles, but along



A.



B.

**Figure 1.2**

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

the way, we explore numerous important relationships between people and the natural environment. Many of the problems and issues that geologists address are of practical value.

*Natural hazards* are a part of living on Earth. Every day they adversely affect millions of people worldwide and are responsible for staggering damages. Among the hazardous Earth processes that geologists study are volcanoes, floods, tsunamis, earthquakes, and

landslides. Of course, geologic hazards are *natural* processes. They become hazards only when people try to live where these processes occur (Figure 1.3).



**Figure 1.3**

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

# World Population Passes 7 Billion

Complicating all environmental issues is rapid world population growth and everyone's aspiration to a better standard of living. There is a ballooning demand for resources and a growing pressure for people to live in environments having significant geologic hazards.

WORLD'S 10 LARGEST METRO AREAS IN 2010  
MILLIONS OF CITIZENS

5 MEXICO CITY, MEXICO  
19,460,000

6 NEW YORK, USA  
19,430,000

This composite satellite image of Earth's city lights helps us appreciate the intensity of human occupation in many parts of the world. In the year 1800, only about 3 percent of the world's people were urban. Today about 51 percent are classified as urban.

4 SAO PAULO, BRAZIL  
20,260,000

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

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

maintaining supplies and with the environmental impacts of their extraction and use.

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

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

## WORLD POPULATION MILESTONES

Growth of population 1800-2011 and projected to 2025

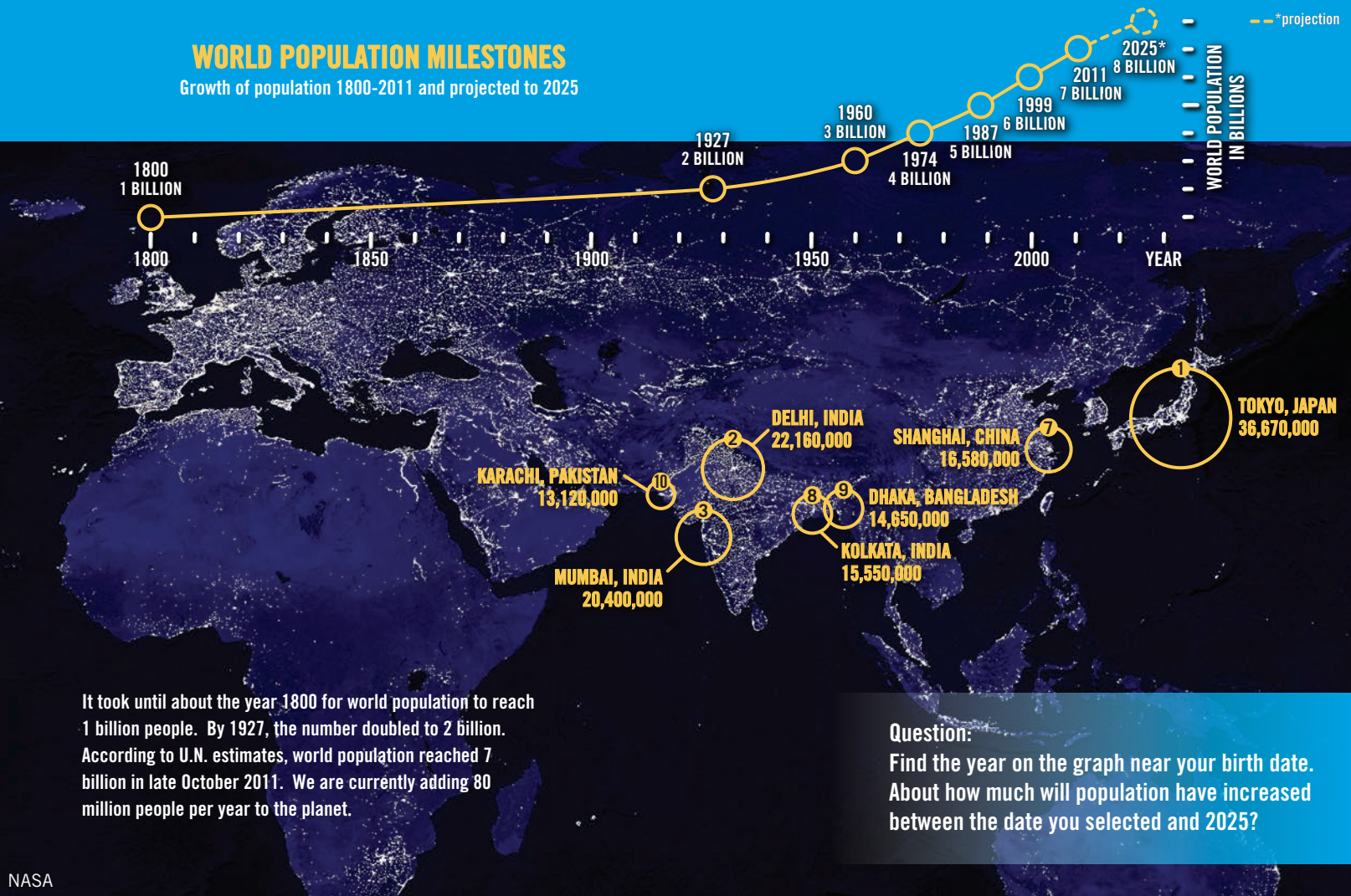


Figure 1.4

### Mineral resources represent an important link between people and geology

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

## 1.1 Concept Checks

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



## 1.2 The Development of Geology

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

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

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

was widely accepted by Europe's scientific and religious leaders, and his chronology was soon printed in the margins of the Bible itself.

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

### 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

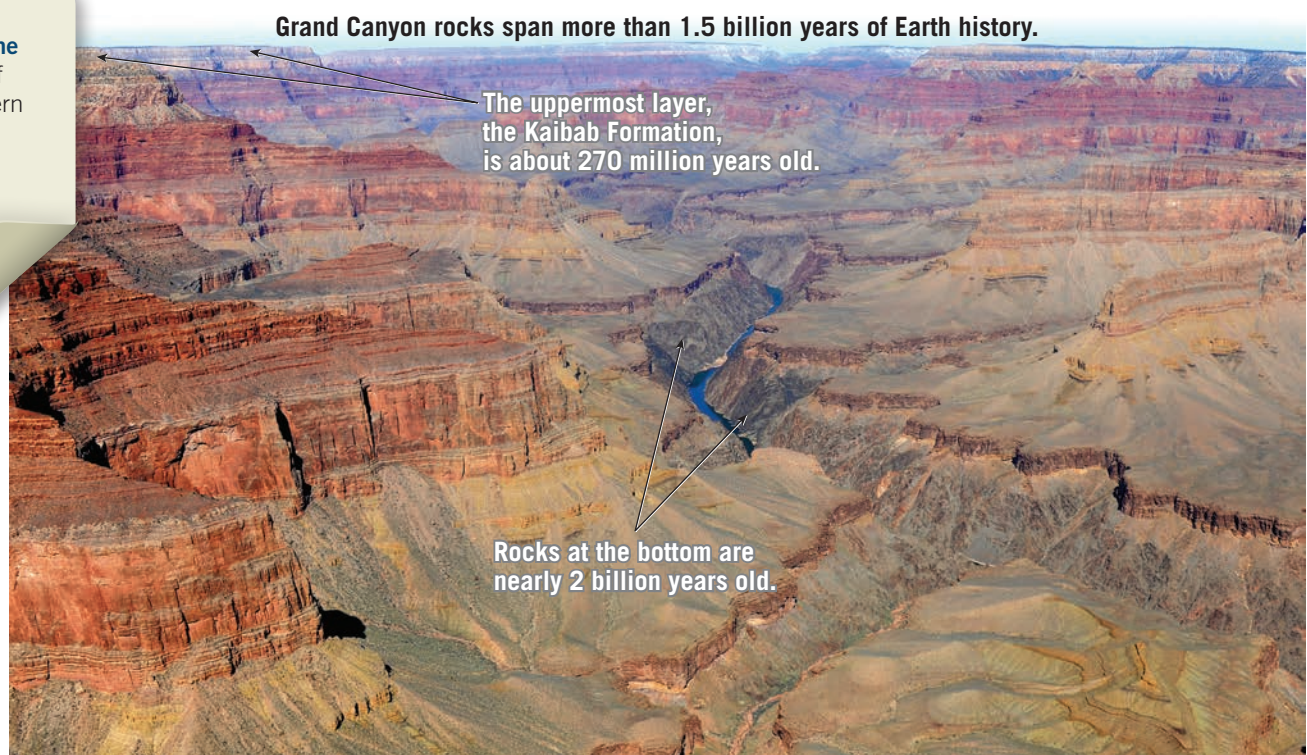
### The Birth of Modern Geology

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

#### SmartFigure 1.5

##### Earth history—Written in the rocks

The Grand Canyon of the Colorado River in northern Arizona. (Photo by Dennis Tasa) (<http://goo.gl/7KwQLk>)



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

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

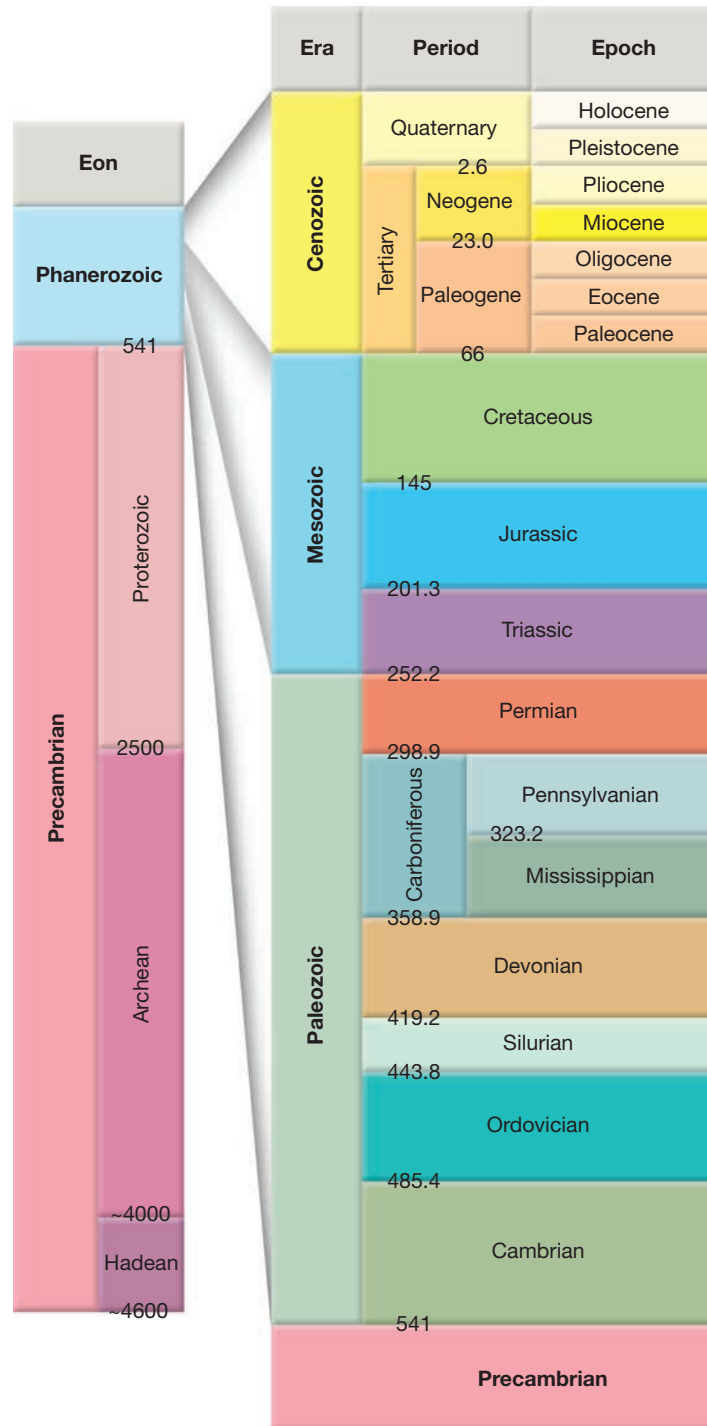
For example, when Hutton argued that mountains are sculpted and ultimately destroyed by weathering and the work of running water, and that their waste materials are carried to the oceans by observable processes, he said, "We have a chain of facts which clearly demonstrate . . . that the materials of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

## Geology Today

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

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

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



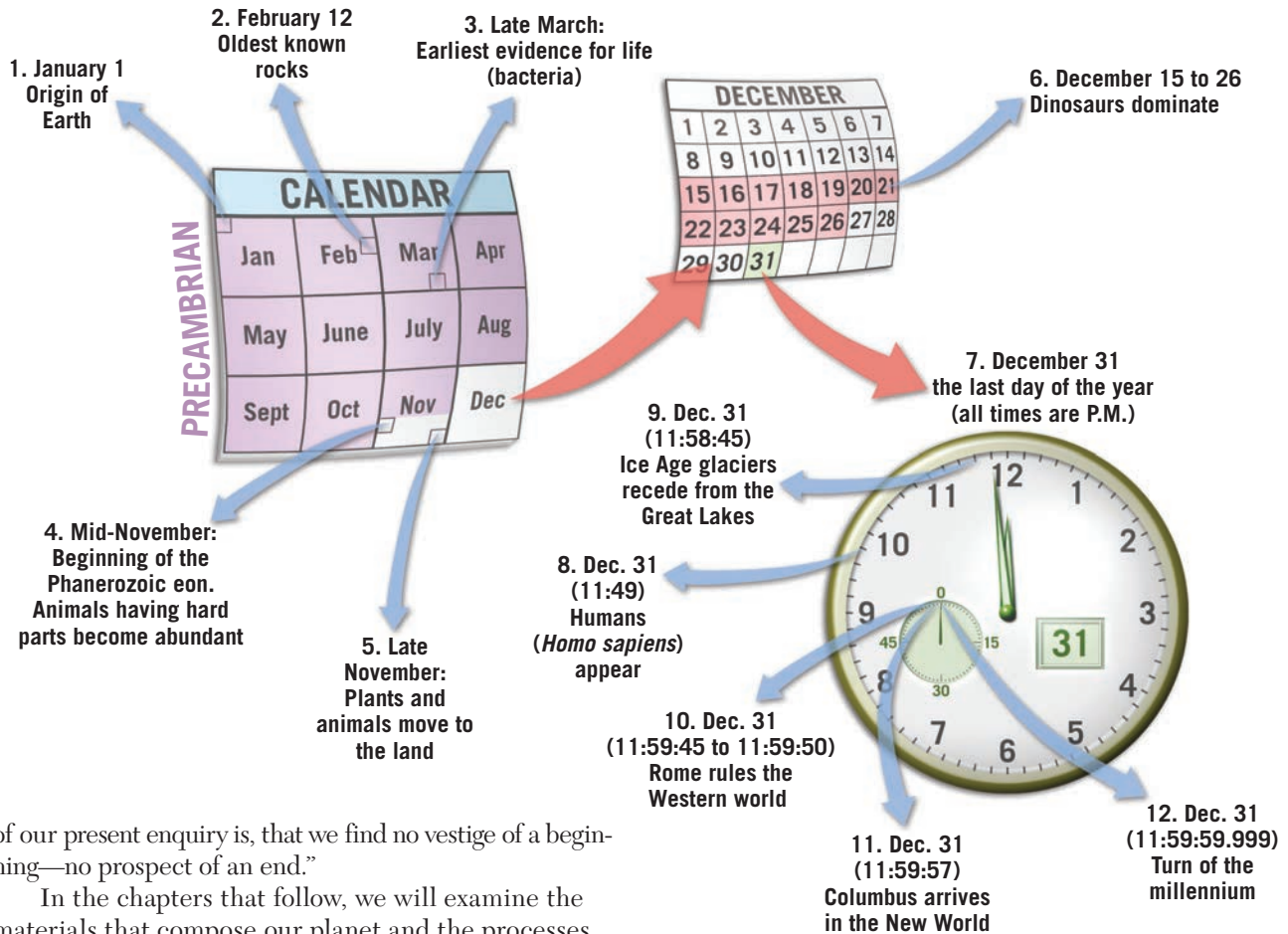
**Figure 1.6**

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

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



## What if we compress the 4.6 billion years of Earth history into a single year?



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

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

### The Magnitude of Geologic Time

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

Today our understanding of radioactivity—and the fact that rocks and minerals contain certain radioactive isotopes having decay rates ranging from decades to billions of years—allows us to accurately determine numerical dates for rocks that represent important events in Earth’s distant past (Figure 1.6). For example,

we know that the dinosaurs died out about 65 million years ago. Today geologists put the age of Earth at about 4.6 billion years. Chapter 9 is devoted to a much more complete discussion of geologic time and the geologic time scale.

The concept of geologic time is new to many 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 100 million years ago may be characterized as “recent” by a geologist, and a rock sample that has been dated at 10 million years may be called “young.” An appreciation for the magnitude of geologic time is important in the

study of geology because many processes are so gradual that vast spans of time are needed before significant changes occur. How long is 4.6 billion years? If you were to begin counting at the rate of one number per second and continued 24 hours a day, 7 days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.6 billion! **Figure 1.7** provides another interesting way of viewing the expanse of geologic time. Although helpful in conveying the magnitude of geologic time, this figure and other analogies, no matter how clever, only begin to help us comprehend the vast expanse of Earth history.

## 1.2 Concept Checks

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

## 1.3 The Nature of Scientific Inquiry

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

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

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then use that knowledge to make

predictions about what should or should not be expected, given certain facts or circumstances. For example, by knowing how oil deposits form, geologists can predict the most favorable sites for exploration and, perhaps as importantly, avoid regions that have little or no potential.



### EYE ON EARTH 1.1

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

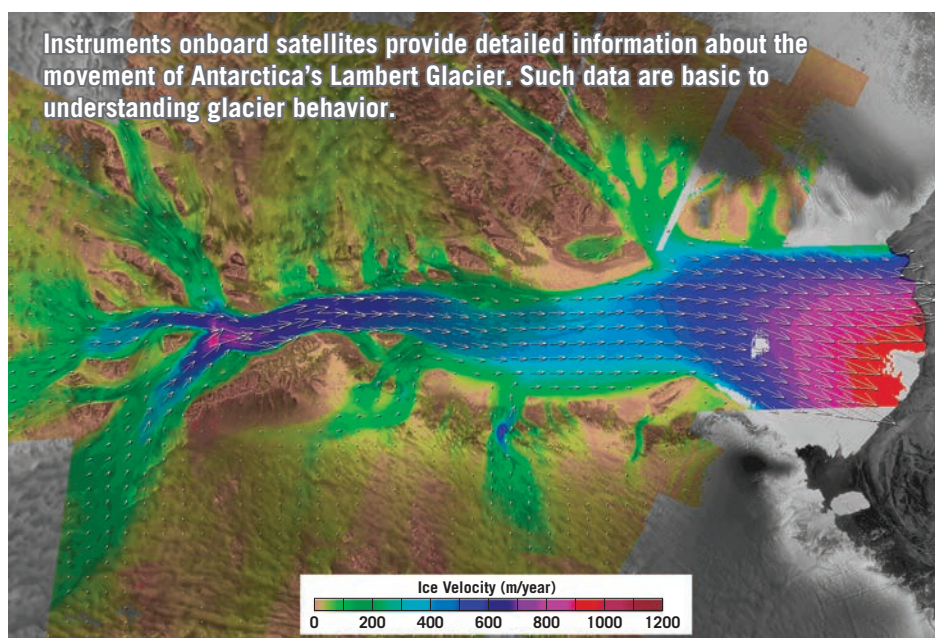
**QUESTION 1** Can you establish a relative time scale for these rocks? That is, can you determine which one of the layers shown here is likely oldest and which is probably youngest?

**QUESTION 2** Explain the logic you used.



(Photo by David Carriere/AGE Fotostock)

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



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

## Hypothesis

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

Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. If a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it might seem. The verification process requires that *predictions* be made, based on the hypothesis being considered, and that the predictions be tested through comparison with objective observations. Put another way, hypotheses must

fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are ultimately discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. As mathematician Jacob Bronowski so ably stated, “Science is a great many things, but in the end they all return to this: Science is the acceptance of what works and the rejection of what does not.”

## Theory

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

## Scientific Methods

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

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

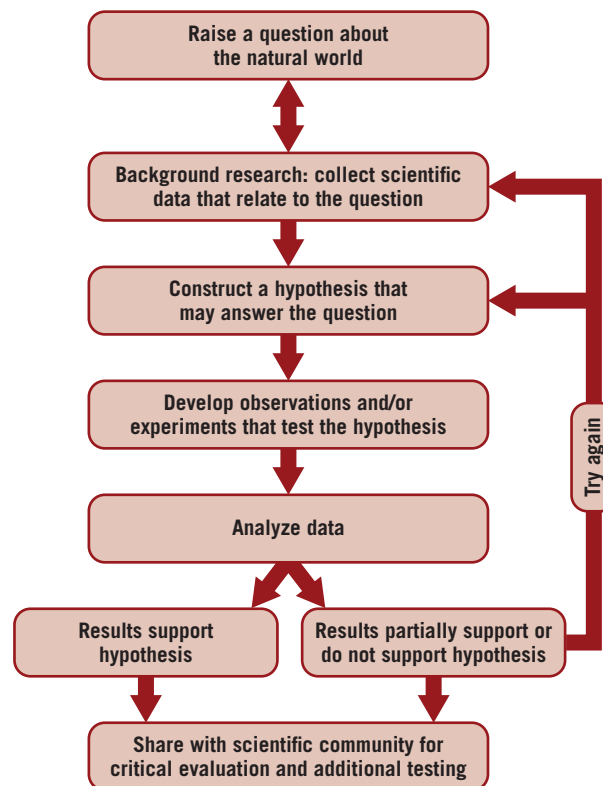
There is no fixed path that scientists always follow that leads unerringly to scientific knowledge. However, many scientific investigations involve the steps outlined in **Figure 1.9**. In addition, some scientific discoveries result from purely theoretical ideas that stand up to extensive examination.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

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

## Plate Tectonics and Scientific Inquiry

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

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



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

together the basic processes known to operate on Earth. The theory that finally emerged, called the *theory of plate tectonics*, provided geologists with the first comprehensive model of Earth’s internal workings.

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

## 1.3 Concept Checks

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

## 1.4 Earth as a System

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

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

## Earth's Spheres

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

As we look closely at our planet from space, it becomes apparent that Earth is much more than rock

and soil. In fact, among the most conspicuous features in both views of Earth in **Figure 1.10** are swirling clouds suspended above the surface of the vast global ocean. These features emphasize the importance of water on our planet.

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

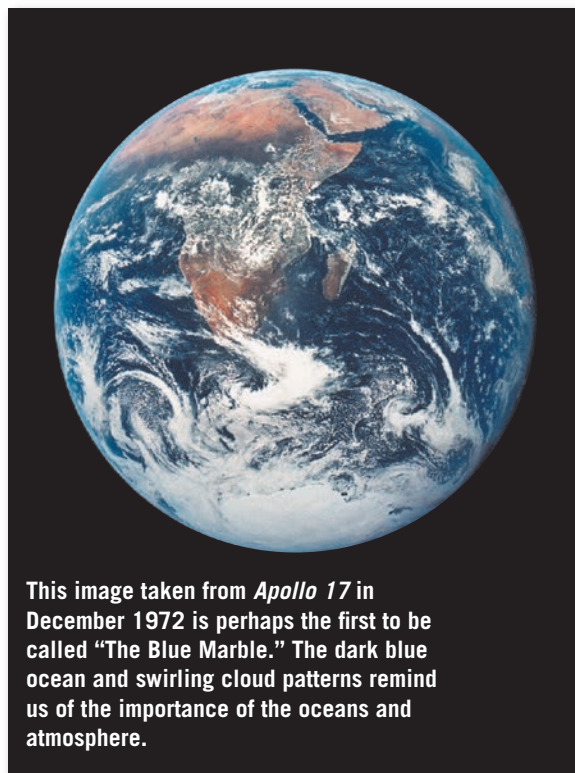
The interactions among Earth's spheres are incalculable. **Figure 1.11** provides us with one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air. In this scene, ocean waves created by the drag of air moving across the water are breaking against the rocky shore.

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

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

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

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



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

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

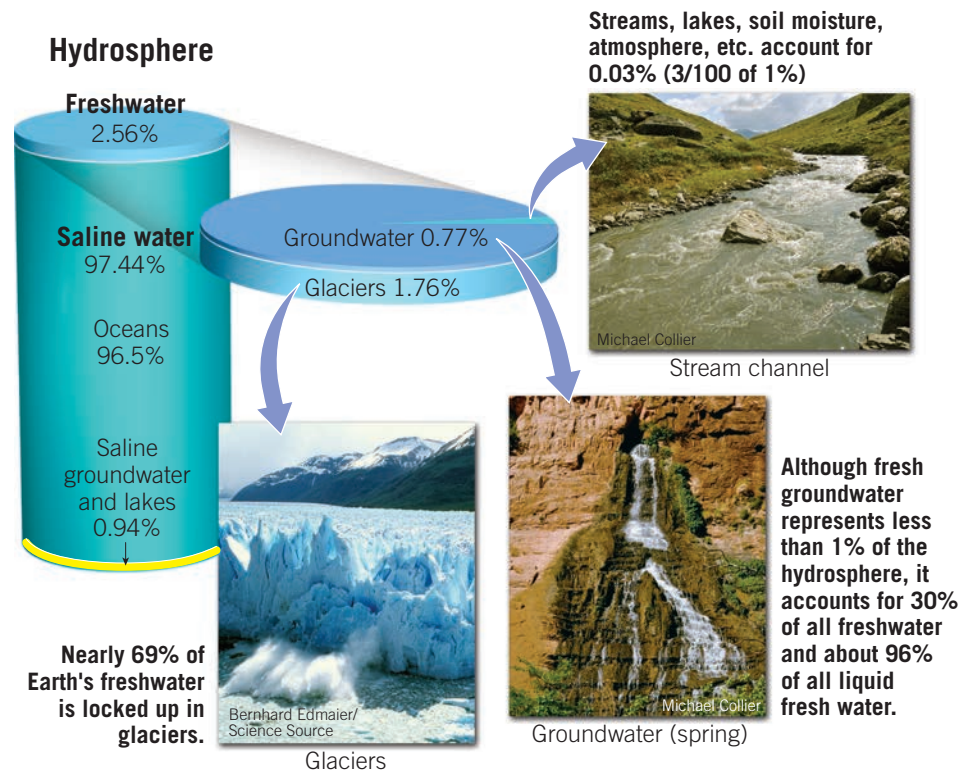
**Biosphere** The **biosphere** includes all life on Earth (Figure 1.14). Ocean life is concentrated in the sunlit surface waters of the sea. Most life on land is also concentrated near the surface, with tree roots and burrowing animals tunneling a few meters underground and flying insects and birds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



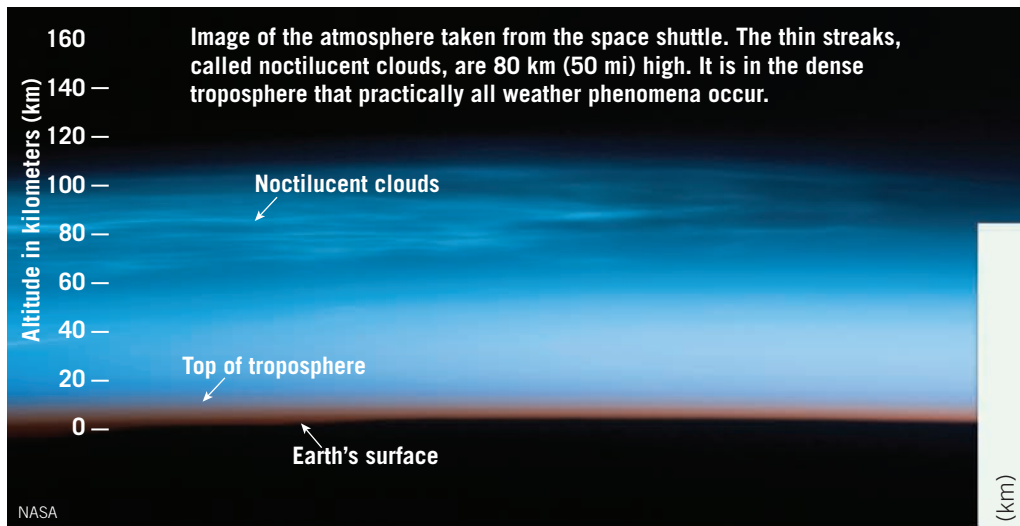
**Figure 1.11**  
**Interactions among Earth's spheres** The shoreline is one obvious interface—a common boundary where different parts of a system interact. In this scene at California's Montano del Oro State Park, ocean waves (hydrosphere) that were created by the force of moving air (atmosphere) break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

life still must be thought of as being confined to a narrow band very near Earth's surface.

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



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



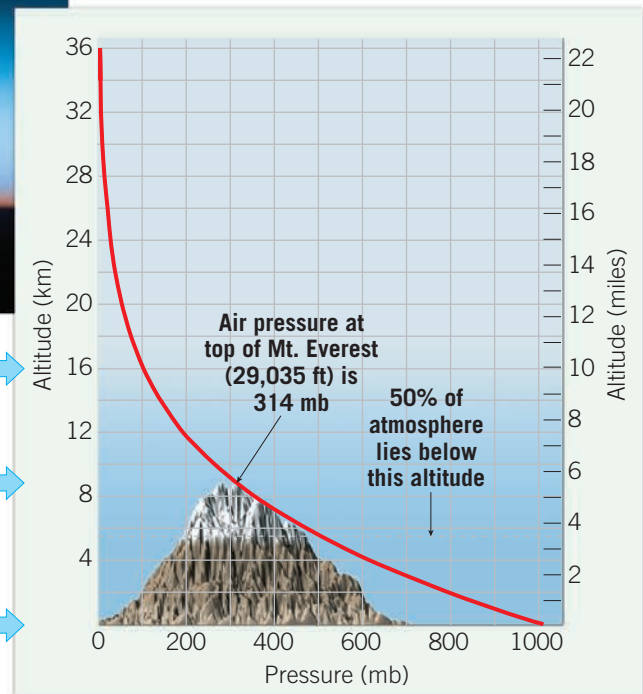
**Figure 1.13**

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

90% of the atmosphere is below 16 km (10 mi)

The air pressure atop Mt. Everest is about one-third that at sea level.

Average sea-level pressure is slightly more than 1000 millibars (about 14.7 lb./sq. in)



The ocean contains a significant portion of Earth's biosphere. Modern coral reefs are unique and complex examples and are home to about 25% of all marine species. Because of this diversity, they are sometimes referred to as the ocean equivalent of a rain forest.



Tropical rain forests are characterized by hundreds of different species per square kilometer.

**Figure 1.14**

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

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

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



## EYE ON EARTH 1.2

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

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

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



(Photo by interlight/Shutterstock)

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

### Earth System Science

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

Scientists have recognized that in order to more fully understand our planet, they must learn how its individual components (land, water, air, and life-forms) are interconnected. This endeavor, called **Earth system science**, aims to study Earth as a *system* composed of numerous interacting parts, or *subsystems*. Rather than look through the limited lens of only one of the traditional sciences—geology, atmospheric science, chemistry, biology, and so on—Earth system science attempts to integrate the knowledge of several

academic fields. Using an interdisciplinary approach, those engaged in Earth system science attempt to achieve the level of understanding necessary to comprehend and solve many of our global environmental problems.

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

### The Earth System

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



**Figure 1.15**

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

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



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

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

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

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

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

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

internal processes that produce volcanoes, earthquakes, and mountains.

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

## 1.4 Concept Checks

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

## 1.5 Origin and Early Evolution of Earth

Outline the stages in the formation of our solar system.

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

### Origin of Our Solar System

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

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

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

fusion in stars converts hydrogen and helium into the other elements found in the universe.)

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

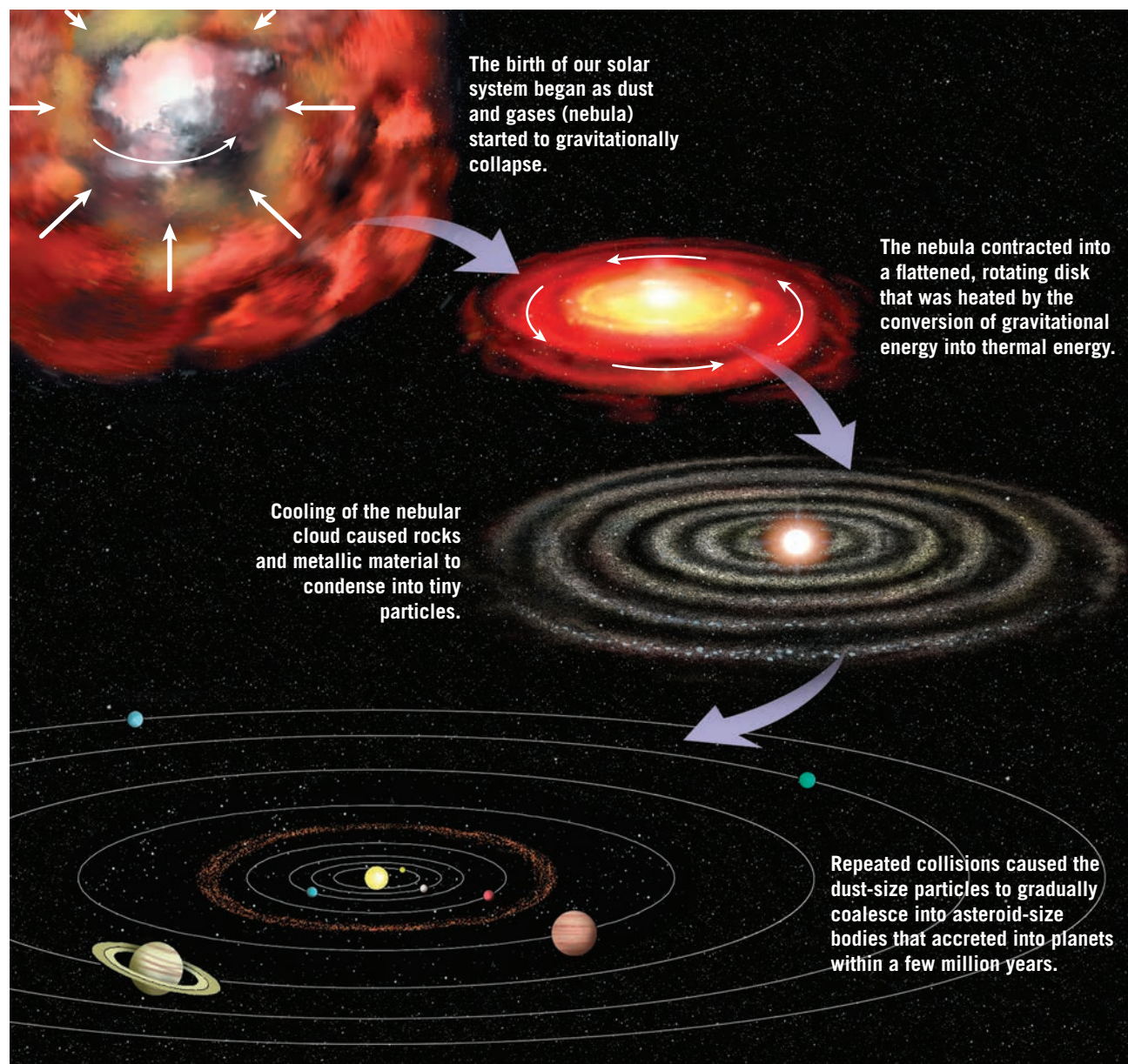
During the collapse, gravitational energy was converted to thermal (heat) energy, causing the temperature of the inner portion of the nebula to dramatically rise. At these high temperatures, the dust grains broke up into molecules and extremely energetic atomic particles. However, at distances beyond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

**SmartFigure 1.17**

**Nebular theory** The nebular theory explains the formation of the solar system. (<https://goo.gl/dRZJBp>)



Tutorial



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

the planetesimals. Those rocky and metallic pieces that remained in orbit are called *meteorites* when they survive an impact with Earth.

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

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

# Solar System: Size and Scale

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



**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**

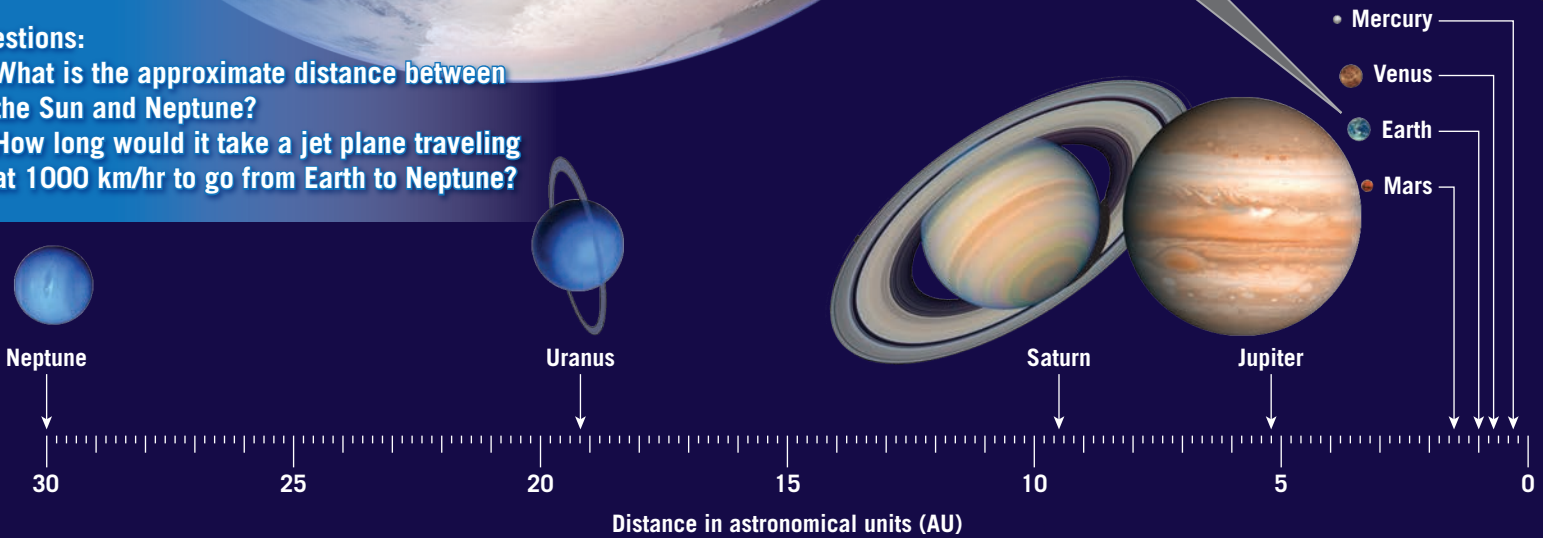
- The average distance between Earth and Sun is 150 million km (93 million mi). This distance is referred to as 1 astronomical unit (AU).
- A jet plane traveling from Earth at 1000 km/hr would require about 17 years to reach the Sun!

Earth  Sun 



**Questions:**

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



**Figure 1.18**

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



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

## Formation of Earth's Layered Structure

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

**Chemical Differentiation and Earth's Layers** The early period of heating resulted in another process of chemical differentiation, whereby melting formed

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

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

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

## 1.5 Concept Checks

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

## 1.6 Earth's Internal Structure

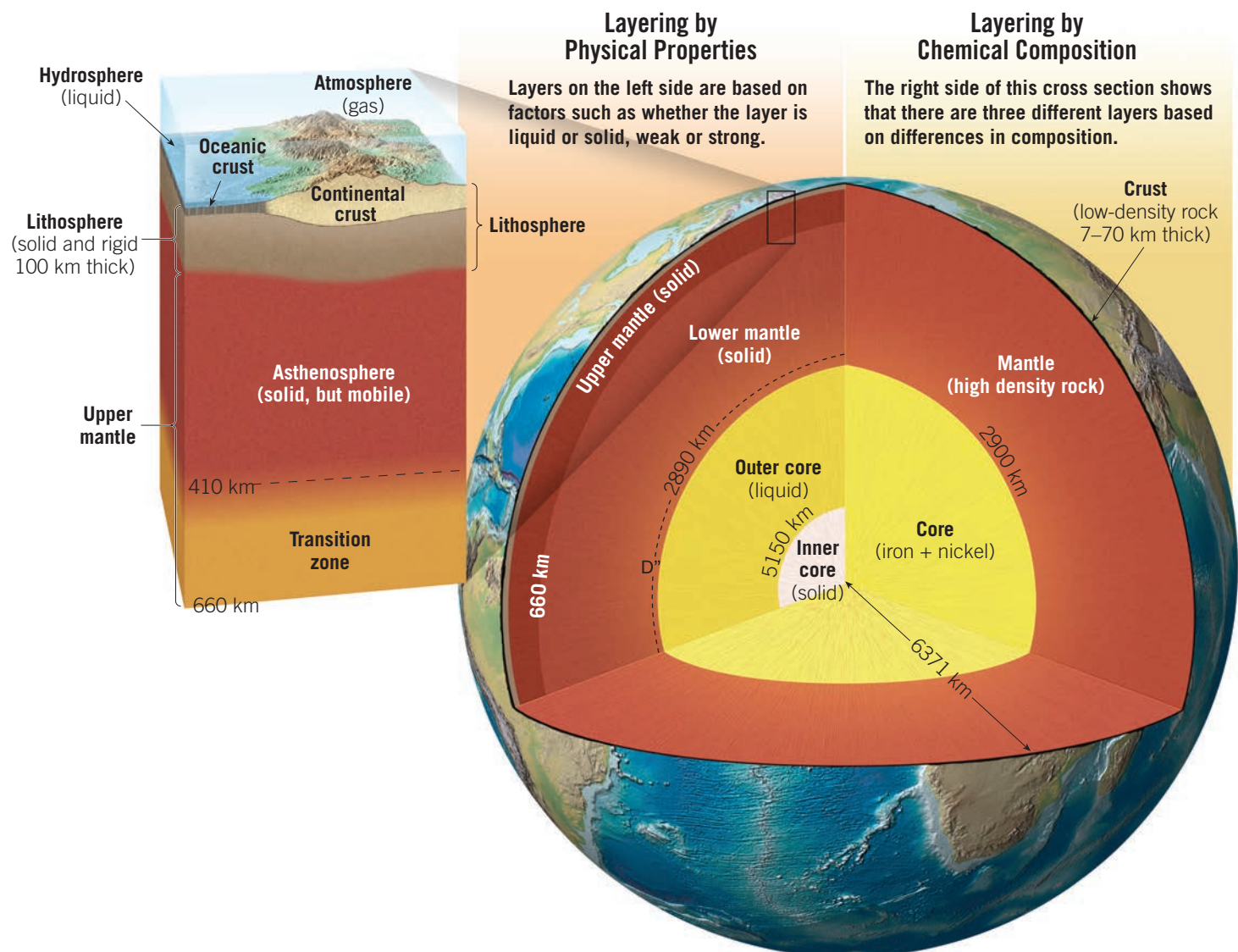
Sketch Earth's internal structure and label and describe the main subdivisions.

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

How did we learn about the composition and structure of Earth's interior? The nature of Earth's interior is primarily determined by analyzing seismic waves from earthquakes. As these waves of energy penetrate the planet, they change speed and are bent and reflected as

they move through zones that have different properties. Monitoring stations around the world detect and record this energy. With the aid of computers, these data are analyzed and used to build a detailed picture of Earth's interior. There is more about this in Chapter 12.

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



## Earth's Crust

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

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

## Earth's Mantle

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

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

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

It is important to emphasize here that the strength of various Earth materials is a function of both their

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

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

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

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

## Earth's Core

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

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

### 1.6 Concept Checks

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

## 1.7 Rocks and the Rock Cycle

Sketch, label, and explain the rock cycle.

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

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

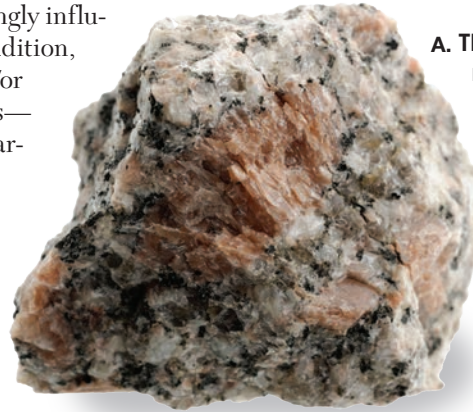
Geologists divide rocks into three major groups: igneous, sedimentary, and metamorphic. Figure 1.21 provides some examples. As you will learn, each group is linked to the others by the processes that act upon and within the planet.

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

### The Basic Cycle

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

If igneous rocks are exposed at the surface, they undergo *weathering*, in which the day-in and day-out influences of the atmosphere, hydrosphere, and



**A. The large crystals of light-colored minerals in granite result from the slow cooling of molten rock deep beneath the surface. Granite is abundant in the continental crust.**



**B. Basalt is rich in dark minerals. Rapid cooling of molten rock at Earth's surface is responsible for the rock's microscopically small crystals. Oceanic crust is composed mainly of basalt.**

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

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

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

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

**Figure 1.21**

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



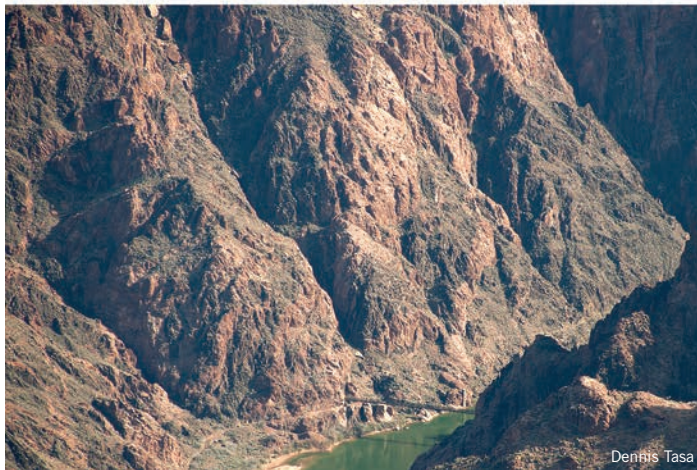
Michael Collier

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

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



Dennis Tasa



Dennis Tasa

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

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

## Alternative Paths

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

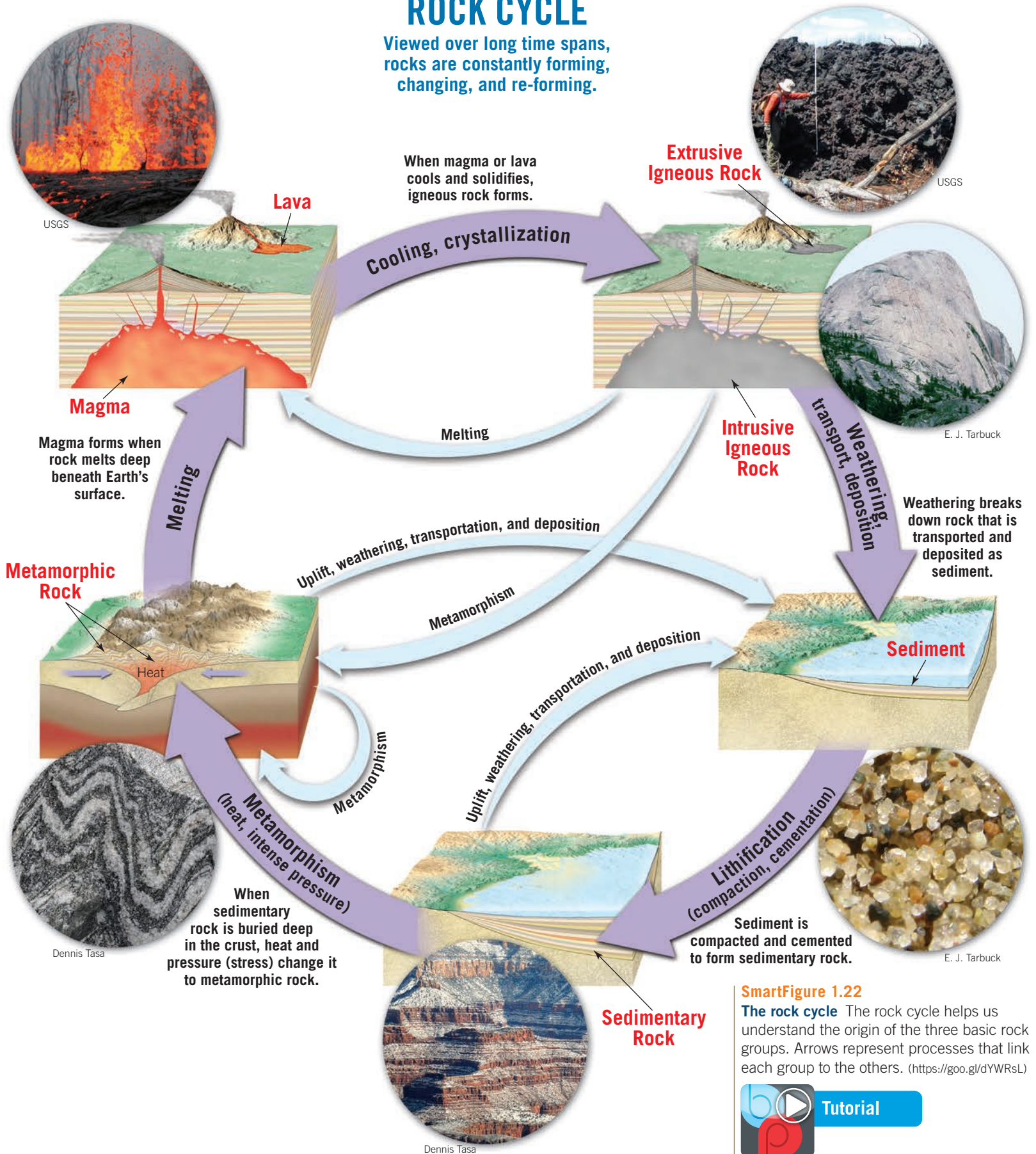
Rather than being exposed to weathering and erosion at Earth's surface, igneous rocks may remain deeply buried. Eventually these masses may be subjected to the strong compressional forces and high temperatures associated with mountain building. When this occurs, they are transformed directly into metamorphic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

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

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

# ROCK CYCLE

Viewed over long time spans, rocks are constantly forming, changing, and re-forming.



**SmartFigure 1.22**  
**The rock cycle** The rock cycle helps us understand the origin of the three basic rock groups. Arrows represent processes that link each group to the others. (<https://goo.gl/dYWRsL>)



however, take time—vast amounts of time. We can observe different parts of the cycle operating all over the world. Today new magma is forming beneath the island of Hawaii. When it erupts at the surface, the lava flows add to the size of the island. Meanwhile, the Colorado Rockies are gradually being worn down by weathering and erosion. Some of this weathered debris will eventually be carried to the Gulf of Mexico, where it will add to the already substantial mass of sediment that has accumulated there.

## 1.8 The Face of Earth

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

The two principal divisions of Earth's surface are the **ocean basins** and the **continents** (Figure 1.23). A significant difference between these two areas is their relative levels. The elevation difference between the ocean basins and the continents is primarily due to differences in their respective densities and thicknesses:

- **Ocean basins.** The average depth of the ocean floor is about 3.8 kilometers (2.4 miles) below sea level, or about 4.5 kilometers (2.8 miles) lower than the average elevation of the continents. The basaltic rocks that comprise the oceanic crust average only 7 kilometers (about 4.5 miles) thick and have an average density of about 3.0 g/cm<sup>3</sup>.
- **Continents.** The continents are remarkably flat features that have the appearance of plateaus protruding above sea level. With an average elevation of about 0.8 kilometer (0.5 mile), continental blocks lie close to sea level, except for limited areas of mountainous terrain. Recall that the continents average about 35 kilometers (22 miles) thick and are composed of granitic rocks that have a density of about 2.7 g/cm<sup>3</sup>.

The thicker, less dense continental crust is more buoyant than the oceanic crust. As a result, continental crust floats on top of the deformable rocks of the mantle at a higher level than oceanic crust for the same reason that a large, empty (less dense) cargo ship rides higher than a small, loaded (denser) one.

### Major Features of the Ocean Floor

If all water were drained from the ocean basins, a great variety of features would be seen, including chains of volcanoes, deep canyons, plateaus, and large expanses of monotonously flat plains. In fact, the scenery would be nearly as diverse as that on the continents (see Figure 1.23). These features and the processes that form them are covered in detail in Chapter 13.

During the past 65 years, oceanographers have used modern depth-sounding equipment and satellite technology to map significant portions of the ocean floor. These

## 1.7 Concept Checks

1. List two rock characteristics that are used to determine the processes that created a rock.
2. Sketch and label a basic rock cycle. Make sure to include alternate paths.

studies have led them to identify three major regions: *continental margins*, *deep-ocean basins*, and *oceanic (mid-ocean) ridges*.

**Continental Margins** The **continental margin** is the portion of the seafloor adjacent to major landmasses. It may include the *continental shelf*, the *continental slope*, and the *continental rise*.

Although land and sea meet at the shoreline, this is *not* the boundary between the continents and the ocean basins. Rather, along most coasts, a gently sloping platform of material, called the **continental shelf**, extends seaward from the shore. Because it is underlain by continental crust, it is clearly a flooded extension of the continents. A glance at Figure 1.23 shows that the width of the continental shelf varies. For example, it is broad along the east and Gulf coasts of the United States but relatively narrow along the Pacific margin of the continent.

The boundary between the continents and the deep-ocean basins lies along the **continental slope**, a relatively steep dropoff that extends from the outer edge of the continental shelf to the floor of the deep ocean (see Figure 1.23). Using this as the dividing line, we find that about 60 percent of Earth's surface is represented by ocean basins and the remaining 40 percent by continents.

In regions where trenches do not exist, the steep continental slope merges into a more gradual incline known as the **continental rise**, a thick wedge of sediment that moved downslope from the continental shelf and accumulated on the deep-ocean floor.

**Deep-Ocean Basins** Situated between the continental margins and oceanic ridges are **deep-ocean basins**. Parts of these regions consist of incredibly flat features



## EYE ON EARTH 1.3

This is a shoreline scene along the east coast of the United States. The Atlantic Ocean is on the right.

**QUESTION 1** Does the shoreline, the line where the water meets the land, mark the outer edge of the North American continent?

**QUESTION 2** Explain your answer to Question 1.



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called **abyssal plains**. The ocean floor also contains extremely deep depressions, some more than 11,000 meters (36,000 feet) deep. Although these **deep-ocean trenches** are relatively narrow and represent only a small fraction of the ocean floor, they are nevertheless very significant features. Some trenches are located adjacent to young mountains that flank the continents. For example, in Figure 1.23 the Peru–Chile trench off the west coast of South America parallels the Andes Mountains. Other trenches parallel island chains called *volcanic island arcs*.

Dotting the ocean floor are submerged volcanic structures called **seamounts**, which sometimes form long, narrow chains. Volcanic activity has also produced several large *lava plateaus*, such as the Ontong Java Plateau located northeast of New Guinea. In addition, some submerged plateaus are composed of continental-type crust. Examples include the Campbell Plateau southeast of New Zealand and the Seychelles Bank northeast of Madagascar.

**Oceanic Ridges** The most prominent feature on the ocean floor is the **oceanic ridge**, or **mid-ocean ridge**. As shown in Figure 1.23, the Mid-Atlantic Ridge and the East Pacific Rise are parts of this system. This broad elevated feature forms a continuous belt winding more than 70,000 kilometers (43,500 miles) around the globe, in a manner similar to the seam of a baseball. Unlike most continental mountains that consist of highly deformed rock, the oceanic ridge system consists of layer upon layer of igneous rock that has been fractured and uplifted.

## Major Features of the Continents

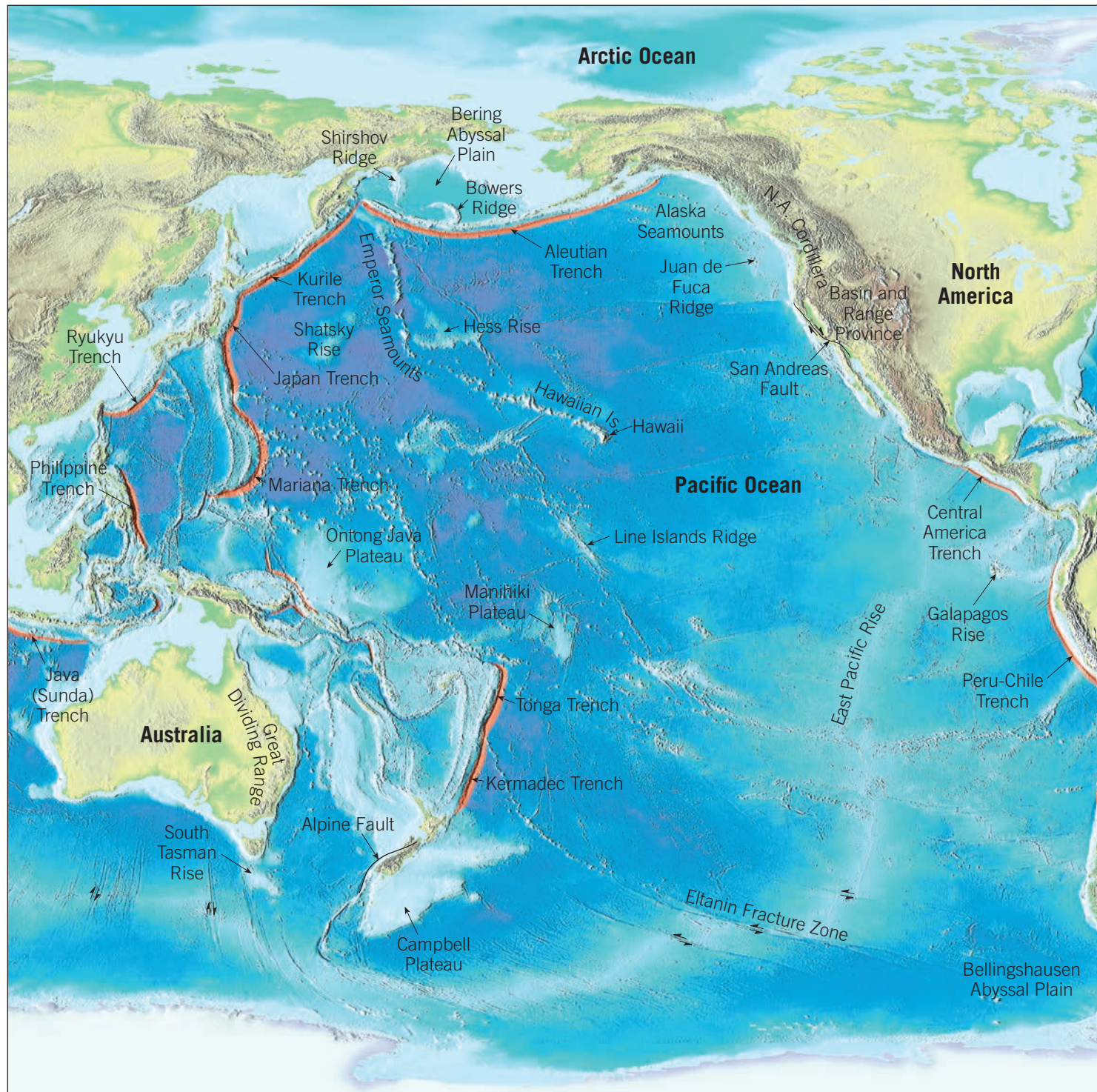
The major features of the continents can be grouped into two distinct categories: uplifted regions of

deformed rocks that make up present-day mountain belts and extensive flat, stable areas that have been eroded nearly to sea level. Notice in Figure 1.24 that the young mountain belts tend to be long, narrow features at the margins of continents and that the flat, stable areas are typically located in the interiors of the continents. Mountain building is discussed in more detail in Chapter 14.

**Mountain Belts** The most prominent continental features are mountains. Although their distribution appears to be random, this is not the case. The youngest mountains (those less than 100 million years old) are located principally in two major zones. The circum-Pacific belt (the region surrounding the Pacific Ocean) includes the mountains of the western Americas and continues into the western Pacific in the form of volcanic island arcs (see Figure 1.23). Island arcs are active mountainous regions composed largely of volcanic rocks and deformed sedimentary rocks. Examples include the Aleutian Islands, Japan, the Philippines, and New Guinea.

The other major **mountain belt** extends eastward from the Alps through Iran and the Himalayas and then dips southward into Indonesia. Careful examination of mountainous terrains reveals that most are places where thick sequences of rocks have been squeezed and highly deformed, as if placed in a gigantic vise. Older mountains are also found on the continents. Examples include the Appalachians in the eastern United States and the Urals in Russia. Their once lofty peaks are now worn low, the result of millions of years of weathering and erosion.

**The Stable Interior** Unlike the young mountain belts that have formed within the past 100 million years, the interiors of the continents, called **cratons**, have been relatively stable (undisturbed) for the past 600 million years or even longer.

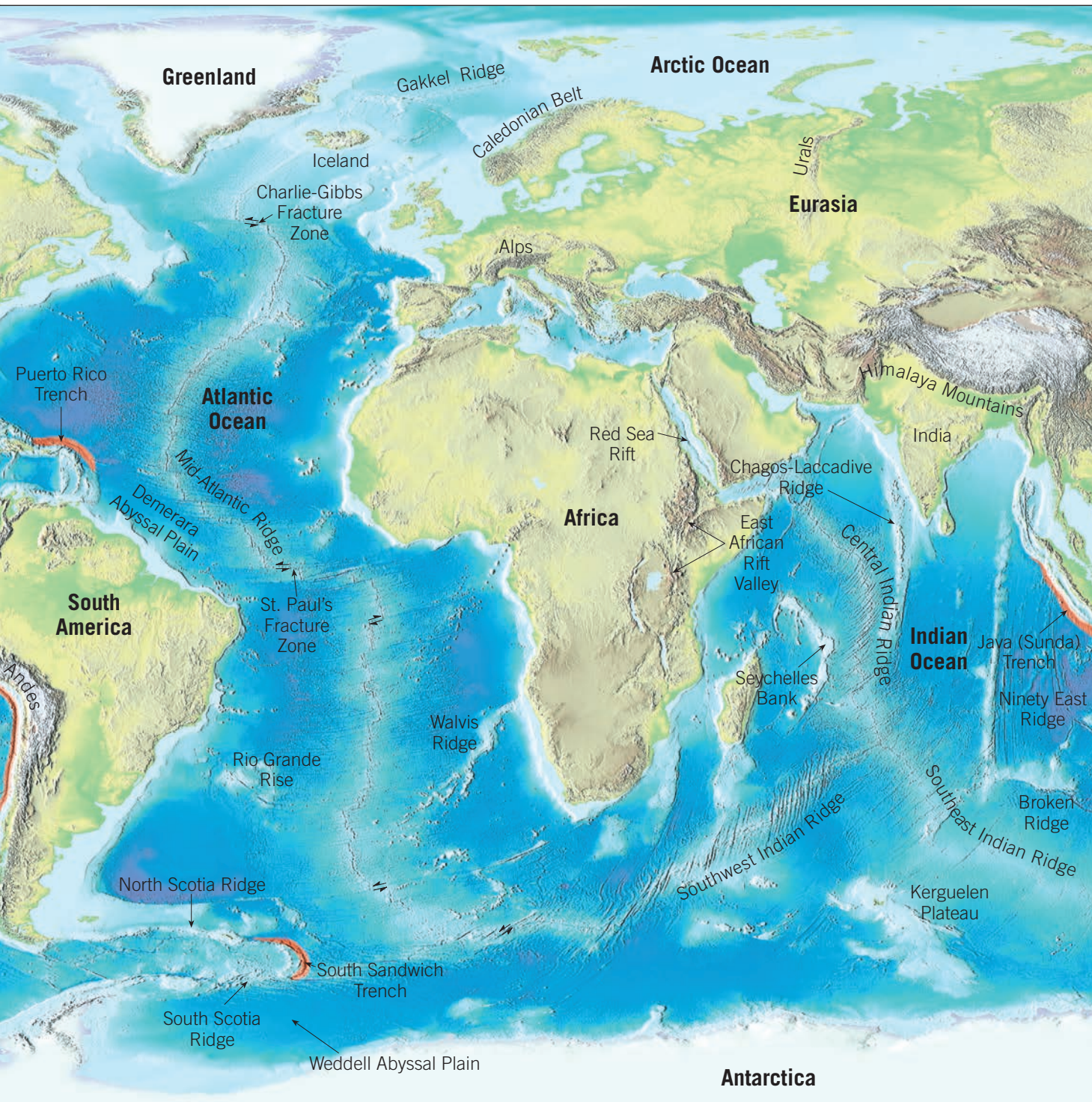


**Figure 1.23**  
**The face of Earth** Major surface features of the geosphere.

Typically these regions were involved in mountain-building episodes much earlier in Earth's history.

Within the stable interiors are areas known as **shields**—expansive, flat regions composed largely of deformed igneous and metamorphic rocks. Notice in Figure 1.24 that the Canadian Shield is exposed in much of the

northeastern part of North America. Radiometric dating of shields indicates that they are truly ancient regions. All contain Precambrian-age rocks more than 1 billion years old, with some samples approaching 4 billion years in age. Even these oldest-known rocks exhibit evidence of enormous forces that have folded, faulted, and metamorphosed them.



Thus, we conclude that these rocks were once part of an ancient mountain system that has since been eroded away to produce these expansive, flat regions.

Other flat areas of the craton exist, where highly deformed rocks, like those found in the shields, are covered by a relatively thin veneer of sedimentary rocks.

These areas are called **stable platforms**. The sedimentary rocks in stable platforms are nearly horizontal, except where they have been warped to form large basins or domes. In North America a major portion of the stable platform is located between the Canadian Shield and the Rocky Mountains.

The Canadian Shield is an expansive region of ancient Precambrian rocks, some more than 4 billion years old. It was recently scoured by Ice Age glaciers.



Superstock

The Appalachians are old mountains. Mountain building began about 480 million years ago and continued for more than 200 million years. Erosion has lowered these once lofty peaks.

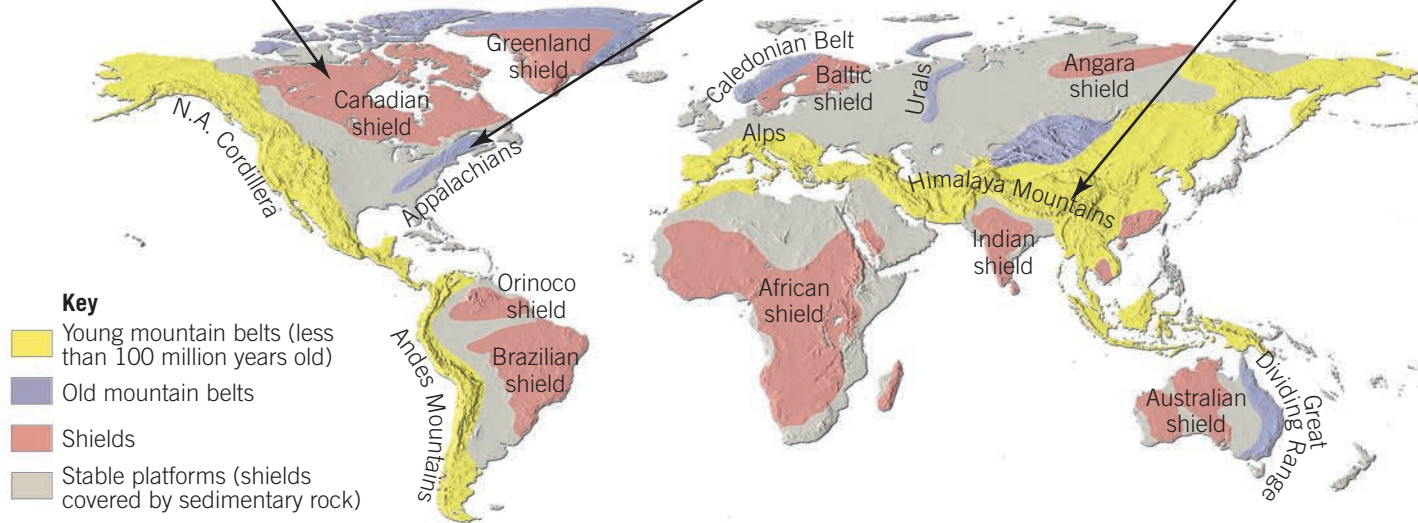


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The rugged Himalayas are the highest mountains on Earth and are geologically young. They began forming about 50 million years ago and uplift continues today.



Alamy Images



### SmartFigure 1.24

**The continents** Distribution of mountain belts, stable platforms, and shields. (<https://goo.gl/z2Sbxd>)



**Tutorial**

Being familiar with the topographic features that comprise the face of Earth is essential to understanding the mechanisms that have shaped our planet. What is the significance of the enormous ridge system that extends through all the world's oceans? What is the connection, if any, between young, active mountain belts and oceanic trenches? What forces crumple rocks to produce majestic mountain ranges? These are a few of the questions that will be addressed beginning in the next chapter, as we investigate the dynamic processes that shaped our planet in the geologic past and will continue to shape it in the future.

## 1.8 Concept Checks

1. Compare and contrast ocean basins and continents.
2. Name the three major regions of the ocean floor. What are some features associated with each?
3. Describe the general distribution of Earth's youngest mountains.
4. What is the difference between shields and stable platforms?

# 1

## Concepts in Review An Introduction to Geology

### 1.1 Geology: The Science of Earth

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

**KEY TERMS** geology, physical geology, historical geology

- Geologists study Earth. Physical geologists focus on the processes by which Earth operates and the materials that result from those processes. Historical geologists apply an understanding of Earth materials and processes to reconstruct the history of our planet.

- People have a relationship with planet Earth that can be positive and negative. Earth processes and products sustain us every day, but they can also harm us. Similarly, people have the ability to alter or harm natural systems, including those that sustain civilization.

- **Q** Consider the question of when a given volcano is likely to erupt, and also the question of whether volcanic eruptions played a part in the extinction of the dinosaurs. Which is an issue that a physical geologist would address? Which question would a historical geologist focus on?

### 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.

**KEY TERMS** catastrophism, uniformitarianism

- Early ideas about the nature of Earth were based on religious traditions and notions of great catastrophes. In 1795, James Hutton emphasized that the same slow processes have acted over great spans of time and are

responsible for Earth's rocks, mountains, and landforms. This similarity of process over vast spans of time led to this principle being dubbed "uniformitarianism."

- Based on the rate of radioactive decay of certain elements, the age of Earth has been calculated to be about 4,600,000,000 (4.6 billion) years. That is an incredibly vast amount of time.

- **Q** In what eon, era, period, and epoch do we live?

### 1.3 The Nature of Scientific Inquiry

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

**KEY TERMS** hypothesis, theory, scientific method

- Geologists make observations, construct tentative explanations for those observations (hypotheses), and then test those hypotheses with field in-

vestigations and laboratory work. In science, a theory is a well-tested and widely accepted view that the scientific community agrees best explains certain observable facts.

- As flawed hypotheses are discarded, scientific knowledge moves closer to a correct understanding, but we can never be fully confident that we know all the answers. Scientists must always be open to new information that forces changes in our model of the world.

### 1.4 Earth as a System

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

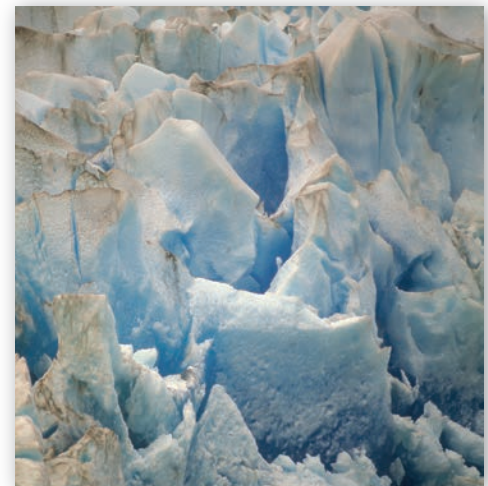
**KEY TERMS** hydrosphere, atmosphere, biosphere, geosphere, Earth system science, system

- Earth's physical environment is traditionally divided into three major parts: the solid Earth, called the geosphere; the water portion of our planet, called the hydrosphere; and Earth's gaseous envelope, called the atmosphere.
- A fourth Earth sphere is the biosphere, the totality of life on Earth. It is concentrated in a relatively narrow zone that extends a few kilometers into the hydrosphere and geosphere and a few kilometers up into the atmosphere.
- Of all the water on Earth, more than 96 percent is in the oceans, which cover nearly 71 percent of the planet's surface.
- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole that is called the Earth system.

- Earth system science uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our planet and its global environmental problems.

- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmosphere, hydrosphere, and at Earth's surface, and (2) heat from Earth's interior that powers the internal processes that produce volcanoes, earthquakes, and mountains.

- **Q** Is glacial ice part of the geosphere, or does it belong to the hydrosphere? Explain your answer.



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## 1.5 Origin and Early Evolution of Earth

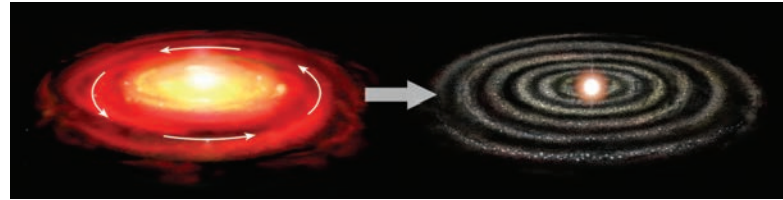
Outline the stages in the formation of our solar system.

**KEY TERMS** nebular theory, solar nebula

- The nebular theory describes the formation of the solar system. The planets and Sun began forming about 4.6 billion years ago from a large cloud of dust and gases.
- As the cloud contracted, it began to rotate and assume a disk shape. Material that was gravitationally pulled toward the center became the protosun. Within the rotating disk, small centers, called planetesimals, swept up more and more of the cloud's debris.
- Because of their high temperatures and weak gravitational fields, the inner planets were unable to accumulate and retain many of the lighter

components. Because of the very cold temperatures existing far from the Sun, the large outer planets consist of huge amounts of lighter materials. These gaseous substances account for the comparatively large sizes and low densities of the outer planets.

- Q** Earth is about 4.6 billion years old. If all of the planets in our solar system formed at about the same time, how old would you expect Mars to be? Jupiter? The Sun?

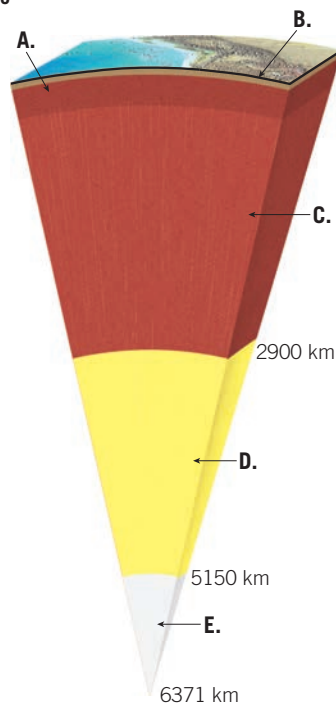


## 1.6 Earth's Internal Structure

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

**KEY TERMS** crust, mantle, lithosphere, asthenosphere, transition zone, lower mantle, core, outer core, inner core

- Compositionally, the solid Earth has three layers: core, mantle, and crust. The core is most dense, and the crust is least dense.
- Earth's interior can also be divided into layers based on physical properties. The crust and upper mantle make a two-part layer called the lithosphere, which is broken into the plates of plate tectonics. Beneath that is the "weak" asthenosphere. The lower mantle is stronger than the asthenosphere and overlies the molten outer core. This liquid is made of the same iron-nickel alloy as the inner core, but the extremely high pressure of Earth's center compacts the inner core into a solid form.



- Q** The diagram represents Earth's layered structure. Does it show layering based on physical properties or layering based on composition? Identify the lettered layers.

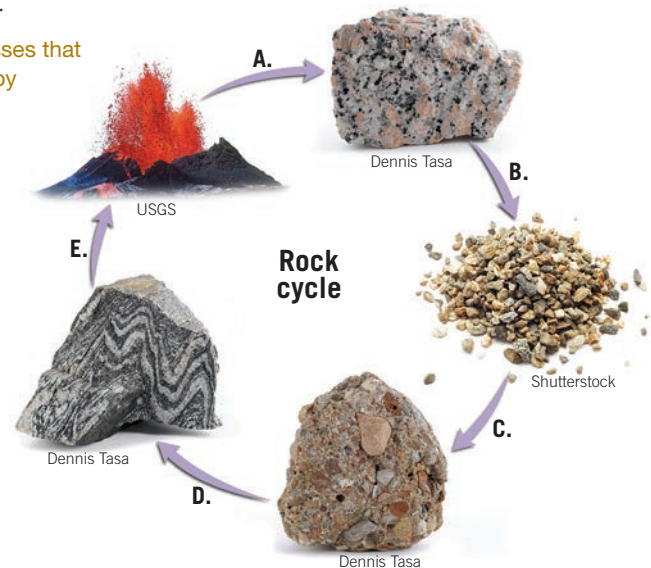
## 1.7 Rocks and the Rock Cycle

Sketch, label, and explain the rock cycle.

**KEY TERMS** rock cycle, igneous rock, sediment, sedimentary rock, metamorphic rock

- The rock cycle is a good model for thinking about the transformation of one rock to another due to Earth processes. All igneous rocks are made from molten rock. All sedimentary rocks are made from weathered products of other rocks. All metamorphic rocks are the products of pre-existing rocks that are transformed at high temperatures or pressures. Given the right conditions, any kind of rock can be transformed into any other kind of rock.

- Q** Name the processes that are represented by each of the letters in this simplified rock cycle diagram.



## 1.8 The Face of Earth

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

**KEY TERMS** ocean basin, continent, continental margin, continental shelf, continental slope, continental rise, deep-ocean basin, abyssal plain, deep-ocean trench, seamount, oceanic ridge (mid-ocean ridge), mountain belt, craton, shield, stable platform

- Two principal divisions of Earth's surface are the ocean basins and the continents. A significant difference is their relative levels. The elevation differences between ocean basins and continents is primarily due to differences in their respective densities and thicknesses.

- There are shallow portions of the oceans that are essentially flooded margins of the continents, and there are deeper portions that include vast abyssal plains and deep-ocean trenches. Seamounts and lava plateaus interrupt the abyssal plain in some places.
- Continents consist of relatively flat, stable areas called cratons. Where a craton is blanketed by a relatively thin layer of sediment or sedimentary rock, it is called a stable platform. Where a craton is exposed at the surface, it is known as a shield. Wrapping around the edges of some cratons are mountain belts, linear zones of intense deformation and metamorphism.

- Q** Put these features of the ocean floor in order from shallowest to deepest: continental slope, deep-ocean trench, continental shelf, abyssal plain, continental rise.

## Give It Some Thought

- Most large-scale geological processes occur over a very long time relative to human life. For instance, mountains are built over several million years. However, they form only a small percentage of geologic time. Calculate the percentage of geologic time that is represented by mountains that took 10 million years to form.
- Refer to the graph in Figure 1.13 to answer the following questions.
  - If you were to climb to the top of Mount Everest, how many breaths of air would you have to take at that altitude to equal one breath at sea level?
  - If you are flying in a commercial jet at an altitude of 12 kilometers (about 39,000 feet), about what percentage of the atmosphere's mass is below you?
- Making accurate measurements and observations is a basic part of scientific inquiry. Identify two images in this chapter that illustrate ways in which scientific data are gathered. Suggest an advantage that might be associated with the examples you select.
- The accompanying photo provides an example of interactions among different parts of the Earth system. It is a view of a mudflow that was triggered by extraordinary rains. Which of Earth's four spheres were involved in this natural disaster that buried a small town on the Philippine island of Leyte? Describe how each contributed to or was influenced by the event.

AP Photo/PatRoque



- Explain why sedimentary rocks are the most abundant on Earth's surface. What processes are involved in the formation and preservation of sedimentary rocks?
- This photo shows the picturesque coastal bluffs and rocky shoreline along a portion of the California coast south of San Simeon State Park. This area, like other shorelines, is described as an *interface*. What does this mean? Describe another interface in the Earth system.



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- You find a pebble of basalt, an igneous rock, in a sedimentary rock. Develop a proper scientific hypothesis to understand and explain how it could be present there. What approaches could you take?

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# 2

## Plate Tectonics: A Scientific Revolution Unfolds

Hikers crossing a crevasse in Khumbu glacier, Mount Everest, Nepal. (Photo by Christian Kober/Robert Harding)





**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:

- 2.1** Summarize the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.
- 2.2** List and explain the evidence Wegener presented to support his continental drift hypothesis.
- 2.3** Summarize the two main objections to the continental drift hypothesis.
- 2.4** List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.
- 2.5** Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.
- 2.6** Compare and contrast the three types of convergent plate boundaries and name a location where each type can be found.
- 2.7** Describe the relative motion along a transform fault boundary and be able to locate several examples on a plate boundary map.
- 2.8** Explain why plates such as the African and Antarctic plates are increasing in size, while the Pacific plate is decreasing in size.
- 2.9** List and explain the evidence used to support the plate tectonics theory.
- 2.10** Describe two methods researchers use to measure relative plate motion.
- 2.11** Describe plate–mantle convection and explain two of the primary driving forces of plate motion.

**P**late tectonics is the first theory to provide a comprehensive view of the processes that produced Earth's major surface features, including the continents and ocean basins. Within the framework of this theory, geologists have found explanations for the basic causes and distribution of earthquakes, volcanoes, and mountain belts. Further, we are now better able to explain the distribution of plants and animals in the geologic past, as well as the distribution of economically significant mineral deposits.

## 2.1 From Continental Drift to Plate Tectonics

Summarize the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.

Prior to the late 1960s most geologists held the view that the ocean basins and continents had fixed geographic positions and were of great antiquity. Scientists came to realize that Earth's continents are not static; instead, they gradually migrate across the globe. These movements cause blocks of continental material to collide, deforming the intervening crust and thereby creating Earth's great mountain chains (Figure 2.1). Furthermore, landmasses occasionally split apart. As continental blocks separate, a new ocean basin emerges between them. Meanwhile, other portions of the sea-floor plunge into the mantle. In short, a dramatically different model of Earth's tectonic processes emerged. Tectonic processes deform Earth's crust to create major structural features, such as mountains, continents, and ocean basins.

### Figure 2.1

The Himalayan mountains where created when the subcontinent of India collided with southeastern Asia. (Photo by Hartmut Postges/Robert Harding)

This profound reversal in scientific thought has been appropriately called a *scientific revolution*. The revolution began early in the twentieth century as a relatively

straightforward proposal termed *continental drift*. For more than 50 years, the scientific community categorically rejected the idea that continents are capable of



movement. North American geologists in particular had difficulty accepting continental drift, perhaps because much of the supporting evidence had been gathered from Africa, South America, and Australia, continents with which most North American geologists were unfamiliar.

After World War II, modern instruments replaced rock hammers as the tools of choice for many researchers. Armed with more advanced tools, geologists and a new breed of researchers, including *geophysicists* and *geochemists*, made several surprising discoveries that rekindled interest in the drift hypothesis. By 1968 these developments had led to the unfolding of a far more encompassing explanation known as the *theory of plate tectonics*.

In this chapter, we will examine the events that led to this dramatic reversal of scientific opinion. We will also briefly trace the development of the *continental drift hypothesis*, examine why it was initially rejected, and consider the evidence that finally led to the acceptance of its direct descendant—the theory of plate tectonics.

## 2.1 Concept Checks

1. Briefly describe the view held by most geologists regarding the ocean basins and continents prior to the 1960s.
2. What group of geologists were the least receptive to the continental drift hypothesis? Why?

## 2.2 Continental Drift: An Idea Before Its Time

List and explain the evidence Wegener presented to support his continental drift hypothesis.

The idea that continents, particularly South America and Africa, fit together like pieces of a jigsaw puzzle came about during the 1600s, as better world maps became available. However, little significance was given to this notion until 1915, when Alfred Wegener (1880–1930), a German meteorologist and geophysicist, wrote *The Origin of Continents and Oceans*. This book outlined Wegener's hypothesis called **continental drift**, which dared to challenge the long-held assumption that the continents and ocean basins had fixed geographic positions.

Wegener suggested that a single **supercontinent** consisting of all Earth's landmasses once existed.\* He named this giant landmass **Pangaea** (pronounced “Pan-jee-ah,” meaning “all lands”) (Figure 2.2). Wegener further hypothesized that about 200 million years ago, during the early part of the Mesozoic era, this supercontinent began to fragment into smaller landmasses. These continental blocks then “drifted” to their present positions over a span of millions of years.

Wegener and others who advocated the continental drift hypothesis collected substantial evidence to support their point of view. The fit of South America and Africa and the geographic distribution of fossils and ancient climates all seemed to buttress the idea that these now separate landmasses were once joined. Let us examine some of this evidence.

### Evidence: The Continental Jigsaw Puzzle

Like a few others before him, Wegener suspected that the continents might once have been joined when he

Modern reconstruction of Pangaea



Wegener's Pangaea, redrawn from his book published in 1915.



\*Wegener was not the first to conceive of a long-vanished supercontinent. Edward Suess (1831–1914), a distinguished nineteenth-century geologist, pieced together evidence for a giant landmass comprising South America, Africa, India, and Australia.

**SmartFigure 2.2**  
**Reconstructions of Pangaea** The supercontinent of Pangaea, as it is thought to have formed in the late Paleozoic and early Mesozoic eras, more than 200 million years ago. (<https://goo.gl/eOttu9>)



**Figure 2.3****Two of the puzzle pieces**

The best fit of South America and Africa along the continental slope at a depth of 500 fathoms (about 900 meters [3000 feet]). (Based on A. G. Smith, "Continental Drift," in *Understanding the Earth*, edited by I. G. Gass, Artemis Press.)



noticed the remarkable similarity between the coastlines on opposite sides of the Atlantic Ocean. However, other Earth scientists challenged Wegener's use of present-day shorelines to "fit" these continents together. These opponents correctly argued that wave erosion and depositional processes continually modify shorelines. Even if continental displacement had taken place, a good fit today would be unlikely. Because Wegener's original jigsaw fit of the continents was crude, it is assumed that he was aware of this problem (see Figure 2.2).

Scientists later determined that a much better approximation of the outer boundary of a continent is the seaward edge of its continental shelf, which lies submerged a few hundred meters below sea level. In the early 1960s, Sir Edward Bullard and two associates constructed a map that pieced together the edges of the continental shelves of South America and Africa at a depth of about 900 meters (3000 feet) (Figure 2.3). The remarkable fit obtained was more precise than even these researchers had expected.

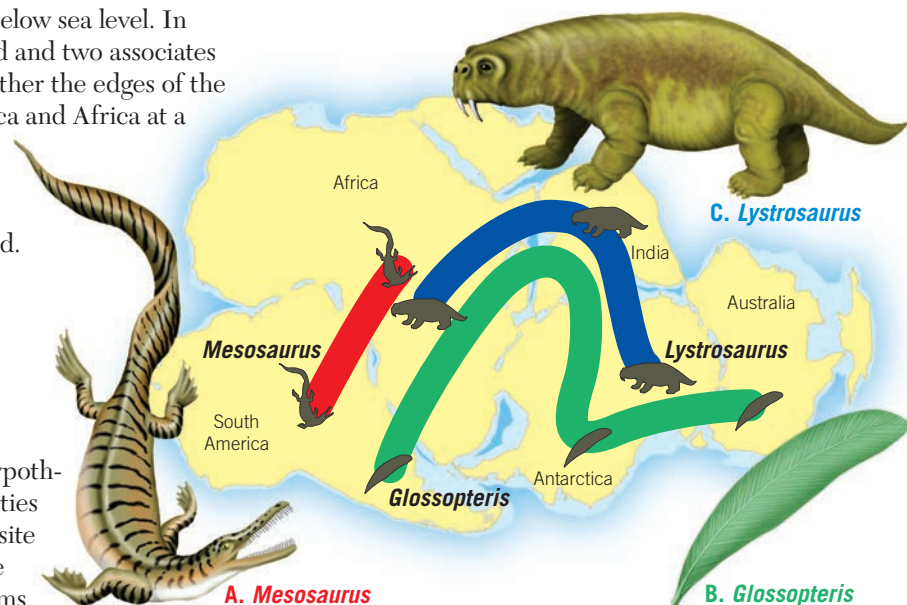
## Evidence: Fossils Matching Across the Seas

Although the seed for Wegener's hypothesis came from the striking similarities of the continental margins on opposite sides of the Atlantic, it was when he learned that identical fossil organisms had been discovered in rocks from both South America and Africa that his pursuit of continental drift became more focused. Wegener learned that most paleontologists

(scientists who study the fossilized remains of ancient organisms) agreed that some type of land connection was needed to explain the existence of similar Mesozoic age life-forms on widely separated landmasses. Just as modern life-forms native to North America are not the same as those of Africa and Australia, during the Mesozoic era, organisms on widely separated continents should have been distinctly different.

**Mesosaurus** To add credibility to his argument, Wegener documented cases of several fossil organisms found on different landmasses, even though their living forms were unlikely to have crossed the vast ocean presently separating them (Figure 2.4). A classic example is *Mesosaurus*, a small aquatic freshwater reptile whose fossil remains are limited to black shales of the Permian period (about 260 million years ago) in eastern South America and southwestern Africa. If *Mesosaurus* had been able to make the long journey across the South Atlantic, its remains should be more widely distributed. As this is not the case, Wegener asserted that South America and Africa must have been joined during that period of Earth history.

How did opponents of continental drift explain the existence of identical fossil organisms in places separated by thousands of kilometers of open ocean? Rafting, trans-oceanic land bridges (isthmian links), and island stepping stones were the most widely invoked explanations for these migrations (Figure 2.5). We know, for example, that during the Ice Age that ended about 8000 years ago, the lowering of sea level allowed mammals (including humans) to cross the narrow Bering Strait that separates Russia and Alaska. Was it possible that land bridges once

**Figure 2.4**

**Fossil evidence supporting continental drift** Fossils of identical organisms have been discovered in rocks of similar age in Australia, Africa, South America, Antarctica, and India—continents that are currently widely separated by ocean barriers. Wegener accounted for these occurrences by placing these continents in their pre-drift locations.

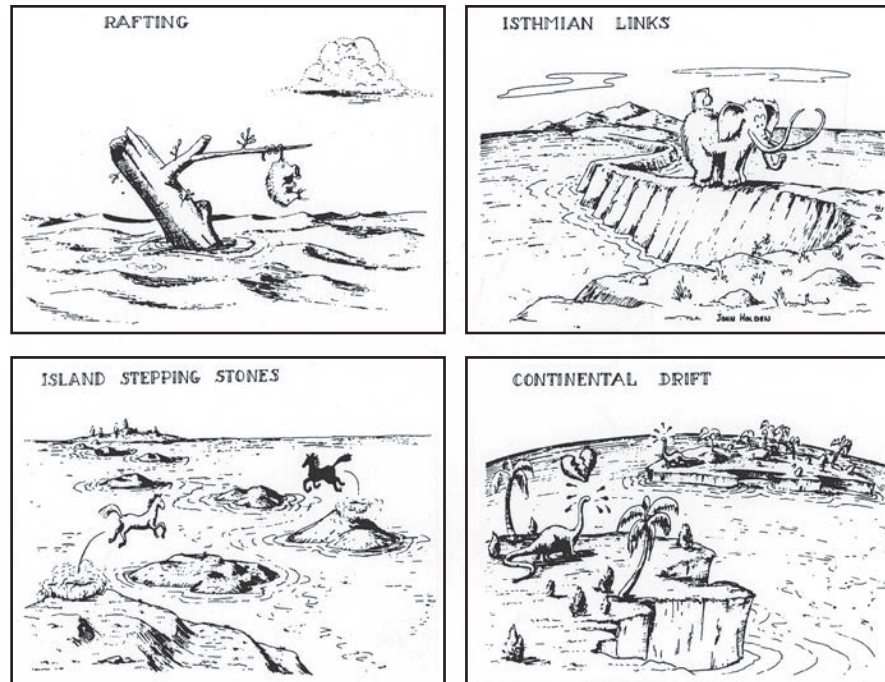
connected Africa and South America but later subsided below sea level? Modern maps of the seafloor substantiate Wegener's contention that if land bridges of this magnitude existed, their remnants would still lie below sea level.

**Glossopteris** Wegener also cited the distribution of the fossil “seed fern” *Glossopteris* as evidence for Pangaea's existence (see Figure 2.4). With tongue-shaped leaves and seeds too large to be carried by the wind, this plant was known to be widely dispersed among Africa, Australia, India, and South America. Later, fossil remains of *Glossopteris* were also discovered in Antarctica.\* Wegener also learned that these seed ferns and associated flora grew only in cool climates—similar to central Alaska. Therefore, he concluded that when these landmasses were joined, they were located much closer to the South Pole.

## Evidence: Rock Types and Geologic Features

You know that successfully completing a jigsaw puzzle requires fitting the pieces together while maintaining the continuity of the picture. The “picture” that must match

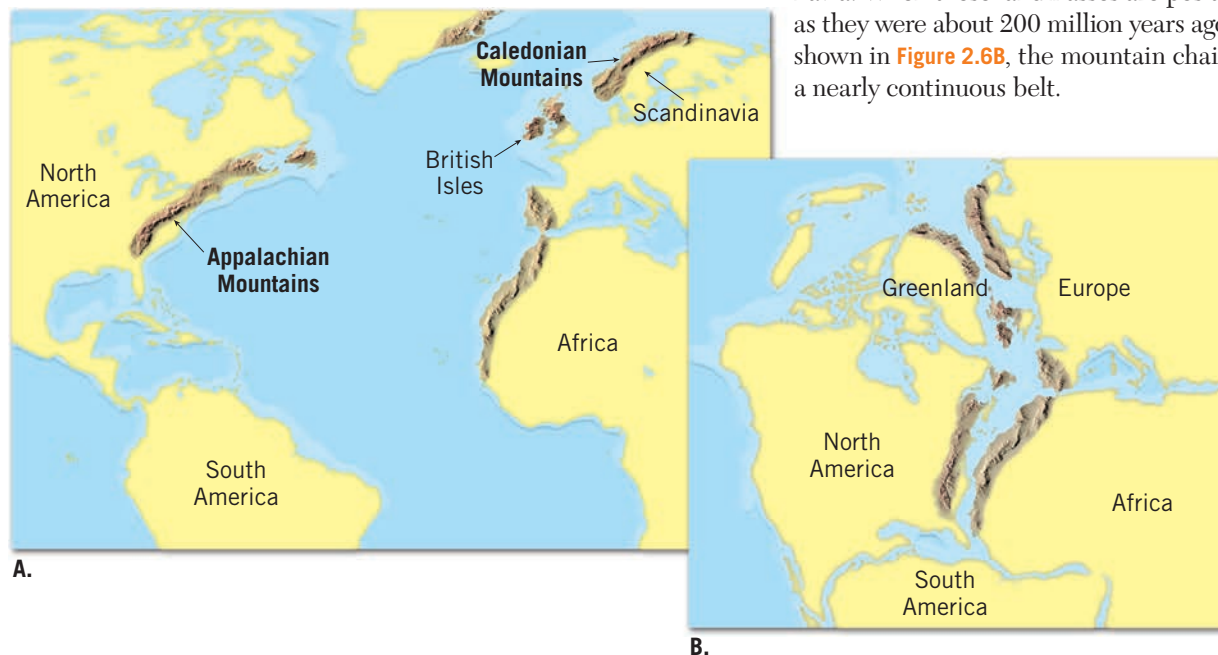
\* In 1912 Captain Robert Scott and two companions froze to death lying beside 35 pounds (16 kilograms) of rock on their return from a failed attempt to be the first to reach the South Pole. These samples, collected on Beardmore Glacier, contained fossil remains of *Glossopteris*.



**Figure 2.5**  
**How do land animals cross vast oceans?** These sketches illustrate various proposals to explain the occurrence of similar species on landmasses now separated by vast oceans. (Used by permission of John C. Holden)

in the “continental drift puzzle” is one of rock types and geologic features such as mountain belts. If the continents were once together, the rocks found in a particular region on one continent should closely match in age and type those found in adjacent positions on the adjoining continent. Wegener found evidence of highly deformed igneous rocks in Brazil that closely resembled similar rocks in Africa.

Similar evidence can be found in mountain belts that terminate at one coastline and reappear on landmasses across the ocean. For instance, the mountain belt that includes the Appalachians trends northeastward through the eastern United States and disappears off the coast of Newfoundland (Figure 2.6A). Mountains of comparable age and structure are found in the British Isles and Scandinavia. When these landmasses are positioned as they were about 200 million years ago, as shown in Figure 2.6B, the mountain chains form a nearly continuous belt.

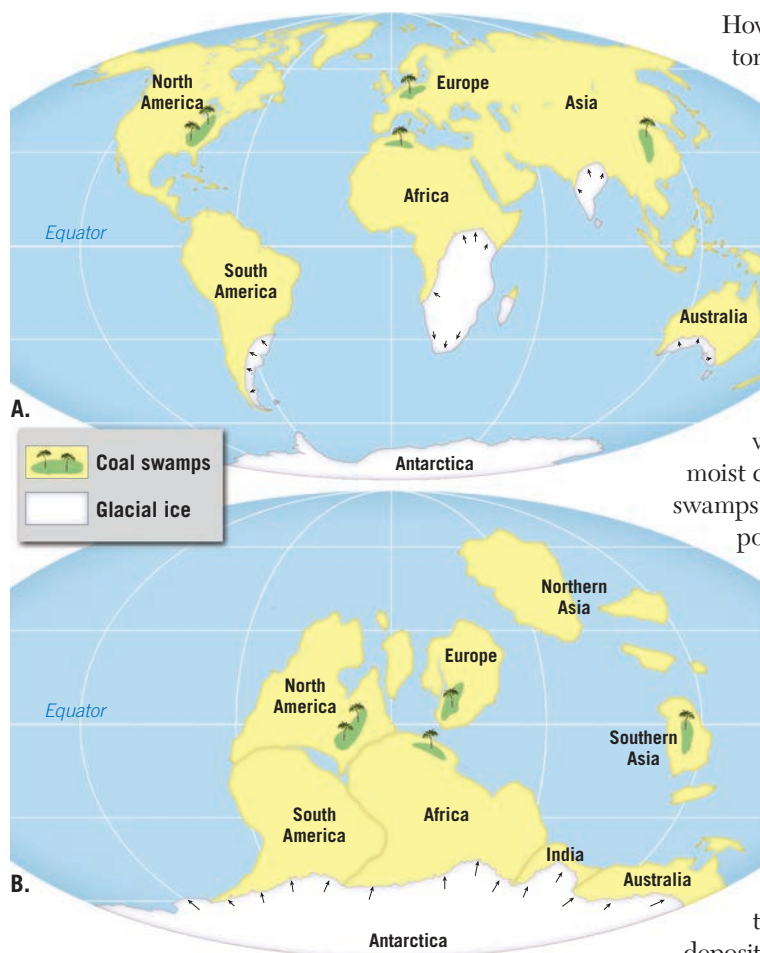


**Figure 2.6**  
**Matching mountain ranges across the North Atlantic**

### Figure 2.7 Paleoclimatic evidence for continental drift

**A.** About 300 million years ago, ice sheets covered extensive areas of the Southern Hemisphere and India. Arrows show the direction of ice movement that can be inferred from the pattern of glacial scratches and grooves found in the bedrock.

**B.** The continents restored to their pre-drift positions account for tropical coal swamps that existed in areas presently located in temperate climates.



Wegener described how the similarities in geologic features on both sides of the Atlantic linked these landmasses: “It is just as if we were to refit the torn pieces of a newspaper by matching their edges and then check whether the lines of print run smoothly across. If they do, there is nothing left but to conclude that the pieces were in fact joined in this way.”†

### Evidence: Ancient Climates

Because Alfred Wegener was a student of world climates, he suspected that paleoclimatic (*paleo* = ancient, *climatic* = climate) data might also support the idea of mobile continents. His assertion was bolstered by evidence that a glacial period dating to the late Paleozoic had been discovered in southern Africa, South America, Australia, and India. This meant that about 300 million years ago, vast ice sheets covered extensive portions of the Southern Hemisphere as well as India (Figure 2.7A). Much of the land area that contains evidence of this Paleozoic glaciation presently lies within 30 degrees of the equator in subtropical or tropical climates.

†Alfred Wegener, *The Origin of Continents and Oceans*, translated from the 4th revised German ed. of 1929 by J. Birman (London: Methuen, 1966).

How could extensive ice sheets form near the equator? One proposal suggested that our planet experienced a period of extreme global cooling. Wegener rejected this explanation because during the same span of geologic time, large tropical swamps existed in several locations in the Northern Hemisphere. The lush vegetation in these swamps was eventually buried and converted to coal (Figure 2.7B). Today these deposits comprise major coal fields in the eastern United States and Northern Europe. Many of the fossils found in these coal-bearing rocks were produced by tree ferns with large fronds—a fact consistent with warm, moist climates.\*\* The existence of these large tropical swamps, Wegener argued, was inconsistent with the proposal that extreme global cooling caused glaciers to form in areas that are currently tropical.

Wegener suggested a more plausible explanation for the late Paleozoic glaciation: the supercontinent of Pangaea. The southern continents being joined together and located near the South Pole would account for the polar conditions necessary to generate extensive expanses of glacial ice over much of these landmasses (Figure 2.7B). At the same time, this geography places today’s northern continents nearer the equator and accounts for the tropical swamps that generated the vast coal deposits.

How does a glacier develop in hot, arid central Australia? How do land animals migrate across wide expanses of the ocean? As compelling as this evidence may have been, 50 years passed before most of the scientific community accepted the concept of continental drift and the logical conclusions to which it led.

\*\* It is important to note that coal can form in a variety of climates, provided that large quantities of plant life are buried.

## 2.2 Concept Checks

1. What was the first line of evidence that led early investigators to suspect that the continents were once connected?
2. Explain why the discovery of the fossil remains of *Mesosaurus* in both South America and Africa, but nowhere else, supports the continental drift hypothesis.
3. Early in the twentieth century, what was the prevailing view of how land animals migrated across vast expanses of open ocean?
4. How did Wegener account for evidence of glaciers in the southern landmasses at a time when areas in North America, Europe, and Asia supported lush tropical swamps?

## 2.3 The Great Debate

Summarize the two main objections to the continental drift hypothesis.

From 1924, when Wegener's book was translated into English, French, Spanish, and Russian, until his death in 1930, his proposed drift hypothesis encountered a great deal of hostile criticism. The respected American geologist R. T. Chamberlain stated, "Wegener's hypothesis in general is of the foot-loose type, in that it takes considerable liberty with our globe, and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories."

### Rejection of the Drift Hypothesis

One of the main objections to Wegener's hypothesis stemmed from his inability to identify a credible mechanism for continental drift. Wegener proposed that gravitational forces of the Moon and Sun that produce Earth's tides were also capable of gradually moving the continents across the globe. However, the prominent physicist Harold Jeffreys correctly argued that tidal forces strong enough to move Earth's continents would have resulted in halting our planet's rotation, which, of course, has not happened.

Wegener also incorrectly suggested that the larger and sturdier continents broke through thinner oceanic crust, much as icebreakers cut through ice. However, no evidence existed to suggest that the ocean floor was weak enough to permit passage of the continents without the continents being appreciably deformed in the process.

In 1930, Wegener made his fourth and final trip to the Greenland ice sheet (Figure 2.8). Although the primary focus of this expedition was to study this great ice cap and its climate, Wegener continued to test his continental drift hypothesis. While returning from Eismitte, an experimental station located in the center of Greenland, Wegener perished along with his Greenland companion. His intriguing idea, however, did not die.

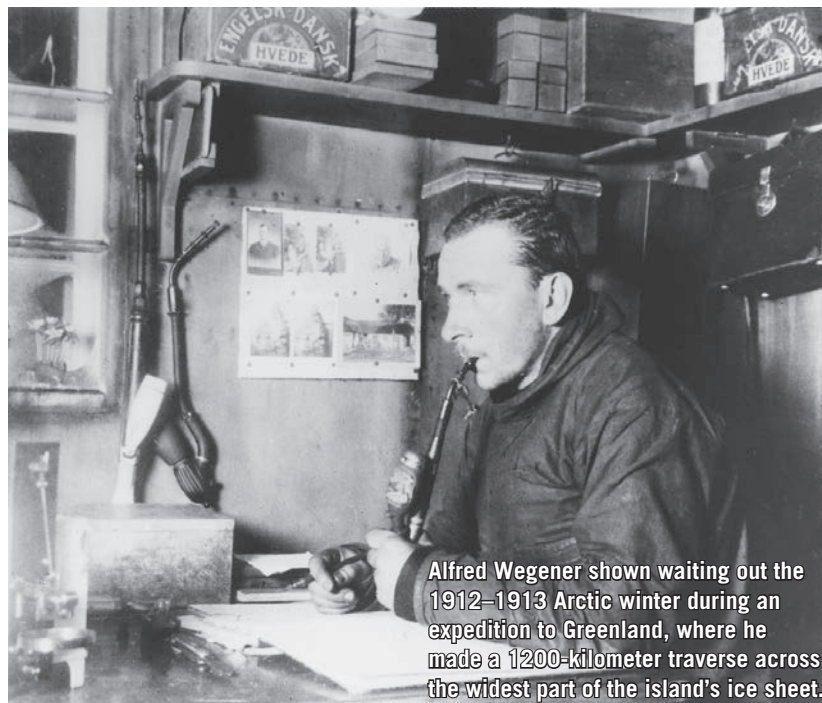
Why was Wegener unable to overturn the established scientific views of his day? Foremost was the fact that, although the central theme of Wegener's drift hypothesis was correct, some details were incorrect. For example, continents do not break through the ocean floor, and tidal energy is much too weak to move continents. Moreover, for any comprehensive scientific theory to gain wide acceptance, it must withstand critical testing from all areas of science. Despite Wegener's great contribution to our understanding of Earth,

not *all* of the evidence supported the continental drift hypothesis as he had proposed it.

Although many of Wegener's contemporaries opposed and even ridiculed his views, some considered his ideas plausible. For those geologists who continued the search, the exciting concept of continents adrift held their interest. Others viewed continental drift as a solution to previously unexplainable observations such as the cause of earthquakes. Nevertheless, most of the scientific community, particularly in North America, either categorically rejected continental drift or treated it with considerable skepticism.

### 2.3 Concept Checks

1. Describe two aspects of Wegener's continental drift hypothesis that were objectionable to most Earth scientists.
2. What analogy did Wegener use to describe how the continents move through the ocean floor?



Alfred Wegener shown waiting out the 1912–1913 Arctic winter during an expedition to Greenland, where he made a 1200-kilometer traverse across the widest part of the island's ice sheet.

**Figure 2.8**  
Alfred Wegener, during an expedition to Greenland  
(Photo courtesy of Archive of Alfred Wegener Institute)

## 2.4 The Theory of Plate Tectonics

List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.

Following World War II, oceanographers equipped with new marine tools and ample funding from the U.S. Office of Naval Research embarked on an unprecedented period of oceanographic exploration. Over the next two decades, a much better picture of large expanses of the seafloor slowly and painstakingly began to emerge. From this work came the discovery of a global oceanic ridge system that winds through all the major oceans.

In other parts of the ocean, more new discoveries were being made. Studies conducted in the western Pacific demonstrated that earthquakes were occurring at great depths beneath deep-ocean trenches. Of equal importance was the fact that dredging of the seafloor did not bring up any oceanic crust that was older than 180 million years. Further, sediment accumulations in the deep-ocean basins were found to be thin, not the thousands of meters that were predicted. By 1968 these developments, among others, had led to the unfolding of a far more encompassing theory than continental drift, known as the **theory of plate tectonics** (*tekto* = to build).

### Rigid Lithosphere Overlies Weak Asthenosphere

According to the plate tectonics model, the crust and the uppermost, and therefore coolest, part of the mantle constitute Earth's strong outer layer, the **lithosphere** (*lithos* = stone). The lithosphere varies in both thickness and density, depending on whether it is oceanic or continental lithosphere (Figure 2.9). Oceanic lithosphere is about 100 kilometers (60 miles) thick in the deep-ocean basins but is considerably thinner along the crest of the oceanic ridge system—a topic we will consider later. By contrast, continental lithosphere averages about 150 kilometers (90 miles) thick but may extend to depths of 200 kilometers

(125 miles) or more beneath the stable interiors of the continents. Further, the composition of both the oceanic and continental crusts affects their respective densities. Oceanic crust is composed of basalt, rich in dense iron and magnesium, whereas continental crust is composed largely of less dense granitic rocks. Because of these differences, the overall density of oceanic lithosphere (crust and upper mantle) is greater than the overall density of continental lithosphere. This important difference will be considered in greater detail later in this chapter.

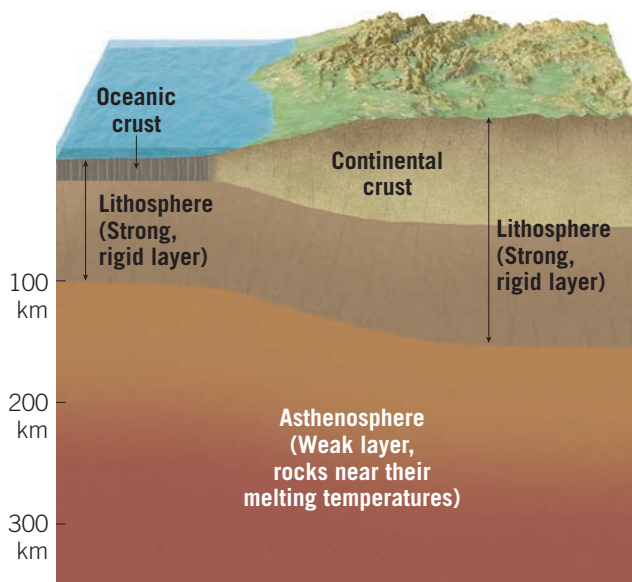
The **asthenosphere** (*asthenos* = weak) is a hotter, weaker region in the mantle that lies below the lithosphere (see Figure 2.9). The temperatures and pressures in the upper asthenosphere (100 to 200 kilometers [60 to 125 miles] in depth) are such that rocks at this depth are very near their melting temperatures and, hence, respond to forces by *flowing*, similar to the way a thick liquid would flow. By contrast, the relatively cool and rigid lithosphere tends to respond to forces acting on it by *bending or breaking but not flowing*. Because of these differences, Earth's rigid outer shell is effectively detached from the asthenosphere, which allows these layers to move independently.

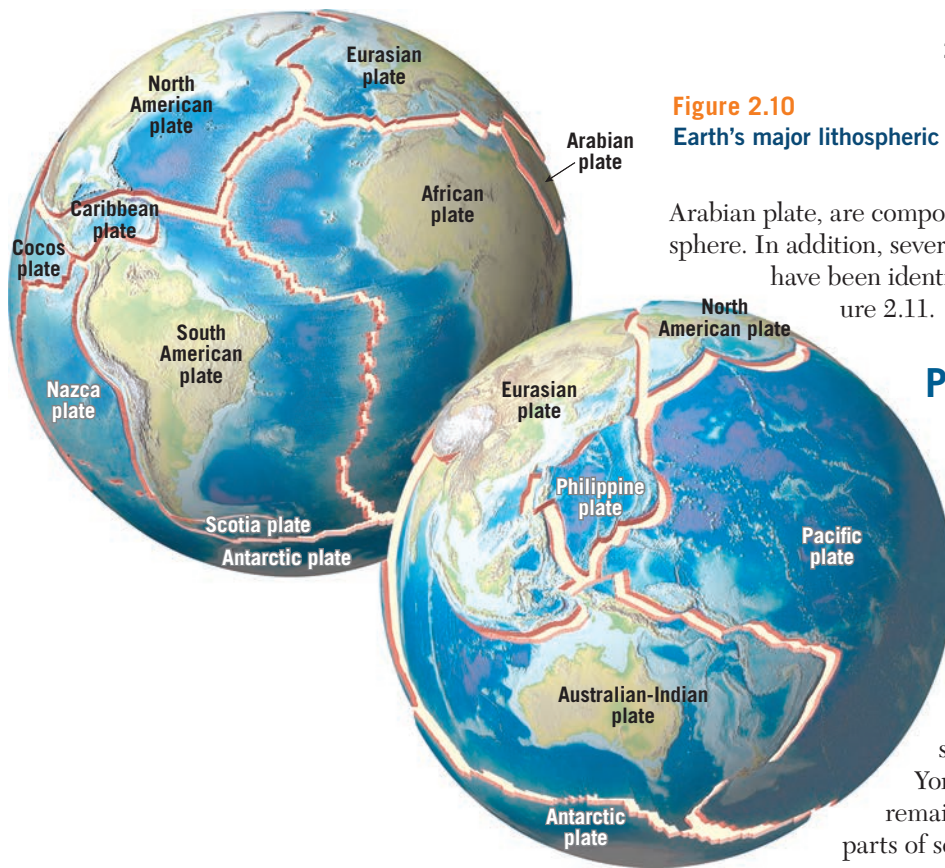
### Earth's Major Plates

The lithosphere is broken into about two dozen segments of irregular size and shape called **lithospheric plates**, or simply **plates**, that are in constant motion with respect to one another (Figure 2.10). Seven major lithospheric plates are recognized and account for 94 percent of Earth's surface area: the *North American*, *South American*, *Pacific*, *African*, *Eurasian*, *Australian-Indian*, and *Antarctic plates*. The largest is the Pacific plate, which encompasses a significant portion of the Pacific basin. Each of the six other large plates consists of an entire continent, as well as a significant amount of oceanic crust. Notice in Figure 2.11 that the South American plate encompasses almost all of South America and about one-half of the floor of the South Atlantic. Note also that none of the plates are defined entirely by the margins of a single continent. This is a major departure from Wegener's continental drift hypothesis, which proposed that the continents move through the ocean floor, not with it.

Intermediate-sized plates include the *Caribbean*, *Nazca*, *Philippine*, *Arabian*, *Cocos*, *Scotia*, and *Juan de Fuca plates*. These plates, with the exception of the

**SmartFigure 2.9**  
Rigid lithosphere overlies the weak asthenosphere  
(<https://goo.gl/KH1iAR>)





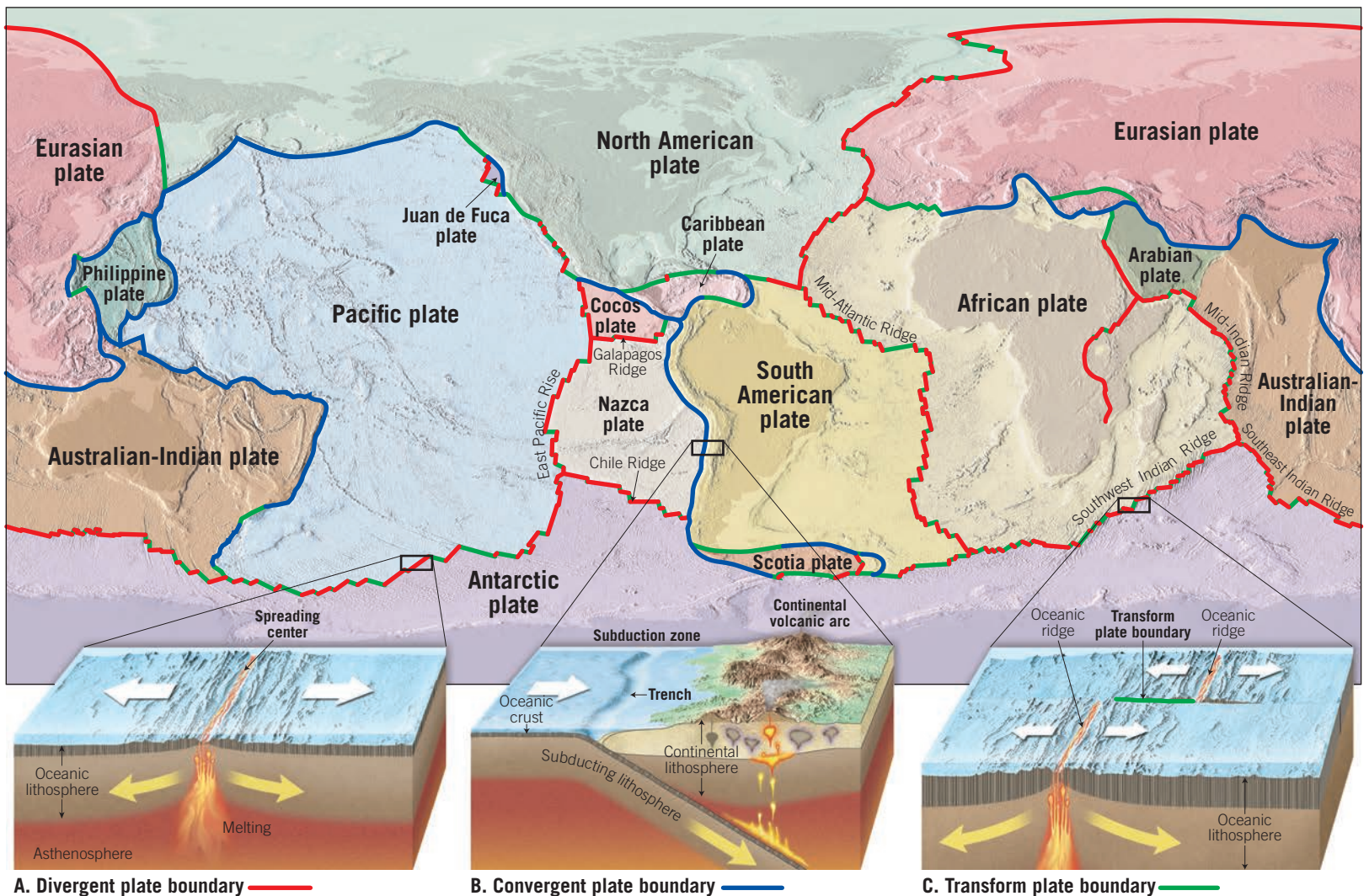
**Figure 2.10**  
Earth's major lithospheric plates

Arabian plate, are composed mostly of oceanic lithosphere. In addition, several smaller plates (*microplates*) have been identified but are not shown in Figure 2.11.

### Plate Movement

One of the main tenets of the plate tectonics theory is that plates move as somewhat rigid units relative to all other plates. As plates move, the distance between two locations on different plates, such as New York and London, gradually changes, whereas the distance between sites on the same plate—New York and Denver, for example—remains relatively constant. However, parts of some plates are comparatively

**Figure 2.11**  
Divergent, convergent, and transform plate boundaries  
(Based on W. B. Hamilton, U.S. Geological Survey)



**A. Divergent plate boundary** — red line

**B. Convergent plate boundary** — blue line

**C. Transform plate boundary** — green line

“weak and can become fragmented” such as southern China, which is literally being squeezed as the Indian subcontinent rams into Asia.

Because plates are in constant motion relative to each other, most major interactions among them (and, therefore, most deformation) occur along their *boundaries*. In fact, plate boundaries were first established by plotting the locations of earthquakes and volcanoes. Plates are bounded by three distinct types of boundaries, which are differentiated by the type of movement they exhibit. These boundaries are depicted in Figure 2.11 and are briefly described here:

- Divergent plate boundaries—where two plates move apart, resulting in upwelling and partial melting of hot material from the mantle to create new seafloor (see Figure 2.11A)
- Convergent plate boundaries—where two plates move together, resulting either in oceanic lithosphere descending beneath an overriding plate, eventually to be reabsorbed into the mantle, or possibly in the collision of two continental blocks to create a mountain belt (see Figure 2.11B)

- Transform plate boundaries—where two plates grind past each other without the production or destruction of lithosphere (see Figure 2.11C)

Divergent and convergent plate boundaries each account for about 40 percent of all plate boundaries. Transform boundaries, or faults account for the remaining 20 percent. In the following sections we will summarize the nature of the three types of plate boundaries.

## 2.4 Concept Checks

1. What new findings about the ocean floor did oceanographers discover after World War II?
2. Compare and contrast Earth's lithosphere and asthenosphere.
3. List the seven largest lithospheric plates.
4. List the three types of plate boundaries and describe the relative motion along each.

## 2.5 Divergent Plate Boundaries and Seafloor Spreading

Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.

Most **divergent plate boundaries** (*di* = apart, *vergere* = to move) are located along the crests of oceanic ridges and can be thought of as *constructive plate margins* because this is where new ocean floor is generated (Figure 2.12). Here, two adjacent plates move away from each other, producing long, narrow fractures in the ocean crust. As a result, hot molten rock from the mantle below migrates upward to fill the voids left as the crust is being ripped apart. This molten material gradually cools to produce new slivers of seafloor. In a slow yet unending manner, adjacent plates spread apart, and new oceanic lithosphere forms between them. For this reason, divergent plate boundaries are also called **spreading centers**.

### Oceanic Ridges and Seafloor Spreading

The majority of, but not all, divergent plate boundaries are associated with *oceanic ridges*: elevated areas of the seafloor characterized by high heat flow and volcanism. The global **oceanic ridge system** is the longest topographic feature on Earth's surface, exceeding 70,000 kilometers (43,000 miles) in length. As shown in Figure 2.11, various segments of the global ridge system have been named, including the Mid-Atlantic Ridge, East Pacific Rise, and Mid-Indian Ridge.

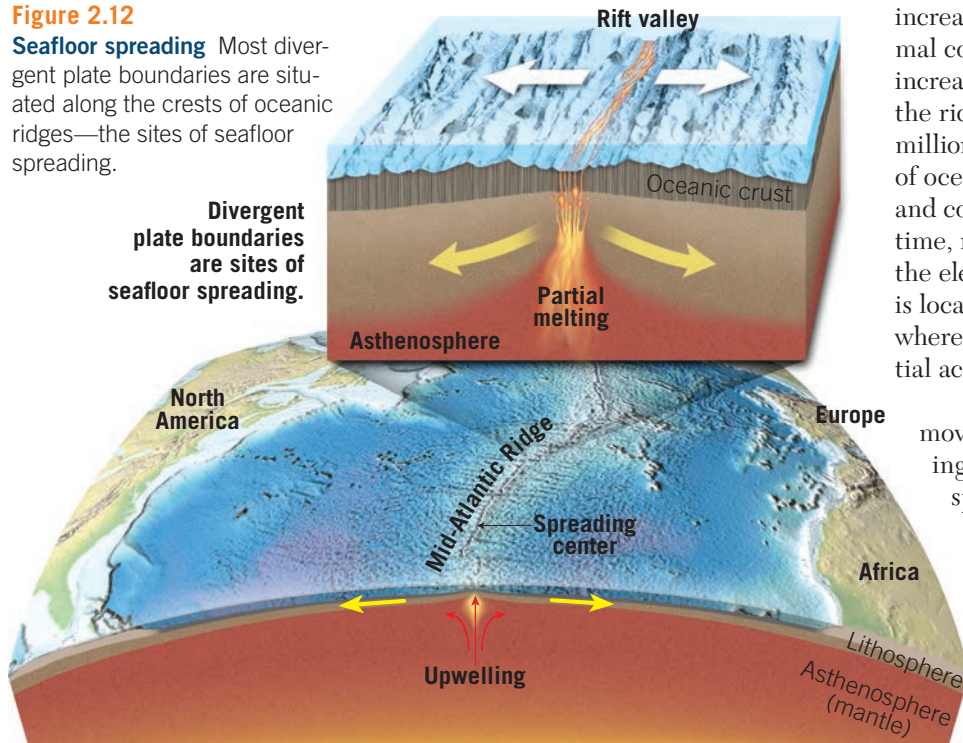
Representing 20 percent of Earth's surface, the oceanic ridge system winds through all major ocean basins, like the seams on a baseball. Although the crest

of the oceanic ridge is commonly 2 to 3 kilometers (1 to 2 miles) higher than the adjacent ocean basins, the term *ridge* may be misleading because it implies “narrow” when, in fact, ridges vary in width from 1000 kilometers (600 miles) to more than 4000 (2500 miles) kilometers. Further, along the crest of some ridge segments is a deep canyonlike structure called a **rift valley** (Figure 2.13). This structure is evidence that tensional (opposing) forces are actively pulling the ocean crust apart at the ridge crest.

The mechanism that operates along the oceanic ridge system to create new seafloor is appropriately called **seafloor spreading**. Spreading typically averages around 5 centimeters (2 inches) per year, roughly the same rate at which human fingernails grow.

**Figure 2.12**

**Seafloor spreading** Most divergent plate boundaries are situated along the crests of oceanic ridges—the sites of seafloor spreading.



Divergent plate boundaries are sites of seafloor spreading.

increasing in density. This thermal contraction accounts for the increase in ocean depths away from the ridge crest. It takes about 80 million years for the temperature of oceanic lithosphere to stabilize and contraction to cease. By this time, rock that was once part of the elevated oceanic ridge system is located in the deep-ocean basin, where it may be buried by substantial accumulations of sediment.

In addition, as the plate moves away from the ridge, cooling of the underlying asthenosphere causes it to become increasingly more rigid.

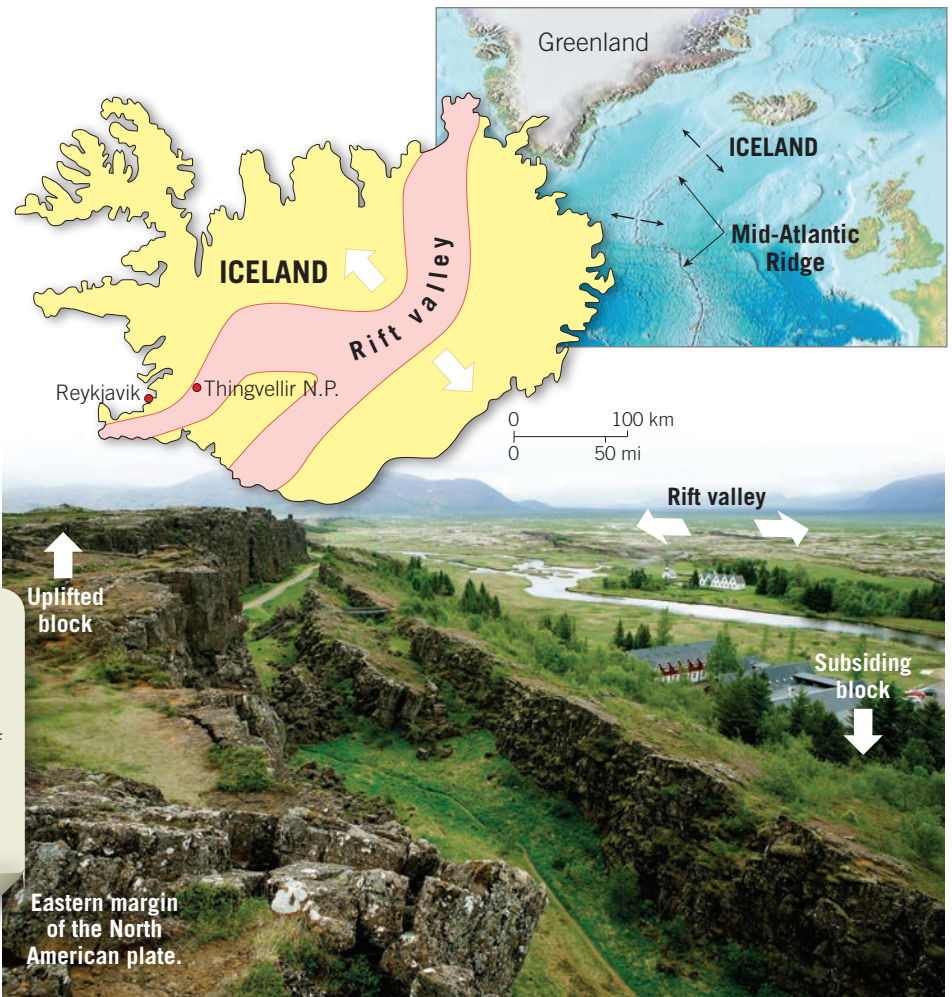
Thus, oceanic lithosphere is generated by cooling of the asthenosphere from the top down. Stated another way, the thickness of oceanic lithosphere is

Comparatively slow spreading rates of 2 centimeters per year are found along the Mid-Atlantic Ridge, whereas spreading rates exceeding 15 centimeters (6 inches) per year have been measured along sections of the East Pacific Rise. Although these rates of seafloor production are slow on a human time scale, they are nevertheless rapid enough to have generated all of Earth's ocean basins within the past 200 million years.

The primary reason for the elevated position of the oceanic ridge is that newly created oceanic lithosphere is hot and, therefore, less dense than cooler rocks found away from the ridge axis. (Geologists use the term *axis* to refer to a line that follows the general trend of the ridge crest.) As soon as new lithosphere forms, it is slowly yet continually displaced away from the zone of upwelling. Thus, it begins to cool and contract, thereby

**SmartFigure 2.13**

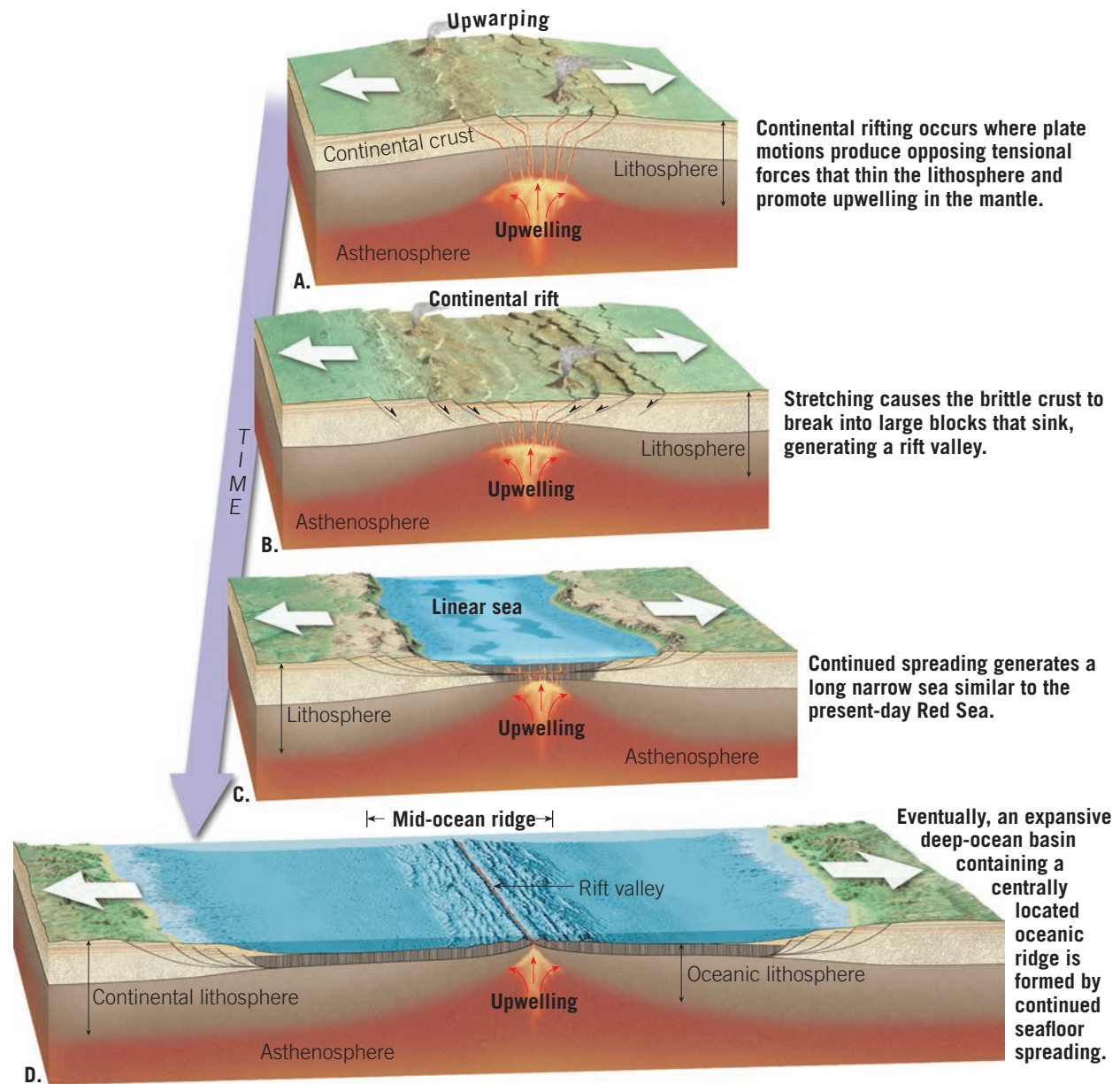
**Rift valley** Thingvellir National Park, Iceland, is located on the western margin of a rift valley roughly 30 kilometers (20 miles) wide. This rift valley is connected to a similar feature that extends along the crest of the Mid-Atlantic Ridge. The cliff in the left half of the image approximates the eastern edge of the North American plate. (Photo by Ragnar Sigurdsson/Arctic/Alamy) (<http://goo.gl/RsbHWM>)



**SmartFigure 2.14**  
**Continental rifting:**  
**Formation of new ocean**  
**basins** (<https://goo.gl/s4RWua>)



Tutorial



age dependent. The older (cooler) it is, the greater its thickness. Oceanic lithosphere that exceeds 80 million years in age is about 100 kilometers (60 miles) thick—approximately its maximum thickness.

## Continental Rifting

Divergent boundaries can develop within a continent, in which case the landmass may split into two or more smaller segments separated by an ocean basin. Continental rifting begins when plate motions produce tensional forces that pull and stretch the lithosphere. This stretching, in turn, promotes mantle upwelling and broad upwarping of the overlying lithosphere (Figure 2.14A). During this process, the lithosphere is thinned, while the brittle crustal rocks break into large blocks. As

the tectonic forces continue to pull apart the crust, the broken crustal fragments sink, generating an elongated depression called a **continental rift**, which can widen to form a narrow sea (Figure 2.14B,C) and eventually a new ocean basin (Figure 2.14D).

An example of an active continental rift is the East African Rift (Figure 2.15). Whether this rift will eventually result in the breakup of Africa is a topic of ongoing research. Nevertheless, the East African Rift is an excellent model of the initial stage in the breakup of a continent. Here, tensional forces have stretched and thinned the lithosphere, allowing molten rock to ascend from the mantle. Evidence for this upwelling includes several large volcanic mountains, including Mount Kilimanjaro and Mount Kenya, the tallest peaks in Africa. Research suggests that if rifting continues, the

rift valley will lengthen and deepen (see Figure 2.14C). At some point, the rift valley will become a narrow sea with an outlet to the ocean. The Red Sea, formed when the Arabian Peninsula split from Africa, is a modern example of such a feature and provides us with a view of how the Atlantic Ocean may have looked in its infancy (see Figure 2.14D).

## 2.5 Concept Checks

1. Sketch or describe how two plates move in relation to each other along divergent plate boundaries.
2. What is the average rate of seafloor spreading in modern oceans?
3. List four features that characterize the oceanic ridge system.
4. Briefly describe the process of continental rifting. Where is it occurring today?



**SmartFigure 2.15**  
**East African Rift valley** The East African Rift valley represents the early stage in the breakup of a continent. Areas shown in red consist of lithosphere that has been stretched and thinned, allowing magma to well up from the mantle. (<https://goo.gl/Gp4pje>)



## EYE ON EARTH 2.1

In December 2011 a new volcanic island formed near the southern end of the Red Sea. Less than 2 years later, in late October 2013, another volcanic island emerged in the same area. These volcanic islands are part of several small islands in the Zubair Group located off the west coast of Yemen, along the Red Sea Rift.

**QUESTION 1** What type of plate boundary produced these new volcanic islands?

**QUESTION 2** What two plates border the Red Sea Rift?

**QUESTION 3** Are these two plates moving *toward* or *away* from each other?



NASA

## 2.6 Convergent Plate Boundaries and Subduction

Compare and contrast the three types of convergent plate boundaries and name a location where each type can be found.

New lithosphere is constantly being produced at the oceanic ridges. However, our planet is not growing larger; its total surface area remains constant. A balance is maintained because older, denser portions of oceanic lithosphere descend into the mantle at a rate equal to seafloor production. This activity occurs along **convergent plate boundaries**, where two plates move toward each other and the leading edge of one is bent downward as it slides beneath the other.

Convergent boundaries are also called **subduction zones** because they are sites where lithosphere is descending (being subducted) into the mantle. Subduction occurs because the density of the descending lithospheric plate is greater than the density of the underlying asthenosphere. Recall that oceanic crust is more dense than continental crust. In general, old oceanic lithosphere is about 2 percent more dense than the underlying asthenosphere, which causes it to subduct. Continental lithosphere, in contrast, is less dense than the underlying asthenosphere and resists subduction. As a consequence, only oceanic lithosphere will subduct to great depths.

**Deep-ocean trenches** are the surface manifestations produced as oceanic lithosphere descends into the mantle (see Figure 1.23, page 58). These large linear depressions are remarkably long and deep. The Peru–Chile trench along the west coast of South America is more than 4500 kilometers (2800 miles) long, and its floor is as much as 8 kilometers (5 miles) below sea level. Western Pacific trenches, including the Mariana and Tonga trenches, tend to be even deeper than those of the eastern Pacific.

Slabs of oceanic lithosphere descend into the mantle at angles that vary from a few degrees to nearly vertical (90 degrees). The angle at which oceanic lithosphere subducts depends largely on its age and, therefore, its density. For example, when seafloor spreading occurs near a subduction zone, as is the case along the coast of Chile, the subducting lithosphere is young and

buoyant, which results in a low angle of descent. As the two plates converge, the overriding plate scrapes over the top of the subducting plate below—a type of forced subduction. Consequently, the region around the Peru–Chile trench experiences great earthquakes, including the 2010 Chilean earthquake—one of the 10 largest on record.

As oceanic lithosphere ages (gets farther from the spreading center), it gradually cools, which causes it to thicken and increase in density. In parts of the western Pacific, some oceanic lithosphere is 180 million years old—the thickest and densest in today’s oceans. The very dense slabs in this region typically plunge into the mantle at angles approaching 90 degrees. This largely explains why most trenches in the western Pacific are deeper than trenches in the eastern Pacific.

Although all convergent zones have the same basic characteristics, they vary considerably depending on the type of crustal material involved and the tectonic setting. Convergent boundaries can form *between one oceanic plate and one continental plate, between two oceanic plates, or between two continental plates* (Figure 2.16).

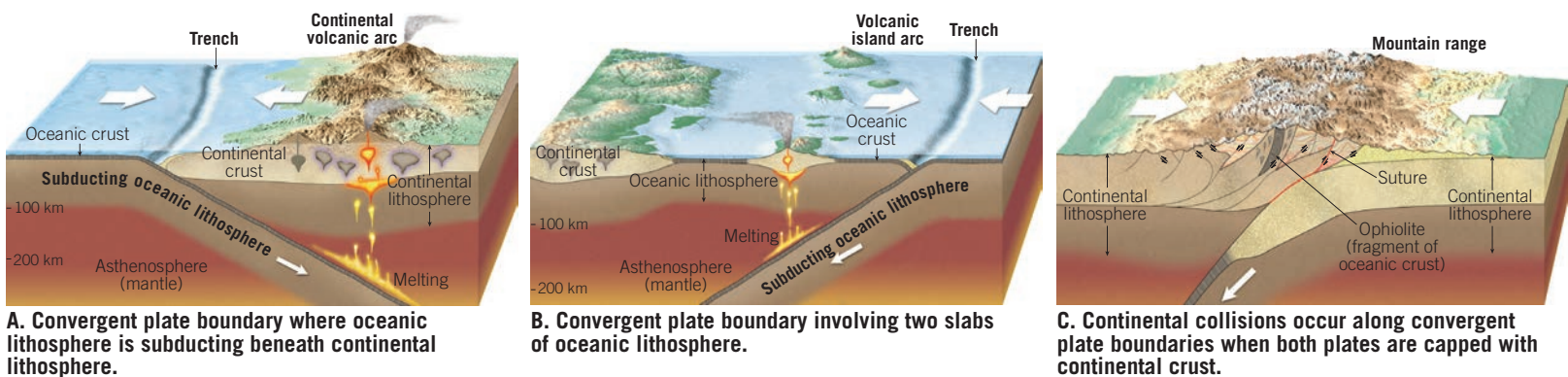
**SmartFigure 2.16**  
Three types of convergent plate boundaries  
(<https://goo.gl/Zlylbf>)



Tutorial

### Oceanic–Continental Convergence

When the leading edge of a plate capped with continental crust converges with a slab of oceanic lithosphere, the buoyant continental block remains “floating,” while the denser oceanic slab sinks into the mantle (see Figure



2.16A). When a descending oceanic slab reaches a depth of about 100 kilometers (60 miles), melting is triggered within the wedge of hot asthenosphere that lies above it. But how does the subduction of a cool slab of oceanic lithosphere cause mantle rock to melt? The answer lies in the fact that water contained in the descending plates acts the way salt does to melt ice. That is, “wet” rock in a high-pressure environment melts at substantially lower temperatures than does “dry” rock of the same composition.

Sediments and oceanic crust contain large amounts of water, which is carried to great depths by a subducting plate. As the plate plunges downward, heat and pressure drive water from the hydrated (water-rich) minerals in the subducting slab. At a depth of roughly 100 kilometers (60 miles), the wedge of mantle rock is sufficiently hot that the introduction of water from the slab below leads to some melting. This process, called **partial melting**, is thought to generate some molten material, which is mixed with unmelted mantle rock. Being less dense than the surrounding mantle, this hot mobile material gradually rises toward the surface. Depending on the environment, these mantle-derived masses of molten rock may ascend through the crust and give rise to a volcanic eruption. However, much of this material never reaches the surface but solidifies at depth—a process that thickens the crust.

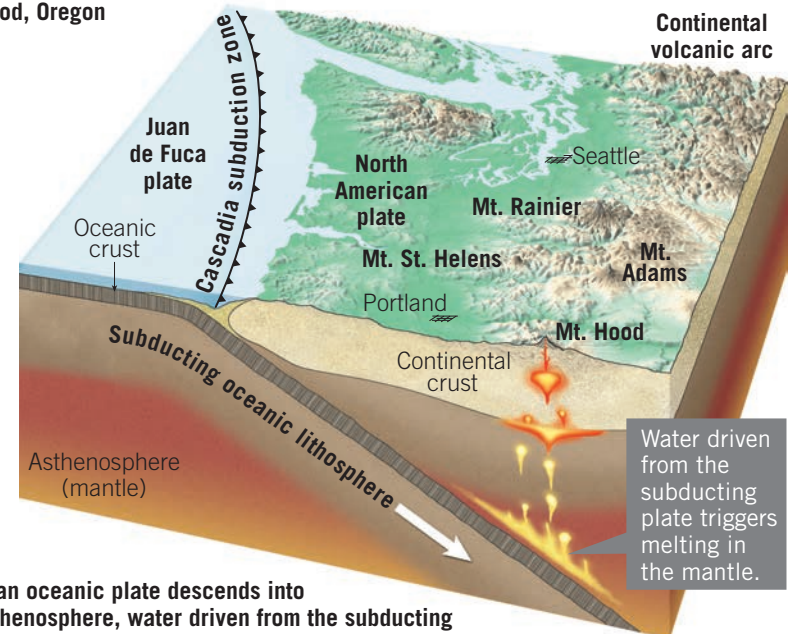
The volcanoes of the towering Andes are the product of molten rock generated by the subduction of the Nazca plate beneath the South American continent (see Figure 2.11). Mountain systems like the Andes, which are produced in part by volcanic activity associated with the subduction of oceanic lithosphere, are called **continental volcanic arcs**. The Cascade Range in Washington, Oregon, and California is another mountain system consisting of several well-known volcanoes, including Mount Rainier, Mount Shasta, Mount St. Helens, and Mount Hood (Figure 2.17). This active volcanic arc also extends into Canada, where it includes Mount Garibaldi and Mount Silverthorne.

## Oceanic–Oceanic Convergence

An *oceanic–oceanic convergent boundary* has many features in common with oceanic–continental plate margins (see Figure 2.16A,B). Where two oceanic slabs converge, one descends beneath the other, initiating volcanic activity by the same mechanism that operates at all subduction zones (see Figure 2.11). Water driven from the subducting slab of oceanic lithosphere triggers melting in the hot wedge of mantle rock above. In this setting, volcanoes grow up from the ocean floor rather than on a continental platform. When subduction is sustained, it will eventually build a chain of volcanic structures large enough to emerge as islands. The newly



Mt. Hood, Oregon



When an oceanic plate descends into the asthenosphere, water driven from the subducting slab lowers the melting temperature of mantle rock sufficiently to generate magma. The Cascade Range is a continental volcanic arc formed by the subduction of the Juan de Fuca plate under the North American plate.

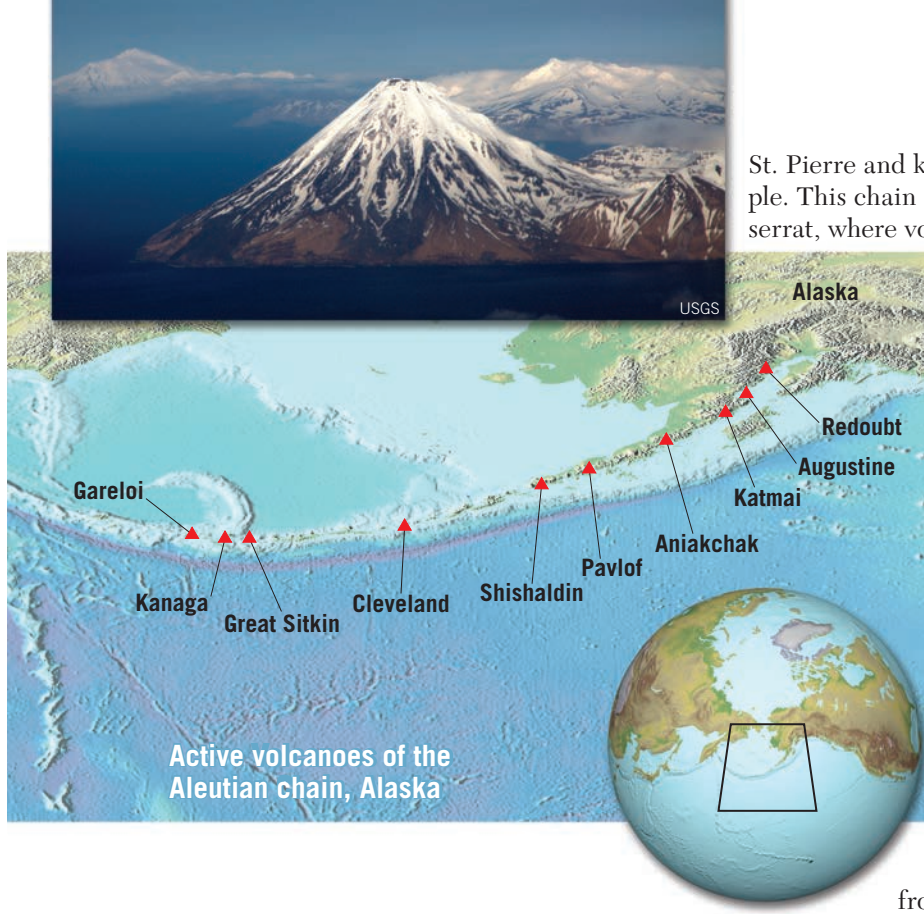
formed land consisting of an arc-shaped chain of volcanic islands is called a **volcanic island arc**, or simply an **island arc** (Figure 2.18).

The Aleutian, Mariana, and Tonga Islands are examples of relatively young volcanic island arcs. Island arcs are generally located 120 to 360 kilometers (75 to 225 miles) from a deep-ocean trench. Located adjacent to the island arcs just mentioned are the Aleutian trench, the Mariana trench, and the Tonga trench.

Most volcanic island arcs are located in the western Pacific. Only two are located in the Atlantic—the Lesser Antilles arc, on the eastern margin of the Caribbean Sea, and the Sandwich Islands, located off the tip of South America. The Lesser Antilles are a product of the subduction of the Atlantic seafloor beneath the Caribbean plate. Located within this volcanic arc are the Virgin Islands of the United States and Britain as well as the island of Martinique, where Mount Pelée erupted in 1902, destroying the town of

**Figure 2.17**  
**Oceanic–continental convergent plate boundary**  
Mount Hood, Oregon, is one of more than a dozen large composite volcanoes in the Cascade Range, a continental volcanic arc.

**Figure 2.18**  
**Volcanoes of the Aleutian Islands** The Aleutian Islands are a volcanic arc produced by the subduction of the Pacific plate beneath the North American plate.



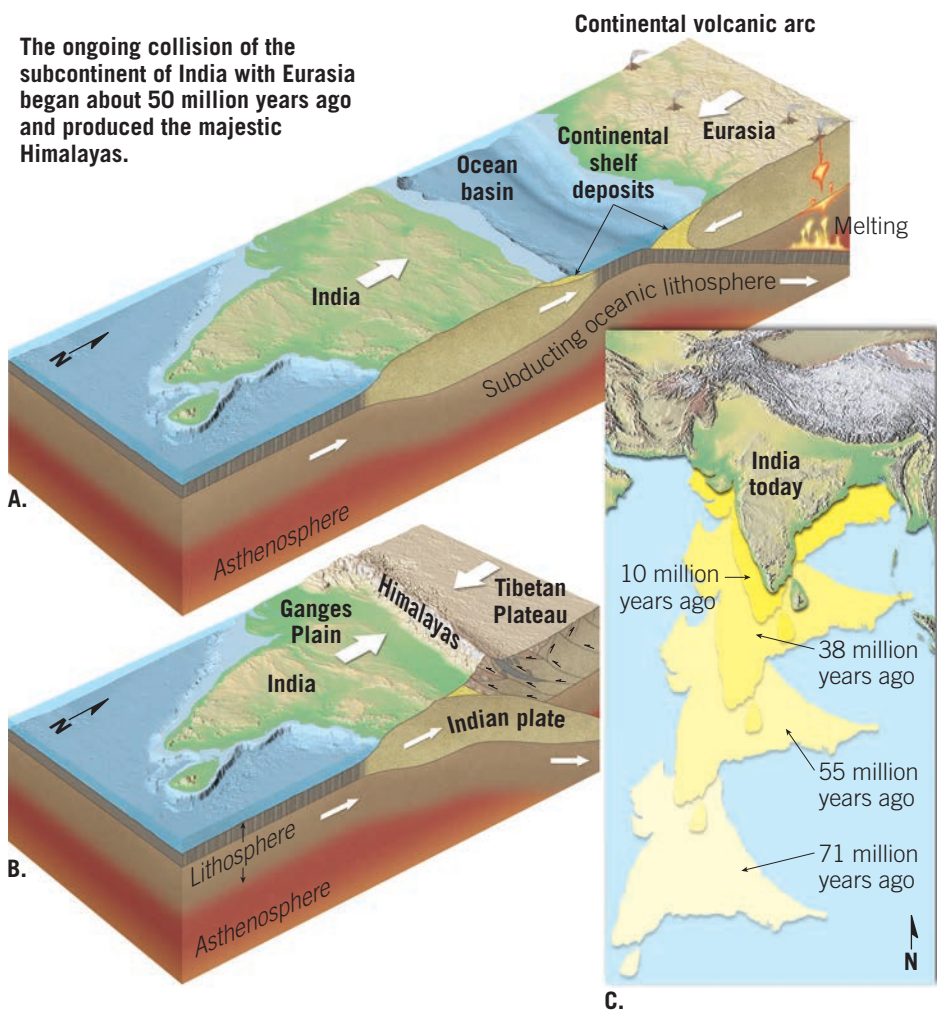
St. Pierre and killing an estimated 28,000 people. This chain of islands also includes Montserrat, where volcanic activity has occurred as recently as 2010.

Island arcs are typically simple structures made of numerous volcanic cones underlain by oceanic crust that is generally less than 20 kilometers (12 miles) thick. By contrast, some island arcs are more complex and are underlain by highly deformed crust that may reach 35 kilometers (22 miles) in thickness. Examples include Japan, Indonesia, and the Alaskan Peninsula. These island arcs are built on material generated by earlier episodes of subduction or on small slivers of continental crust that have rafted away from the mainland.

**SmartFigure 2.19**  
**The collision of India and Eurasia formed the Himalayas**  
 (https://goo.gl/9IDLvo)

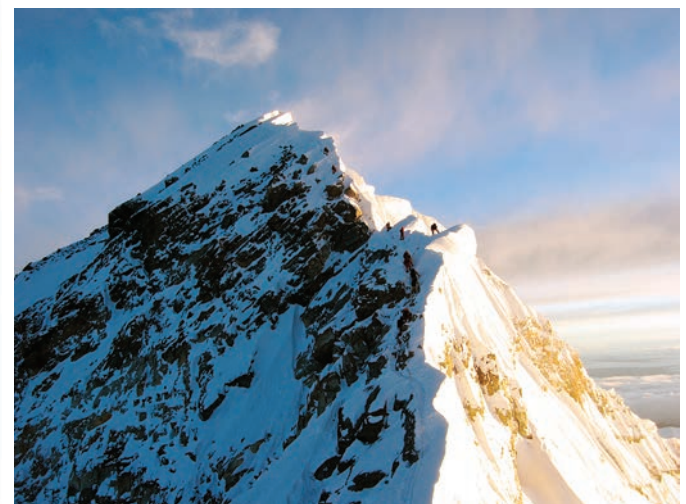


The ongoing collision of the subcontinent of India with Eurasia began about 50 million years ago and produced the majestic Himalayas.



## Continental–Continental Convergence

The third type of convergent boundary results when one landmass moves toward the margin of another because of subduction of the intervening seafloor (Figure 2.19A). Whereas oceanic lithosphere tends to be dense and sinks into the mantle, the buoyancy of continental material inhibits it from being subducted. Consequently, a collision between two converging continental fragments ensues (Figure 2.19B). This event folds and deforms the accumulation of sediments and sedimentary rocks along the continental margins as if they



(Photo by Peter Giovannini/Robert Harding)

had been placed in a gigantic vise. The result is the formation of a new mountain belt composed of deformed sedimentary and metamorphic rocks that often contain slivers of oceanic lithosphere.

Such a collision began about 50 million years ago, when the subcontinent of India rammed into Asia, producing the Himalayas—the most spectacular mountain range on Earth (Figure 2.19C). During this collision, the continental crust buckled and fractured and was generally shortened horizontally and thickened vertically. In addition to the Himalayas, several other major mountain systems, including the Alps, Appalachians, and Urals, formed as continental fragments collided. This topic will be considered further in Chapter 14.

## 2.6 Concept Checks

1. Explain why the rate of lithosphere production is roughly equal to the rate of lithosphere destruction.
2. Why does oceanic lithosphere subduct, while continental lithosphere does not?
3. What characteristic of a slab of oceanic lithosphere leads to the formation of deep-ocean trenches instead of shallow trenches?
4. What distinguishes a continental volcanic arc from a volcanic island arc?
5. Briefly describe how mountain belts such as the Himalayas form.

## 2.7 Transform Plate Boundaries

Describe the relative motion along a transform fault boundary and be able to locate several examples on a plate boundary map.

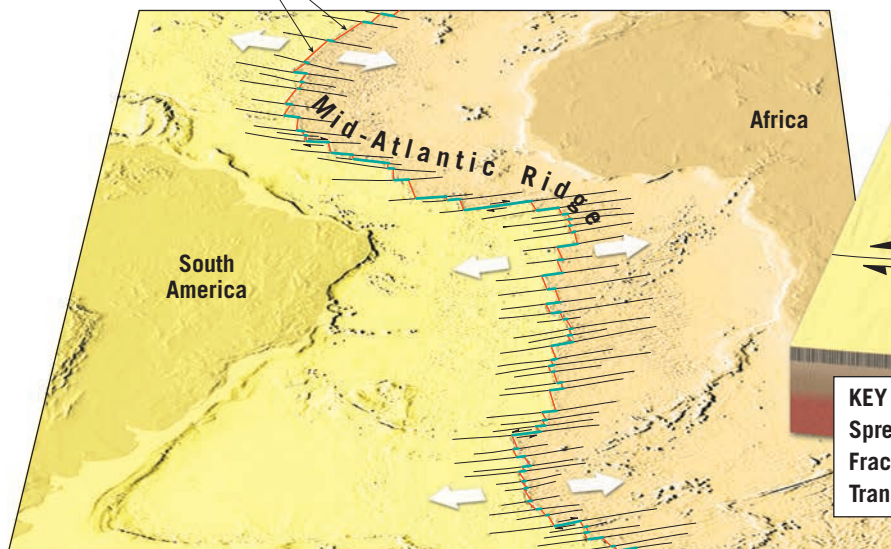
Along a **transform plate boundary**, also called a **transform fault**, plates slide horizontally past one another, without the production or destruction of lithosphere. The nature of transform faults was discovered in 1965 by Canadian geologist J. Tuzo Wilson, who proposed that these large faults connected two spreading centers (divergent boundaries) or, less commonly, two trenches (convergent boundaries). Most transform faults are found on the ocean floor, where they offset segments of the oceanic ridge system, producing a steplike plate margin (Figure 2.20A). Notice that the zigzag shape of the Mid-Atlantic Ridge in Figure 2.11 roughly reflects the shape of the original rifting that caused the breakup of the supercontinent of Pangaea. (Compare the shapes of the continental margins of the landmasses on both sides of the Atlantic with the shape of the Mid-Atlantic Ridge.)

### SmartFigure 2.20 Transform plate boundaries

(<https://goo.gl/SaoJ2o>)



Most transform faults offset segments of a spreading center, producing a zigzag-appearing plate margin.



A. The Mid-Atlantic Ridge, with its zigzag pattern, roughly reflects the shape of the rifting zone that resulted in the breakup of Pangaea.

B. Fracture zones are long, narrow scar-like features in the seafloor that are roughly perpendicular to the offset ridge segments. They include both the active transform fault and its “fossilized” trace.

