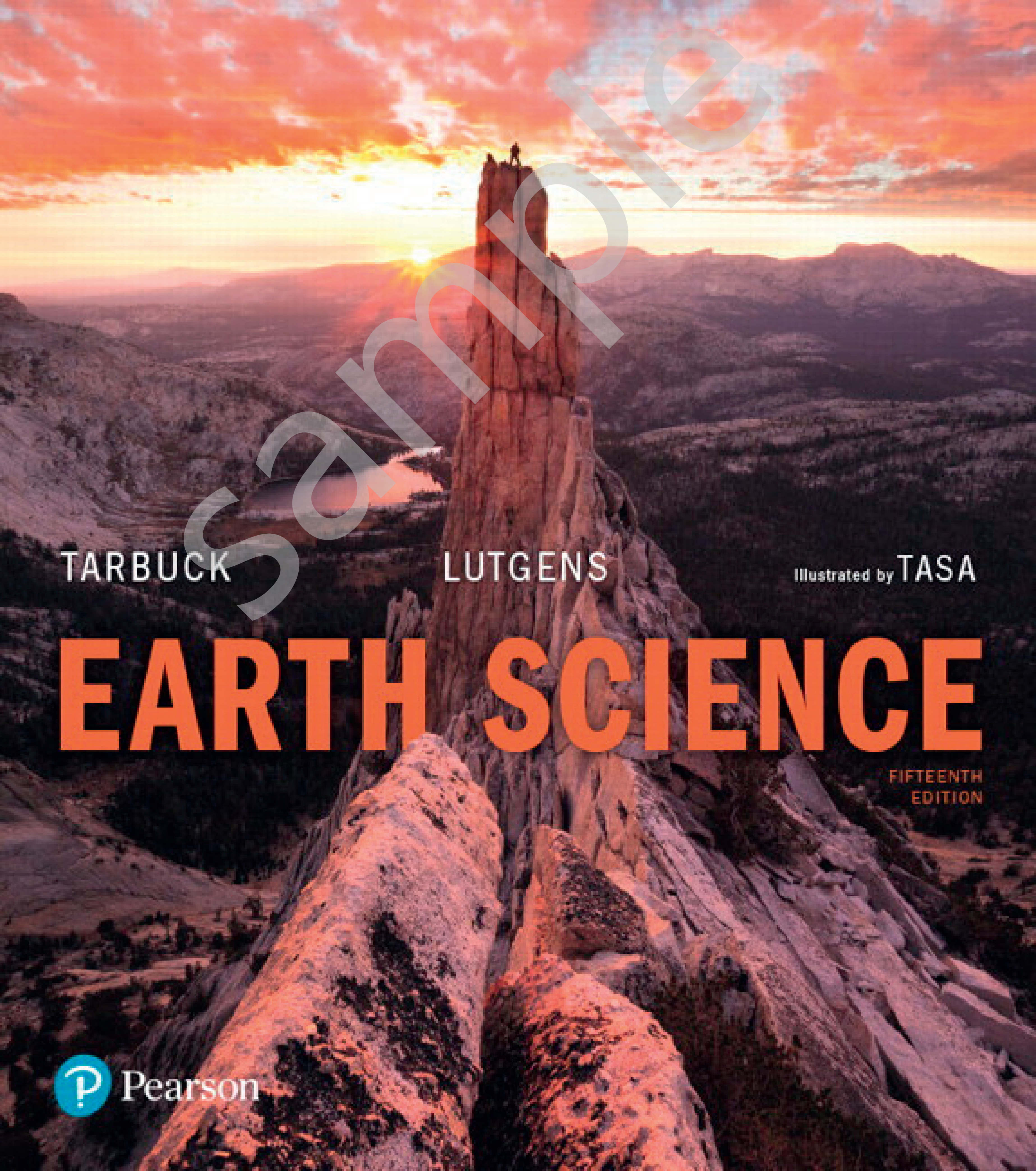


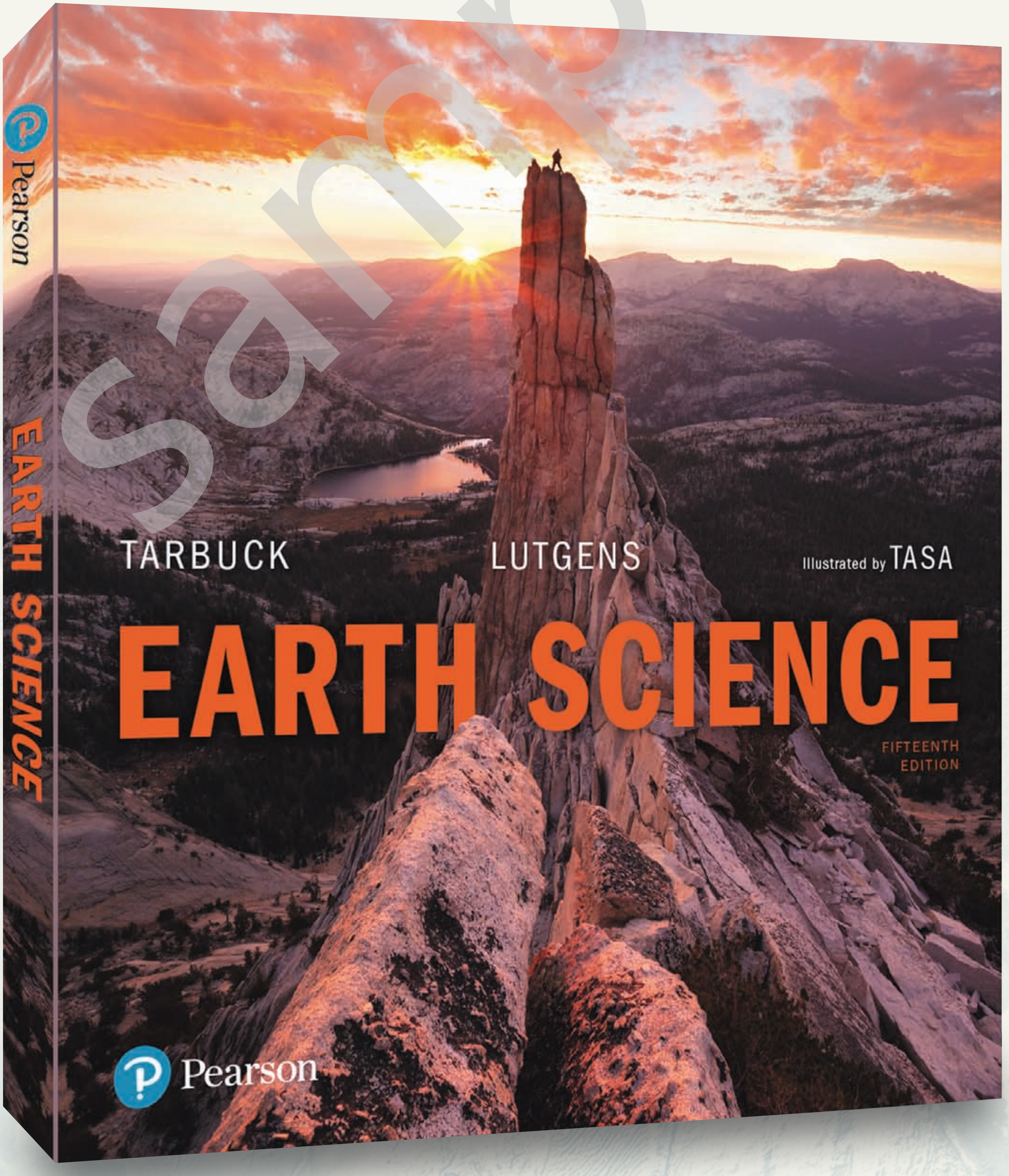
TARBUCK LUTGENS Illustrated by TASA

EARTH SCIENCE

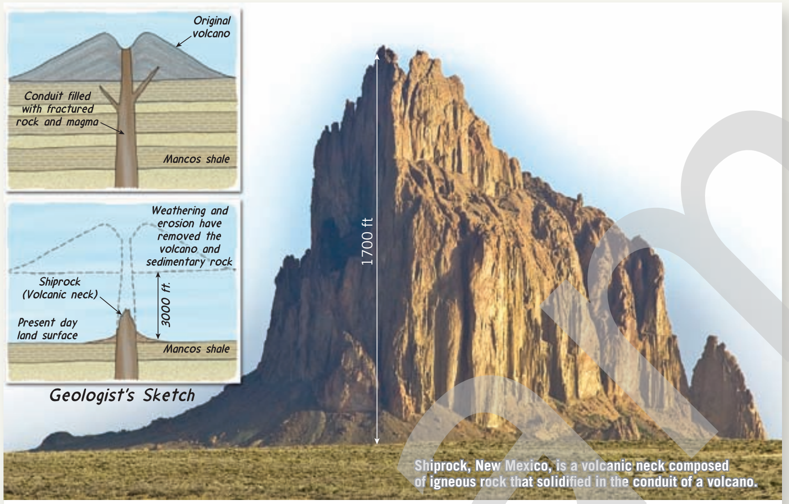
FIFTEENTH EDITION

Pearson

Use Dynamic Media to Bring Earth Science to Life



Bring Field Experience to Students’ Fingertips...



SmartFigure 6.26 Volcanic neck
Shiprock, New Mexico, is a volcanic neck that stands about 520 meters (1700 feet) high. It consists of igneous rock that crystallized in the vent of a volcano that has long since been eroded. (Photo by Dennis Tasa)

TUTORIAL
https://goo.gl/TjW5uh

How to download a QR Code Reader

Using a smartphone, students are encouraged to download a QR Code reader app from Google Play or the Apple App Store. Many are available for free. Once downloaded, students open the app and point the camera to a QR Code. Once scanned, they’re prompted to open the url to immediately be connected to the digital world and deepen their learning experience with the printed text.

NEW! QR Codes link to SmartFigures

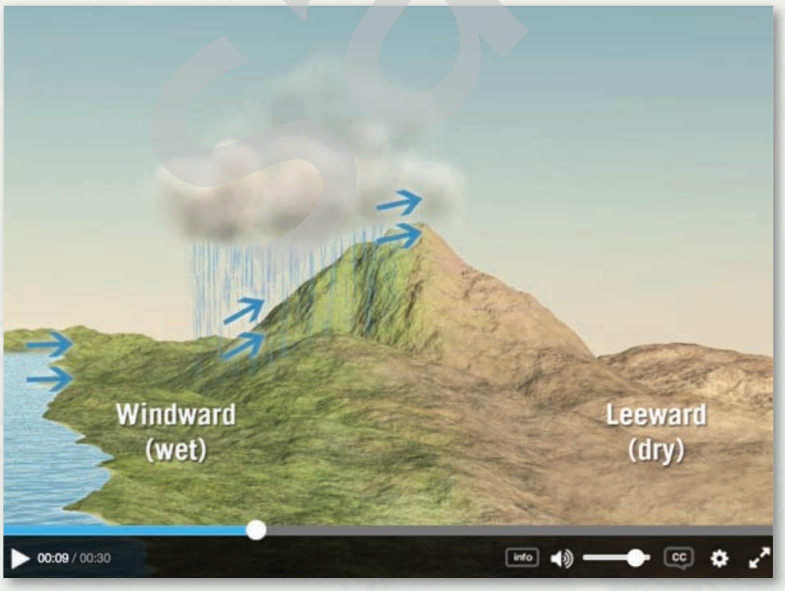
Quick Response (QR) codes link to over 238 videos and animations, giving readers immediate access to five types of dynamic media: Project Condor Quadcopter Videos, Mobile Field Trips, Tutorials, Animations, and Videos to help visualize physical processes and concepts. SmartFigures extend the print book to bring Earth Science to life.

NEW! SmartFigures: Project Condor Quadcopter Videos

Bringing Earth Science to life for students, three geologists, using a quadcopter-mounted GoPro camera, have ventured into the field to film 10 key geologic locations and processes. These process-oriented videos, accessed through QR codes, are designed to bring the field to the classroom and improve the learning experience within the text.

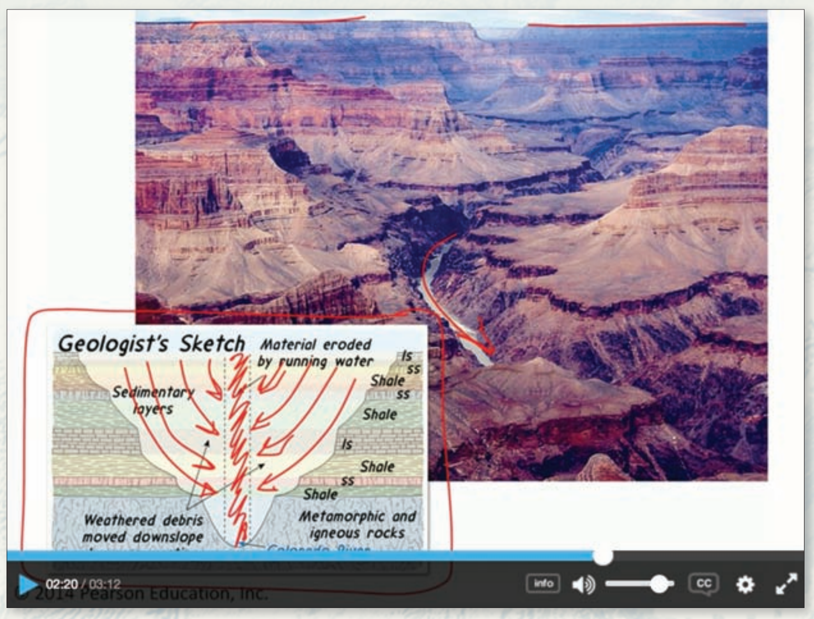
...with SmartFigures

NEW! SmartFigures: Mobile Field Trips
On each trip, students will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to visit and learn about iconic landscapes that relate to discussions in the chapter. These extraordinary field trips are accessed by using QR codes throughout the text. New Mobile Field Trips for the 15th edition include *Formation of a Water Gap, Ice Sculpts Yosemite, Fire and Ice Land, Dendrochronology*, and *Desert Geomorphology*.



NEW! SmartFigures: Animations
Brief animations created by text illustrator Dennis Tasa animate a process or concept depicted in the textbook's figures. With QR codes, students are given a view of moving figures rather than static art to depict how geologic processes move throughout time.

HALLMARK! SmartFigures: Tutorials
These brief tutorial videos present the student with a 3- to 4-minute feature (mini-lesson), most narrated and annotated by Professor Callan Bentley. Each lesson examines and explains the concepts illustrated by the figure. With over 150 SmartFigure Tutorials inside the text, students have a multitude of ways to enjoy art that teaches.



Clear Learning Path in Each Chapter

Each chapter in this 15th edition begins with *Focus on Concepts*: a set of learning objectives that correspond to the chapter's major sections. By identifying key knowledge and skills, these objectives help students prioritize the material. Each major section concludes with *Concept Checks* so that students can check their learning. Three end-of-chapter features continue the learning path. *Concepts in Review* are coordinated with the *Focus on Concepts* at the beginning of the chapter and with the numbered sections within the chapter, providing a readable and concise overview of key ideas, with photos, diagrams, and questions. The questions and problems in *Give It Some Thought* and *Examining the Earth System* challenge learners by requiring higher order thinking skills to analyze, synthesize, and apply the material.

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

6

Volcanoes and Other Igneous Activity

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:

- **6.1** Compare and contrast the 1980 eruption of Mount St. Helens with the most recent eruption of Kilauea, which began in 1983.
- **6.2** Explain why some volcanic eruptions are explosive and others are quiescent.
- **6.3** List and describe the three categories of materials extruded during volcanic eruptions.
- **6.4** Draw and label a diagram that illustrates the basic features of a typical volcanic cone.
- **6.5** Summarize the characteristics of shield volcanoes and provide one example of this type of volcano.
- **6.6** Describe the formation, size, and composition of cinder cones.
- **6.7** List the characteristics of composite volcanoes and describe how they form.
- **6.8** Describe the major geologic hazards associated with volcanoes.
- **6.9** List volcanic landforms other than shield, cinder, and composite volcanoes and describe their formation.
- **6.10** Compare and contrast these intrusive igneous structures: dikes, sills, batholiths, stocks, and laccoliths.
- **6.11** Summarize the major processes that generate magma from solid rock.
- **6.12** Explain how the global distribution of volcanic activity is related to plate tectonics.

Eruption of ash from Mount Bromo Volcano, 2011, in Java, Indonesia.
(Photo provided by Richard Roscoe/Stocktrek Images, Inc./Alamy Stock Photo)

2) Each chapter section concludes with ***Concept Checks***, a set of questions that is tied to the section's learning objectives and allows students to monitor their grasp of significant facts and ideas.

CONCEPT CHECKS 6.8

1. Describe pyroclastic flows and explain why they are capable of traveling great distances.
2. What is a lahar?
3. List at least three volcanic hazards besides pyroclastic flows and lahars.

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

6 **CONCEPTS IN REVIEW**

Volcanoes and Other Igneous Activity

6.1 Mount St. Helens Versus Kilauea

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

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

6.2 The Nature of Volcanic Eruptions

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

KEY TERMS: magma, lava, effusive eruption, viscosity, eruption column

- The two primary factors determining the nature of a volcanic eruption are the viscosity (resistance to flow) of the magma and its gas content. In general, magmas that contain more silica are more viscous, while those with lower silica content are more fluid. Temperature also influences viscosity. Hot lavas are more fluid, while cool lavas are more viscous.
- Basaltic magmas, which are fluid and have low gas content, tend to generate effusive (nonexplosive) eruptions. In contrast, silica-rich magmas (andesitic and rhyolitic), which are the most viscous and contain the greatest quantity of gases, are the most explosive.

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

USGS

EXAMINING THE EARTH SYSTEM

1 Speculate about some of the possible consequences that a great and prolonged increase in explosive volcanic activity might have on each of Earth's four spheres.

Jon A Helgason/Yay Micro/AGE Fotostock

4) ***Give It Some Thought*** and ***Examining the Earth System*** activities challenge learners by requiring higher-order thinking skills to analyze, synthesize, and apply chapter material.

GIVE IT SOME THOUGHT

1 Examine the accompanying photo and complete the following:
   a. What type of volcano is shown? What features helped you classify it as such?
   b. What is the eruptive style of such volcanoes? Describe the likely composition and viscosity of its magma.
   c. Which type of plate boundary is the likely setting for this volcano?
   d. Name a city that is vulnerable to the effects of a volcano of this type.

USGS

Exposing Students to Source Data and the Tools of Science

NEW! Each chapter of the 15th edition now concludes with new *Data Analysis* activities. These brief capstone activities send students outside of the book to online science tools and data sets from organizations such as NASA, NOAA, and USGS, empowering students to apply and extend chapter concepts and develop their data analysis and critical thinking skills

DATA ANALYSIS

Recent Volcanic Activity

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

ACTIVITIES

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

1. What information is displayed on this page?
2. Click on Criteria and Disclaimers. Which volcanoes are not displayed on this map?
3. In what areas is most of the volcanic activity concentrated?
4. Click on Weekly Report. List the new volcanic activity locations. List three ongoing volcanic activity locations.

Click on the name of a volcano under New Activity/Unrest.

5. Where is this volcano located? Be sure to include the city, country, volcanic region name, latitude, and longitude.
6. What is the primary volcanic type?
7. Do some investigating online and in your textbook. What are the key characteristics for this type of volcano?
8. Briefly describe the most recent activity. How was this activity observed?
9. What are the dates for the most recent activity?
10. Click on Eruptive History. What is the earliest date listed for this volcano?
11. Find this volcano on the map on the previous page. Is this volcano near a plate boundary? If so, between which plates? (Use your textbook to determine the location of plate boundaries.)

Go to the Volcanic Ash Advisory Center (VAAC) page at www.ssd.noaa.gov/VAAC/washington.html.

12. List the VAAC locations.
13. Click on Current Volcanic Ash Advisories. When was the most recent Volcanic Ash Advisory issued? What is the location of this advisory?
14. Which of the new volcanic activity locations from question 4 currently have Volcanic Ash Advisories? For each, what is the date of the most recent advisory?

DATA ANALYSIS

The Aral Sea

The Aral Sea was once the fourth-largest lake in the world. This lake has now decreased in size by more than 80%, and the southern Aral Sea has disappeared altogether. This has had devastating effects of the communities around the lake.

ACTIVITIES

Go to NASA's Earth Observatory site at http://earthobservatory.nasa.gov, select World of Change under Special Collections and scroll to select Shrinking Aral Sea. As you step forward in time, you will see the aerial extent of the Aral Sea.

1. When did the Aral Sea begin to shrink? Why did the Aral Sea begin to shrink?
2. How has the shrinking lake affected the quality of the water and farmland in the area?
3. How has the lake's reduction affected summer and winter temperatures?

Step forward in time to see changes in the Aral Sea. The green region is the lake, and the white region around the lake is salt deposits. You may also click on Google Earth to step through time and use the measuring tool to answer some of these questions.

4. What is the east–west distance between the easternmost edge of the Aral Sea in 1960 and the edge of the southern Aral Sea in 2000? 1960 and 2005? 1960 and 2010? 1960 and 2015?
5. What is the distance change between 2000 and 2005? 2005 and 2010? 2005 and 2015?
6. What is the average rate of distance change since 2000? (Remember that rate of change is the distance change divided by the number of years.)
7. Why was there a significant decline in the overall size of the southern Aral Sea after 2005?

Go to "Shrinking Aral Sea" on NASA's Earth Observatory site (https://earthobservatory.nasa.gov/Features/WorldOfChange/aral_sea.php).

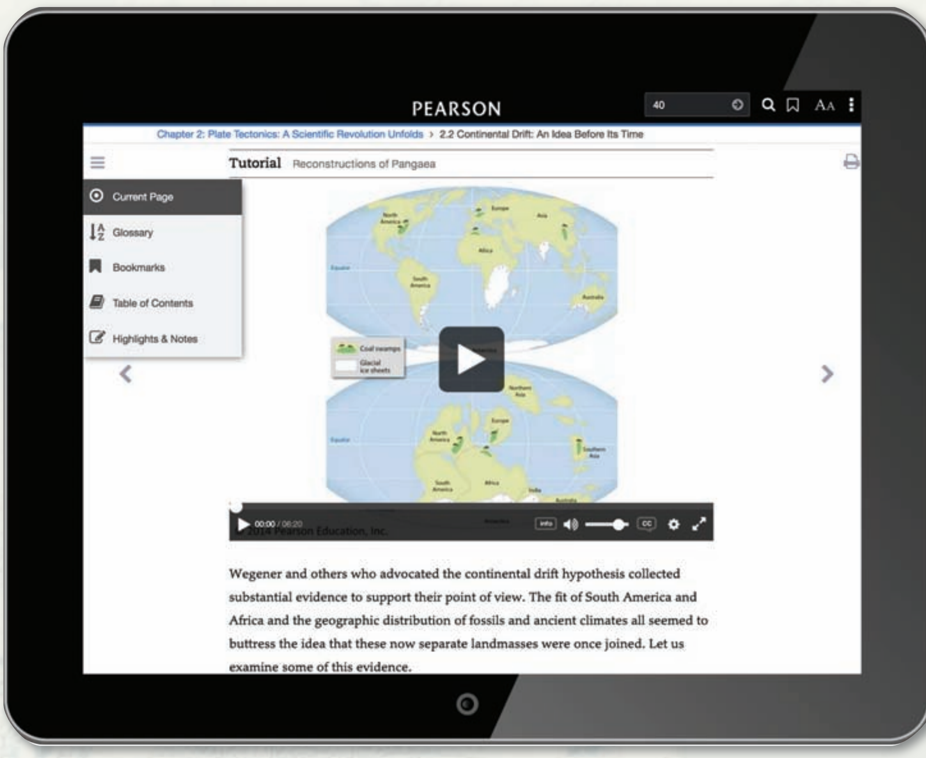
8. Compare this image to the Aral Sea images from Earth Observatory. Approximately when was the dust storm image taken? (Giving a range of years is fine.)
9. From which direction is the wind blowing?
10. How long is the dust storm at its longest distance? How wide is the dust storm at its widest distance?
11. Which towns are in the path of this dust storm?

Continuous Learning
Before, During, and After Class

BEFORE CLASS

Mobile Media and Reading Assignments Ensure Students Come to Class Prepared

Updated! Dynamic Study Modules help students study effectively by continuously assessing student performance and providing practice in areas where students struggle the most. Each Dynamic Study Module, accessed by computer, smartphone, or tablet, promotes fast learning and long-term retention.



NEW! Interactive eText 2.0 gives students access to the text whenever they can access the internet. eText features include:

- Now available on smartphones and tablets.
- Seamlessly integrated videos and other rich media.
- Accessible (screen-reader ready).
- Configurable reading settings, including resizable type and night reading mode.
- Instructor and student note-taking, highlighting, bookmarking, and search.

Pre-Lecture Reading Quizzes are easy to customize and assign

Reading Quiz Questions ensure that students complete the assigned reading before class and stay on track with reading assignments. Reading Questions are 100% mobile ready and can be completed by students on mobile devices.

with MasteringGeology™

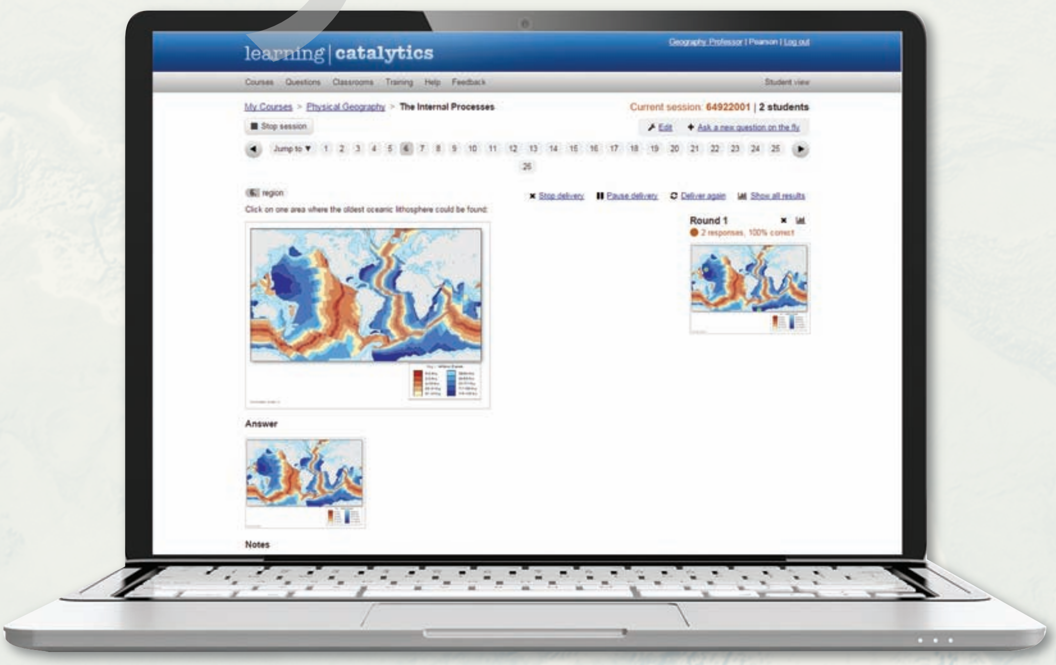
DURING CLASS

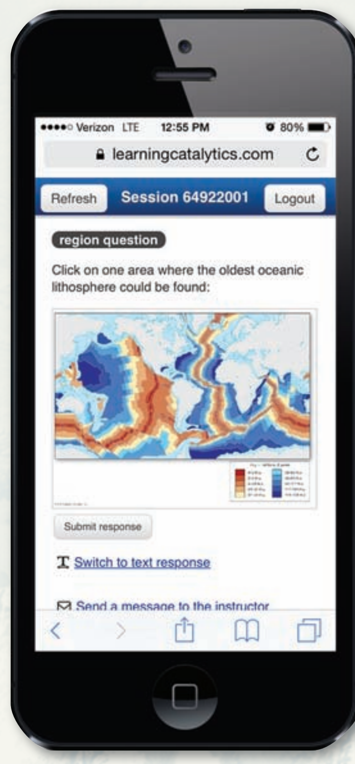
Engage students with Learning Catalytics

What has teachers and students excited? Learning Catalytics, a 'bring your own device' student engagement, assessment, and classroom intelligence system, allows students to use their smartphone, tablet, or laptop to respond to questions in class. With Learning Catalytyics, you can:

- Assess students in real time using open-ended question formats to uncover student misconceptions and adjust lecture accordingly.
- Automatically create groups for peer instruction based on student response patterns, to optimize discussion productivity.

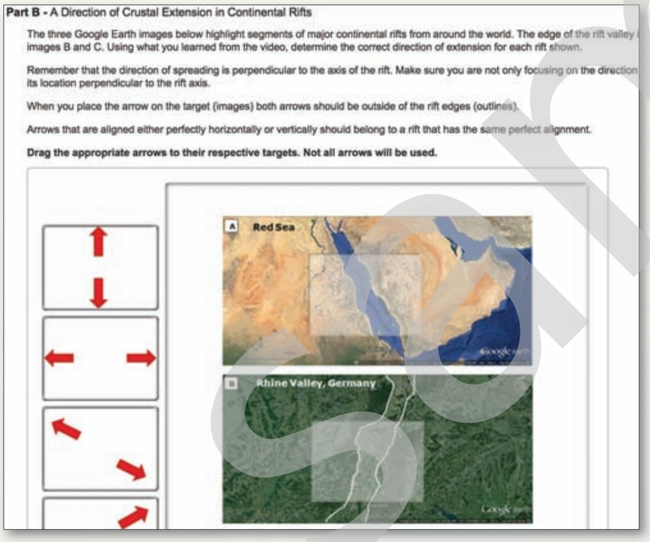
> ***"My students are so busy and engaged answering Learning Catalytics questions during lecture that they don't have time for Facebook."***
>
> Declan De Paor, Old Dominion University



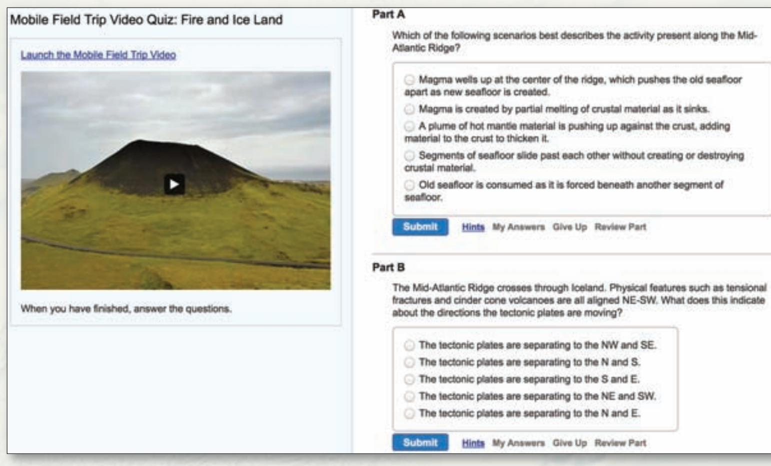


AFTER CLASS

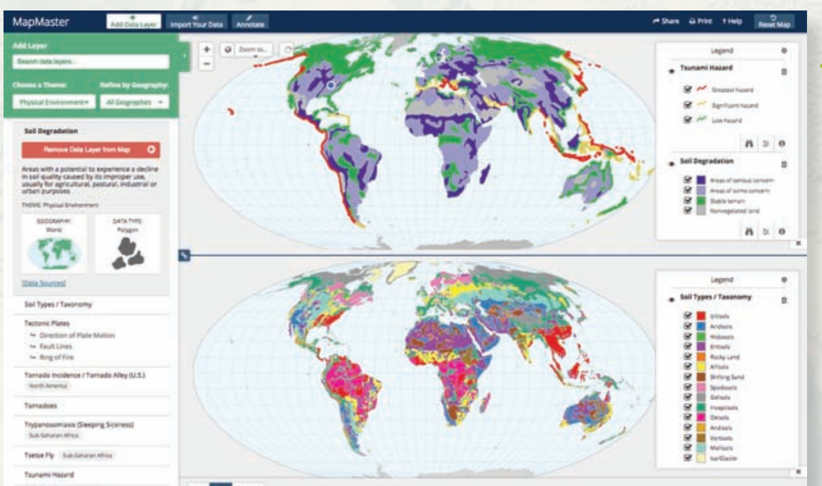
Easy to Assign, Customizable, Media-Rich, and Automatically Graded Assignments



NEW! Project Condor Quadcopter Videos
A series of quadcopter videos with annotations, sketching, and narration help improve the way students learn about monoclines, streams and terraces, and so much more. In MasteringGeology™, these videos are accompanied by assessments to test student understanding.

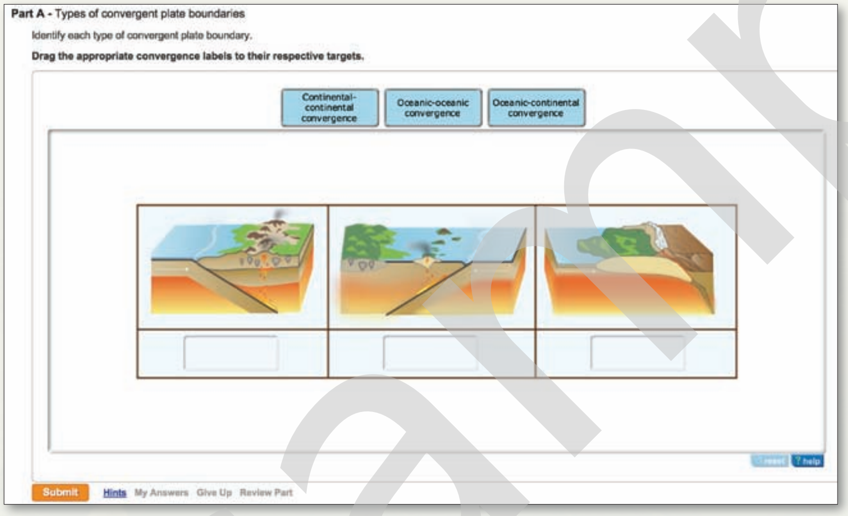


NEW! 24 Mobile Field Trips take students to iconic locations with Michael Collier in the air and on the ground to learn about places that relate to concepts in the chapter. In Mastering, these videos are accompanied by auto-gradable assessments that will track what students have learned.



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

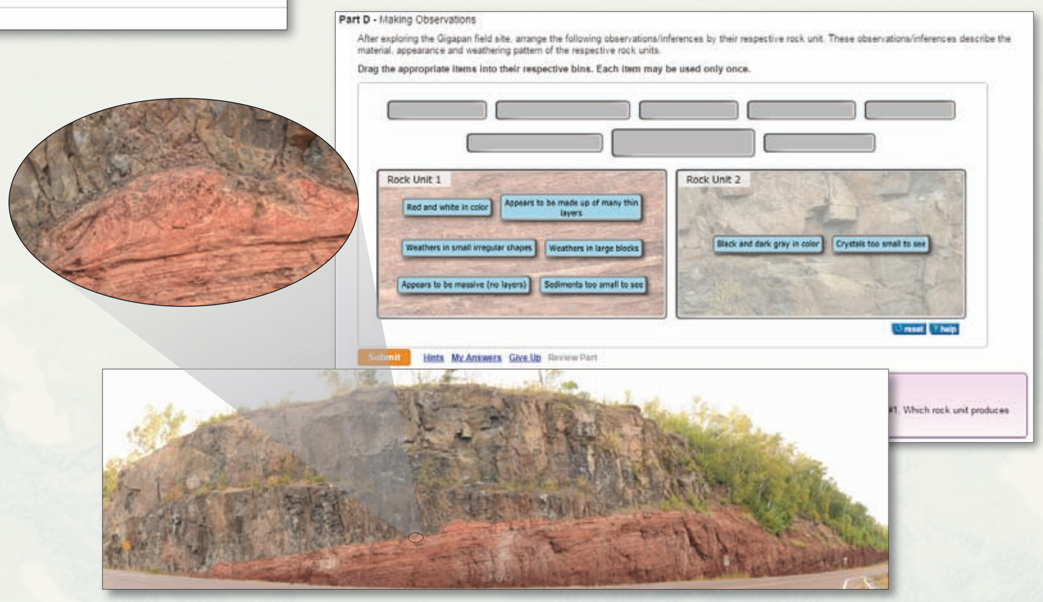
www.masteringgeology.com

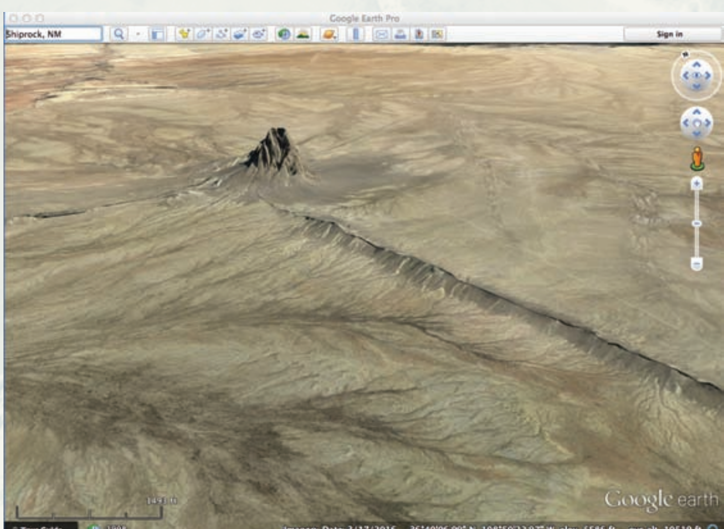


GeoTutors

These coaching activities help students master the most challenging physical geoscience concepts with highly visual, kinesthetic activities focused on critical thinking and application of core geoscience concepts.

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

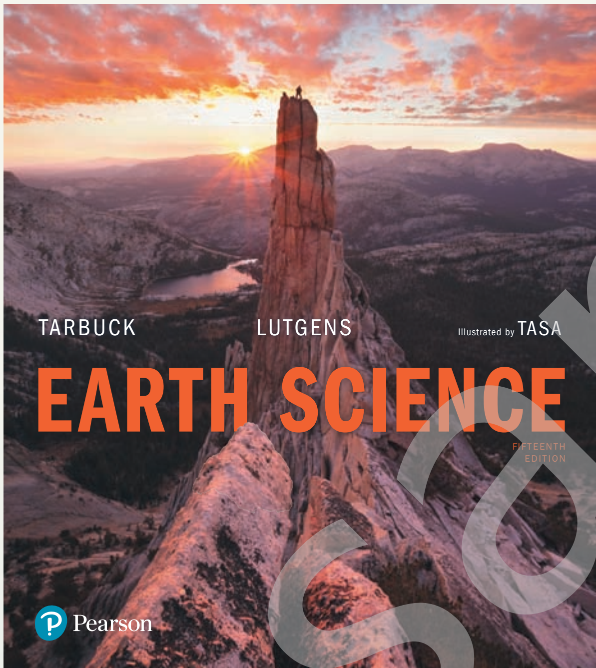




Encounter Activities

Using Google Earth™ to visualize and explore Earth's physical landscape, Encounter activities provide rich, interactive explorations of geology and Earth Science concepts. Dynamic assessments include questions related to core geoscience concepts. All explorations include corresponding Google Earth KMZ media files, and questions include hints and specific wrong-answer feedback to help coach students toward mastery of the concepts.

Resources for YOU, the Instructor



MasteringGeology™ provides everything you need to prep for your course and deliver a dynamic lecture, all in one convenient place. Resources include:

LECTURE PRESENTATION ASSETS FOR EACH CHAPTER

- PowerPoint Lecture Outlines
- PowerPoint Clicker Questions and Jeopardy-style quiz show questions
- All book images and tables in JPEG and PowerPoint formats

TEST BANK

- The Test Bank in Microsoft Word format
- Computerized Test Bank, which includes all the questions from the printed test bank in a format that allows you to easily and intuitively build exams and quizzes.

TEACHING RESOURCES

- *Instructor Resource Manual* in Microsoft Word and PDF formats
- Full access to eText 2.0
- Pearson Community Website (https://communities.pearson.com/northamerica/s/)

Measuring Student Learning Outcomes?

All MasteringGeology assignable content is tagged to learning outcomes from the book, the Earth Science Literacy Initiatives “Big Ideas”, and Bloom’s Taxonomy. You also have the ability to add your own learning outcomes, helping you track student performance against your learning outcomes. You can view class performance against the specified learning outcomes and share those results quickly and easily by exporting to a spreadsheet.

EARTH SCIENCE

FIFTEENTH
EDITION

TARBUCK LUTGENS Illustrated by TASA

EARTH SCIENCE

FIFTEENTH EDITION

Pearson

330 Hudson Street, NY NY 10013

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Along with developing and exploring digital solutions to our market's needs, Pearson has a strong commitment to achieving carbonneutrality. As of 2009, Pearson became the first carbon- and climate-neutral publishing company, having reduced our absolute carbon footprint by 22% since then. Pearson has protected over 1,000 hectares of land in Columbia, Costa Rica, the United States, the UK and Canada. In 2015, Pearson formally adopted The Global Goals for Sustainable Development, sponsoring an event at the United Nations General Assembly and other ongoing initiatives. Pearson sources 100% of the electricity we use from green power and invests in renewable energy resources in multiple cities where we have operations, helping make them more sustainable and limiting our environmental impact for local communities.

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BRIEF CONTENTS

CONTENTS

SmartFigure Media

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

CONDOR VIDEO
Continental Rifting
https://goo.gl/RXv8qH

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Chapter 4

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Chapter 18

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Chapter 24

PREFACE

Earth Science, 15th edition, is a college-level text designed for an introductory course in Earth Science. It consists of seven units that emphasize broad and up-to-date coverage of basic topics and principles in geology, oceanography, meteorology, and astronomy. The book is intended to be a meaningful, nontechnical survey for undergraduate students who may have a modest science background. Usually these students are taking an Earth Science class to meet a portion of their college's or university's general requirements.

In addition to being informative and up-to-date, *Earth Science*, 15th edition, strives to meet the need of beginning students for a readable and user-friendly text and a highly usable "tool" for learning basic Earth Science principles and concepts.

New and Important Features

This 15th edition is an extensive and thorough revision of *Earth Science* 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 Science* 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.
- **Revised organization** In the geology portion of the text, the unit on *Forces Within* now precedes the unit on *Sculpting Earth's Surface*. This was done in response to many users and reviewers of previous editions who wanted the theory of plate tectonics presented earlier in the text because of the unifying role it plays in our understanding of planet Earth. Of course, each unit is basically independent of the others and can be taught in any order desired by the instructor.
- **SmartFigures that make *Earth Science* much more than a traditional textbook.** Through its many editions, an important strength of *Earth Science* has always been clear, logically organized, and well-illustrated explanations. Now, complementing and reinforcing this strength are a series of SmartFigures. Simply by scanning the Quick Response (QR) code next to a SmartFigure with a mobile device, students can follow hundreds of unique and innovative avenues that will increase their insight and understanding of important ideas and concepts. SmartFigures are truly art that teaches! This fifteenth edition of *Earth Science* has more than 220 SmartFigures, of five different types, including many new videos and animations:

  1. **SmartFigure Tutorials.** Each of these 3- to 4-minute features, most 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 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 *Project Condor* videos take you to locations in the American West. By coupling aerial footage acquired by a drone quadcopter aircraft with ground-level views, effective narratives, annotations, and helpful animations, these videos transport you into the field and engage you in real-life case studies.
  4. **SmartFigure Animations.** These animations and accompanying narrations bring art to life, illustrating and explaining difficult-to-visualize topics and ideas more effectively than static art alone.
  5. **SmartFigure Videos.** Rather than providing a single image to illustrate an idea, these figures include short video clips that help illustrate such diverse subjects as mineral properties and the structure of ice sheets.

- **Revised active learning path.** *Earth Science* is designed for learning. Here is how it is accomplished. Each chapter has been designed to be self-contained so that materials may be taught in a different sequence, according to the preference of the instructor or the needs of the laboratory.

  1. 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.
  2. 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.
  3. *Concepts in Review* is an end-of-chapter feature that coordinates with the *Focus on Concepts* at the start of the chapter and with the numbered sections within the chapter. It is a readable and concise overview of key ideas, with photos, diagrams, and questions that also help students focus on important ideas and test their understanding of key concepts.
  4. The questions and problems in *Give It Some Thought* and *Examining the Earth System* challenge learners by involving them in activities that require higher-order thinking skills, such as application, analysis, and synthesis of chapter material. In addition, the activities in *Examining the Earth System* are intended to develop an awareness of and appreciation for some of the Earth system's many interrelationships.

5. The end-of-chapter review material now includes an all-new capstone activity called *Data Analysis* that sends students online to use a variety of interactive science resources and data sets from sources such as USGS, NASA, and NOAA to use various tools to perform data analysis and critical thinking tasks.

- **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. Overall, the *Earth Science* 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 (Tutorials, Condor Videos, Animation, Mobile Field Trips, Videos) activities, GigaPan® activities, "Encounter" Earth activities using Google Earth™ activities, GeoTutor activities on the most challenging topics in the geosciences, Geoscience Animation activities, and more. MasteringGeology™ also includes all instructor resources, a robust Study Area with resources for students, and an optional eText version of the textbook.

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Used each year by over 3 million science students, the Mastering platform is the most effective and widely used online tutorial, homework, and assessment system for the sciences. Now available with *Earth Science*, 15th edition, **MasteringGeology™** offers tools for use before, during, and after class:

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

For Instructors

Instructor Resource Manual (Download Only) The *Instructor Resource Manual* has been designed to help seasoned and new instructors alike, offering the following sections in each chapter: an introduction to the chapter, outline, learning objectives/focus on concepts; teaching strategies; teacher resources; and answers to *Concept Checks* and *Give It Some Thought* questions from the textbook. www.pearsonhighered.com/irc

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 the test in a variety of customized formats. This 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 Literacy Initiatives 'Big Ideas', and the Pearson Science Global Outcomes to help instructors better map the assessments against both broad and specific teaching and learning objectives. The Test Bank is also available in Microsoft Word and can be imported into Blackboard, and other LMS. www.pearsonhighered.com/irc

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- Word and PDF versions of the *Instructor Resource Manual*.

For Students

***Applications and Investigations in Earth Science*, 9th Edition (0134746244)**

This manual can be used for any Earth Science lab course, in conjunction with any text. This versatile and adaptable collection of introductory-level laboratory experiences goes beyond traditional offerings to examine the basic principles and concepts of the Earth sciences. With integration of mobile-ready Pre-Lab Videos, the **Ninth Edition** minimizes the need for faculty instruction in the lab, freeing instructors to interact directly with students. Widely praised for its concise coverage and dynamic illustrations by Dennis Tasa, the text contains twenty-three step-by-step exercises that reinforce major topics in geology, oceanography, meteorology, and astronomy.

This edition includes a new lab exercise on Volcanoes, and incorporates MasteringGeology™–the most complete, easy-to-use, and engaging tutorial and assessment tool available. MasteringGeology includes a variety of highly visual, applied, kinesthetic, and automatically-gradable activities to support each lab, as well as a robust Study Study Area with a variety of media and reference resources, and an eText version of the lab manual.

***Laboratory Manual in Physical Geology*, 11th Edition** by the American Geosciences Institute and the National Association of Geoscience Teachers, edited by Vincent Cronin, illustrated by Dennis G. Tasa (0134446607)

This user-friendly, best-selling lab manual examines the basic processes of geology and their applications to everyday life. Featuring contributions from more than 170 highly regarded geologists and geoscience educators, along with an exceptional illustration program by Dennis Tasa, *Laboratory Manual in Physical Geology*, 11^{th} edition, offers an inquiry- and activities-based approach that builds skills and gives students a more complete learning experience in the lab. Pre-lab videos linked from the print labs introduce students to the content, materials, and techniques they will use each lab. These teaching videos help TAs prepare for lab setup and learn new teaching skills. Now with more than 10 new lab activities, the lab manual is also available in MasteringGeology with Pearson eText, allowing teachers to use activity-based exercises to build students' lab skills.

***Dire Predictions: Understanding Global Climate Change*, 2nd Edition** by Michael Mann, Lee R. Kump (0133909778)

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

Acknowledgments

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- As you read this text, you will see dozens of extraordinary photographs by Michael Collier. Most are aerial shots taken from his 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 Geosciences 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 Science*, 15^{th} edition. Thanks, Michael.
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Ed Tarbuck
Fred Lutgens

EARTH SCIENCE 15E: MAJOR CHANGES IN THIS EDITION

Global:

- Units 2 and 3 of the book are transposed, so that tectonics and related phenomena are now covered before surface processes.
- Many new SmartFigures are added, including three new types of SmartFigures: *Project Condor* Videos, Animations (many by Dennis Tasa), and Videos.
- Much of the Tasa art is improved with bolder labels or better placement of labels and text.
- New *Data Analysis* activities now conclude each chapter.

Chapter 1:

- The text description of the standard scientific method is replaced with the pictorial version in Figure 1.8.
- In "The Solar System Forms," the description of the collapse of the protosolar nebula is revised and updated.
- Section 1.4, "Earth as a System," now includes the sections on Earth's spheres (hydrosphere, geosphere, biosphere, atmosphere), formerly covered in their own section.
- The 14^{th} edition section that introduced Earth's structure and the basic features of plate tectonics ("A Closer Look at the Geosphere") has been eliminated. In its place, the discussion of the geosphere in Section 1.4 is expanded to introduce Earth's layered structure.
- Section 1.5, "The Face of Earth," is reorganized to cover the ocean basins before the continents, rather than the reverse.
- The 14^{th} edition *GeoGraphics* on world population is eliminated.
- Four new figures are added (Figures 1.1, 1.2, 1.8, 1.18), and three Tasa figures are substantively altered (Figs 1.9. 1.14, 1.16). Six 14^{th} edition figures are deleted (Figures 1.1, 1.3, 1.16–1.19).
- One *Give It Some Thought* question is modified; two 14^{th} edition questions are deleted. One *Examining the Earth System* question is deleted.

Chapter 2:

- In Section 2.4, "Properties of Minerals," the distinction between diagnostic and ambiguous properties is added at the start.
- In Section 2.5, "Mineral Groups," the treatment of the silicate groups is extensively revised. The opening paragraphs of the section "Important Nonsilicate Minerals" are also revised.
- The title of Section 2.6 is changed to "Minerals: A Nonrenewable Resource" from "Natural Resources."
- Two new figures are added: Figure 2.25 and Figure 2.32 (which replaces 14^{th} edition Table 2.1 and Figure 2.31). Six figures are substantively revised: 2.5, 2.8, 2.9, 2.11, 2.12, 2.24; *GeoGraphics* 2.1 is also revised.
- One *Give It Some Thought* question is added and one modified; two 14^{th} edition questions are deleted.

Chapter 3:

- Section "Silica Content as an Indicator of Composition" is removed (in Section 3.2).
- Section "Detrital sedimentary rocks" in Section 3.3 is significantly revised.
- Section "Other Metamorphic Rocks" is added at the end of Section 3.4.
- Section "Nonmetallic Mineral Resources" in Section 3.5 is substantially revised.
- Section "Energy Resources" in Section 3.5 is updated and substantially revised, including the addition of Figure 3.38 to illustrate hydraulic fracturing.
- Three new figures are added: Figures 3.6, 3.22, and 3.38. Eight figures are altered substantively: 3.7, 3.16–3.18, 3.20, 3.21, 3.30, and 3.34.
- One *Give It Some Thought* question is added and one modified; two 14^{th} edition questions are deleted.

Chapter 4:

- The section "Rigid Lithosphere Overlies Weak Asthenosphere" is revised to emphasize the importance of density differences (in Section 4.3).
- The treatment of mantle plumes is updated ("Evidence: Mantle Plumes and Hot Spots" in Section 4.8).
- "Forces that Drive Plate Motion" omits mantle drag (in Section 4.10).
- "Models of Plate–Mantle Convection" in Section 4.10 is updated.
- Two 14^{th} edition figures are deleted (Figures 7.9, 7.11). Fourteen figures are altered substantively: 4.9–4.11, 4.14, 4.15, 4.18, 4.19, 4.21, 4.22, 4.29–4.31, 4.35, and 4.36.
- One *Give It Some Thought* question is added; two are augmented with new question parts.

Chapter 5:

- The chapter introduction describes the 2015 Nepal earthquake.
- The section "Faults and Large Earthquakes" is reorganized to discuss convergent boundaries before transform boundaries, and both discussions are substantially revised. (In Section 5.1.)
- A revised and expanded section "Fault Rupture and Propagation" replaces the 14^{th} edition section "Fault Rupture" (in Section 5.1).
- Section 5.3, "Locating the Source of an Earthquake," is new to the chapter; in the 14^{th} edition, this topic was handled by the *GeoGraphics* "Finding the Epicenter of an Earthquake" (now omitted).
- The section "Intensity Scales" in Section 5.3 now covers the USGS "Did You Feel It?" Community Internet Intensity maps.

- Section 5.6 now covers intraplate as well as plate-boundary earthquakes. (In the 14th edition, intraplate earthquakes were handled in the *GeoGraphics* "Historic Earthquakes East of the Rockies," now omitted.)
- In Section 5.7, the discussion of earthquake prediction and forecasting is extensively revised and updated. A new section "Minimizing Earthquake Hazards" is added, including discussion of earthquake-resistant structures and earthquake warning systems.
- In Section 5.8, the section "Probing Earth's Interior: "Seeing" Seismic Waves" is significantly revised, as are portions of "Earth's Layered Structure."
- Seven new figures are added: 5.13 and 5.14 (which replace the 14th edition *GeoGraphics* "Finding the Epicenter of an Earthquake"); 5.31 and 5.32 (which replace the 14th edition *GeoGraphics* "Historic Earthquakes East of the Rockies"); 5.16, 5.36, and 5.37. Two 14th edition figures are deleted (8.1 and 8.14), in addition to the two *GeoGraphics* just mentioned.
- Six figures are altered substantively: 5.5, 5.18, 5.19, 5.26, 5.35, and 5.38, as well as *GeoGraphics* 5.1.
- Two *Give It Some Thought* questions are added and one is revised; six questions from the 14th edition are deleted.

Chapter 6:

- Considerable editing is done throughout to improve clarity.
- Section 6.2 is substantially rewritten, particularly the sections "Magma: Source Materials for Volcanic Eruptions" and "Effusive Versus Explosive Eruptions."
- More emphasis is put on the fact that most volcanism is submarine (for instance, first paragraph under "Lava Flows" in Section 6.3; the expanded Figure 6.8 on pillow lavas; and the opening paragraph of Section 6.11.)
- Some descriptive text is deleted from the end of "Kilauea: Hawaii's Most Active Volcano" in favor of the *GeoGraphics* on the East Rift Zone (end of Section 6.5)
- 2014 Mount Ontaki incident is added to section on pyroclastic flows, in place of 1991 Mt Unzen flow.
- The section on the destruction of Pompeii is added to Section 6.8; the *GeoGraphics* on this topic is removed.
- The *Eye on Earth* feature on the 1991 Mt Pinatubo eruption is replaced with one about the 2015 eruption of Mount Sinabung.
- The discussion of eruption mechanism for Yellowstone-type caldera eruptions is updated and tightened.
- The discussion of kimberlite and related pipes is deleted from the end of Section 6.9.
- Extensive editing for clarity and readability is done in the section "Decrease in Pressure: Decompression Melting" (in Section 6.11).
- In Section 6.12, volcanism at divergent boundaries is covered before that at convergent boundaries.
- A paragraph on intraplate volcanism associated with mantle plumes is added at the end of Section 6.12.
- Three new figures are added (6.19, 6.31, 6.39); six figures are substantively altered (6.3, 6.8, 6.12, 6.20, 6.21, 6.33, 6.34); two *GeoGraphics* are deleted.
- Three *Give It Some Thought* questions are replaced with new questions; two 14th edition questions are deleted. One *Examining the Earth System* question is deleted.

Chapter 7:

- Section 7.1 is substantially rewritten to improve clarity and effectiveness, including revised treatment of stress and strain, the types of rock deformation, and the factors that affect deformation style.
- The distinction between faults and joints is now covered at the start of Section 7.3.
- The treatment of joints is substantially revised ("Joints" in Section 7.3).
- The description of thrust faulting in the formation of the Himalayas is revised for clarity (paragraph 4 under "The Himalayas" in Section 7.6).
- The description of isostatic balance and its effects is substantially rewritten to improve clarity (Section 7.7).
- More than half of the 35 numbered figures are either substantively revised (19 figures) or new (3 figures). New: 7.4, 7.5, 7.22. Substantively revised: 7.3, 7.6–7.8, 7.12, 7.14, 7.16–7.19, 7.20, 7.21, 7.23–7.25, 7.27, 7.29, 7.30, 7.32. *Eye on Earth* 7.1 and *GeoGraphics* 7.1 are also revised. Three 14th edition figures are omitted: 10.4, 10.18, and 10.20.
- One new *Give It Some Thought* questions is added; three 14th edition questions are deleted.

Chapter 8:

- "Mass movement" is used throughout the chapter in place of "mass wasting."
- The section "Differential Weathering" in Section 4.2 now includes the content of the 14th edition Section 4.3, "Rates of Weathering"; the concept of differential weathering now introduces the section.
- In Section 8.4, "Controls of Soil Formation," the section on climate is revised and is placed second rather than third.
- Section 8.5, "Describing and Classifying Soils," includes the topics of the 14th edition Sections 4.6 ("The Soil Profile") and 4.7 ("Classifying Soils").
- In Section 8.6, erosion by water and by wind are now covered in one section.
- The section "Controls and Triggers of Mass Movement" in Section 8.7 is significantly revised. The Oso, Washington slide is added as an example of water as a trigger.
- Section 8.8, "Types of Mass Movement," includes the topics of the 14th edition Sections 4.11 ("Classifying Mass Wasting Processes"), 4.12 ("Rapid Forms of Mass Wasting"), and 4.13 ("Slow Forms of Mass Wasting").
- Within Section 8.8, the treatment of the mechanism for long-runout landslides is updated (section "Rate of Movement" in Section 8.8);

the section "Debris Flow" provides a more unified treatment of dry versus wet debris flows and omits the Nevado del Ruiz lahars; and the final paragraph on liquefaction is omitted (because it is treated in Chapter 5, which now precedes this chapter).

- One figure is replaced with a new version (Fig. 8.23); four figures are revised substantively (Figs 8.10, 8.19, 8.28, 8.29, and also *Eye on Earth* 8.3); two 14th edition figures are deleted (Figs 4.20, 4.28).
- Two 14th edition *Give It Some Thought* questions are deleted.

Chapter 9:

- "Stream Erosion," now covers corrosion as a means of forming bedrock channels in soluble rocks. Also, in "Suspended Load," Figure 9.14 added to help explain the significance of settling velocity. (Both in Section 9.4.)
- Coverage of stream terraces (including Figure 9.22) is added at the end of Section 9.6.
- Section 9.7 now covers intermittent growth of alluvial fans in dry area
- A discussion of the April 2011 Mississippi flooding us added at the start of "Causes of Floods" in Section 9.8; the description of the1889 dam burst on the Little Conemaugh River is removed.
- The section "Artificial Levees" in Section 9.8 is revised to describe the use of floodways to protect levees.
- Section 9.10 is reorganized to cover wells and artesian systems before springs.
- Seven new figures are added (9.4, 9.8, 9.14, 9.22, 9.26, 9.27, 9.40); three figures are substantively revised (9.2, 9.21, 9.35); five 14th edition figures are deleted (5.1, 5.16, 5.24, 5.25, 5.38). One *GeoGraphics* and one *Eye on Earth* are also deleted.
- One new *Give It Some Thought* question is added; two 14th edition questions are deleted. One *Examining the Earth System* question is added, and four are deleted.

Chapter 10:

- The section on observing and measuring the movement of glacial ice is revised and tightened (in Section 10.2).
- The introduction to "Landforms Created by Glacial Erosion" is rewritten to emphasize the distinction between the effects of valley glaciers and ice sheets (in Section 10.3).
- Section 10.4 is revised to include separate sections on glacial till and stratified drift.
- Section 10.5, "Other Effects of Ice Age Glaciers," is reorganized, and section on sea-level changes are updated.
- Section 10.6 is revised to include Section 10.7 from the previous edition ("Causes of Ice Ages"); it also includes some updating, clarification, and shortening.
- Ten figures are added or substantively altered: 10.4 (photo replaces sketch), 10.8 (new figure part added), 10.9 (new example of retreating glacier), 10.10 (new photo), 10.12 (altered), 10.13 (new figure), 10.17 (new figure), 10.18 (altered), 10.34 (altered), 10.35 (altered).
- One *Give It Some Thought* question is added and one deleted. One *Examining the Earth System* question is deleted.

Chapter 11:

- Section 11.5 is retitled "Numerical Dating with Nuclear Decay" (from "Dating with Radioactivity"), and the text is changed to refer to unstable nuclei and nuclear decay in preference to radioactive nuclei and radioactivity.
- The section "Changes to Atomic Nuclei" (formerly "Radioactivity") is significantly revised for clarity, including revision of Figure 11.19.
- Within the section "Radiometric dating," the description of how daughter nuclei accumulate in a crystal is expanded for clarity.
- Vignettes are added to Figure 11.21 to help convey the concept of half-life.
- The discussion of loss of isotopes as a source of dating error is revised for clarity and no longer refers to closed and open systems (in the section "Using Unstable Isotopes").
- Section 11.7, "The Geologic Time Scale," is moved to the end of the chapter; it no longer comes between the sections "Numerical Dating with Nuclear Decay" and "Determining Numerical Dates for Sedimentary Strata."
- The section "Precambrian Time" within Section 11.7 provides more detail on why the time scale is less detailed for the Precambrian than the Phanerozoic.
- Eight figures are substantively revised (Figures 11.15, 11.16, 11.19–11.22, 11.24, 11.25). One 14th edition *GeoGraphics* is deleted.

Chapter 12:

- The opening paragraphs of Section 12.1 are revised to discuss exoplanet discoveries and the concept of a habitable zone.
- In Section 12.3 ("Origin and Evolution of the Atmosphere and Oceans"), the section "Earth's Primitive Atmosphere" is somewhat expanded, and the section "Oxygen in the Atmosphere" is significantly revised, including an expanded treatment of the Great Oxygenation Event.
- The section "Making Continental Crust" is partially revised and includes mention of the Isua rocks.
- In "Supercontinents and Climate," the discussion of Antarctic glaciation is updated.
- Sections 12.6 through 12.9, on the origin and evolution of life, are significantly updated and revised throughout, and a new section on the end-Cretaceous extinction ("Demise of the Dinosaurs") is added, replacing the former *GeoGraphics* on this topic.
- Nine new figures are added:12.1, 12.2, 12.17, 12.24, 12.28, 12.29 (replacing the 14th edition 12.29), and 12.33–12.35. Six figures are substantively altered (12.3, 12.10, 12.12, 12.16, 12.18, 12.32). Six 14th edition figures are deleted (12.1, 12.2, 12.13, 12.18 12.20, 12.22).
- Three *Give It Some Thought* questions are modified; three 14th edition questions are deleted.

Chapter 13:

- Four figures are substantively altered (13.5, 13.6, 13.13, 13.17); Figure 13.22 now incorporates the photo from a former *Eye on Earth*, which is deleted.

Chapter 14:

- Four figures are substantively altered: Figures 14.2, 14.3, 14.13 (now incorporates the former Table 14.2), and 14.14.
- Three 14th edition *Give It Some Thought* questions are deleted.

Chapter 15:

- The order of Sections 15.7 and 15.8 is reversed: Section 15.7 ("Contrasting America's Coasts") now precedes Section 15.8 (Stabilizing the Shore).
- Section 15.7 is reorganized so that it starts by classifying coasts as emergent and submergent.
- In Section 15.8, the conversion of vulnerable shoreline to parks in Staten Island after Hurricane Sandy is added as an example of coastal land-use change.
- Two figures are substantively altered (15.7, 15.25). Three figures are added: 15.8 (replaces 14th edition 15.8), 15.26, 15.29 (replaces 14th edition 15.26). Two 14th edition figures are deleted (15.30, 15.36).
- One *Examining the Earth System* question is deleted.

Chapter 16:

- In Section 16.2, a paragraph about tropospheric ozone as a pollutant is added.
- Figure 16.18 on the solstices and equinoxes is added, and the corresponding text coverage is made briefer (end of Section 16.4).
- Coverage of thermals is added to the section "Mechanism of Heat Transfer: Convection) (in Section 16.5).
- The description of the greenhouse effect is revised for clarity (end of Section 16.6).
- Two figures are substantively altered (16.6, 16.16). Three figures are added: 16.4, 16.14 (replaces 14th edition 16.14), 16.18, 16.20, 16.23 (replaces 14th edition 16.22). One 14th edition figure is deleted (16.9), as well as figure parts from Figures 16.7 and 16.8. The 14th edition *GeoGraphics* is also deleted.
- One *Examining the Earth System* question is deleted.

Chapter 17:

- In Section 7.2, the sections "Dew Point Temperature" and "How Is Humidity Measured?" are significantly revised for clarity.
- Sections 17.3 ("Adiabatic Temperature Changes and Cloud Formation") and 17.4 ("Processes that Lift Air") are substantially revised to improve clarity.
- Section 17.7, "Types of Fog," is thoroughly rewritten to improve clarity.
- The description of how hail forms is revised for clarity (Section "Hail" in Section 17.9).
- Eleven figures are substantively altered (17.4–17.6, 17.12, 17.14, 17.17–27.19, 17.20, 17.27, 17.34); *GeoGraphics* 17.1 also modified. Two figures are added (17.29, 1731), and also *Eye on Earth* 17.1. One *Eye on Earth* from the 14th edition is deleted.
- One new *Give It Some Thought* question is added; four questions from the 14th edition are deleted. Two *Examining the Earth System* questions are deleted.

Chapter 18:

- Section 18.7 ("El Nino, La Nina, and the Southern Oscillation") is substantially revised.
- Six figures are substantively altered (18.3, 18.14, 18.17, 18.18, 18.24, 18.25). Two figures are added: 18.6 (replaces 14th edition 18.6), 18.8 (replaces 14th edition 18.8). Two 14th edition figures are deleted (18.26, 18.27), as well as the 14th edition *GeoGraphics*.
- One *Examining the Earth System* question is deleted.

Chapter 19:

- The introduction to fronts is revised (beginning of Section 9.2).
- The sections "Tornado Development and Occurrence" and "Tornado Climatology" are significantly revised (in Section 19.5).
- A subsection "The Role of Satellites" is added to the section "Monitoring Hurricanes" in Section 19.6.
- Eight figures are substantively altered (19.2, 19.3, 19.5, 19.14, 19.16, 19.22, 19.28, 19.34). Two figures are added: 19.25 (replaces 14th edition 19.26) and 19.33. One 14th edition figure is deleted (19.15), as well as the 14th edition *GeoGraphics*.
- One new *Give It Some Thought* question is added; one question from the 14th edition is deleted.

Chapter 20:

- Section 20.8, "Human Impact on Global Climate," is revised and brought up to date. This section also now covers aerosols (formerly covered in its own later section).
- Section 20.10, "Some Possible Consequences of Global Warming," revised and brought up to date.
- Two new figures are added: 20.26 (replaces 14th edition Fig 20.27) and 20.28. Three figures are substantively altered (20.19, 20.20, 20.25). Two 14th edition figures are deleted (20.15, 20.29). The *GeoGraphics* and one *Eye on Earth* from the 14th edition are deleted.
- One *Give It Some Thought* question id deleted.

Chapter 21:

- This chapter is edited extensively for conciseness and clarity.
- Section 21.1 is significantly revised for clarity, particularly the section "The Golden Age of Astronomy."
- Section 21.2 is significantly revised for conciseness and, in places, for clarity. Also, Kepler's third law is now expressed mathematically (section "Johannes Kepler"), and, for Newton's law of gravitation, the exact proportionality between mass, distance, and gravitational force is given (section "Isaac Newton").
- Within Section 21.3, "Patterns in the Night Sky" (formerly titled "Positions in the Sky"), star positions are now described in terms of direction and altitude rather than right ascension and declination. Also, the new section "Measurements Using the Celestial Sphere" now covers angular size and angular distance.
- Section 21.4, "The Motions of Earth," no longer describes precession de novo; instead, it reviews the cycles of eccentricity, axial tilt, and precession that were described in Chapter 10.
- Section 21.5, "Motions of the Earth–Moon System," now discusses tidal locking as the reason why one side of the Moon always faces Earth.
- Two new figures are added (21.21, 21.22). Six figures are substantively altered (21.6, 21.11, 21.15, 21.17, 21.18, 21.27). One 14th edition figure is deleted (21.27).
- Two new *Give It Some Thought* questions are modified; two 14th edition questions are deleted. One *Examining the Earth System* question is deleted.

Chapter 22:

- In addition to the sections updated for currency (noted below), the chapter is revised extensively for clarity and conciseness.
- The sections "Nebular Theory: Formation of the Solar System," "Mars: The Red Planet," "Comets: Dirty Snowballs," and "Dwarf Planets" are updated to reflect current research, as is the treatment of cryovolcanism on moons of the outer planets.
- Four new figures are added (22.16, 22.18, 22.33, 22.36). Twelve figures are substantively altered (22.2, 22.4, 22.7, 22.12, 22.17, 22.20, 22.23, 22.28 22.29, 22.30, 22.32, 22.25), as well as is *GeoGraphics* 22.1. Five 14th edition figures are deleted (22.11, 22.22, 22.25, 22.35, 22.37).
- One 14th edition *Give It Some Thought* question is deleted; one *Examining the Earth System* question is deleted.

Chapter 23:

- In addition to the changes discussed below, the text and figures are revised extensively for clarity and conciseness. The chapter now puts more emphasis on current knowledge and less on history.
- Section 23.2, "What Can We Learn from Light?" is thoroughly revised. Line spectra are now referred to as emission and absorption spectra, rather than bright-line and dark-line spectra. The treatment of what spectra tell us about composition and temperature is expanded and put in its own subsections. The explanation of the Doppler effect is revised for clarity. The section now covers the speed of light in vacuum.
- Section 23.3, "Collecting Light Using Optical Telescopes," is almost completely rewritten, with a stronger focus on how observing is done today. The treatment of active optics, adaptive optics, telescope arrays, and astrophotography using film and CCDs is expanded and divided into new subsections.
- Section 23.4, "Radio- and Space-Based Astronomy," is largely rewritten or new, with sections on spaced-based observatories in radio, infrared, x-ray, and gamma-ray wavelengths and on the James Webb Space Telescope.
- Section 23.5, "Our Star: The Sun" is revised, reorganized, and somewhat expanded, with separate sections on the Sun's surface, atmosphere, and interior. It also now covers hydrogen fusion by the p–p process as the source of the Sun's energy.
- Section 23.6, "The Active Sun," is significantly revised, with more coverage of the structure and role of Sun's magnetic field.
- More than half of the figures in the chapter (17 of 30) are revised, replaced, or new. Six figures are substantively altered: 23.1–23.3, 23.20, 23.21, 23.24. Eleven are new: 23.4, 23.6, 23.7, 23.8 (replaces 14th edition 23.6), 23.13, 23.16, 23.18, 23.20, 23.21 (replaces 14th edition 23.17), 23.27, 23.29. Ten 14th edition figures are deleted: 23.4, 23.6, 23.9, 23.13, 23.16, 23.17–23.19, 23.22, 23.25.
- Two 14th edition *Give It Some Thought* questions are deleted.

Chapter 24:

- Section 24.1, "Classifying Stars," now covers stellar luminosity, color, and temperature as well as the H-R diagram and the classes of stars.
- The 14th edition Section 24.2 on the types of nebulae is deleted; retained material is placed elsewhere in this chapter and in Chapter 23.
- Section 24.2, "Stellar Evolution," is extensively revised and updated.
- Sections 24.3 ("Stellar Remnants") and 24.4 ("Galaxies and Galaxy Clusters") are significantly revised for clarity and conciseness, and Section 24.4. includes new information on dwarf galaxies.
- The section on the Universe is moved to the end of the chapter, revised, and combined with the treatment of cosmology.
- Two new figures are added (24.4, 24.9); Figure 24.1 is replaced with a new photo of a different object. Six figures substantively altered (24.2, 24.3, 24.5, 24.8, 24.10, 24.20)). Five 14th edition figures are deleted (24.3–24.7).
- Three 14th edition *Give It Some Thought* questions are deleted; one *Examining the Earth System* question is deleted.

Introduction to Earth Science

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 List and describe the sciences that collectively make up Earth science. Discuss the scales of space and time in Earth science.

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

1.3 Outline the stages in the formation of our solar system.

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

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

All four of Earth's major spheres are represented in this image from Jasper National Park in the Canadian Rockies. (Photo by Adam Burton/Getty Images)

THE SPECTACULAR ERUPTION OF A VOLCANO, the magnificent scenery of a rocky coast, and the destruction created by a hurricane are all subjects for an Earth scientist. The study of Earth science deals with many fascinating and practical questions about our environment. What forces produce mountains? Why is our daily weather variable? Is climate really changing? How old is Earth, and how is it related to other planets in the solar system? What causes ocean tides? What were the Ice Ages like, and will there be another? Where should we search for water?

The subject of this text is *Earth science*. To understand Earth is not an easy task because our planet is not a static and unchanging mass. Rather, it is a dynamic body with many interacting parts and a long and complex history.

1.1 What Is Earth Science?

List and describe the sciences that collectively make up Earth science. Discuss the scales of space and time in Earth science.

Earth science is the name for all the sciences that collectively seek to understand Earth and its neighbors in space. It includes geology, oceanography, meteorology, and astronomy. Throughout its long existence, Earth has been changing. In fact, it is changing as you read this page and will continue to do so into the foreseeable future. Sometimes the changes are rapid and violent, as when severe storms, landslides, and volcanic eruptions occur. Conversely, many changes take place so gradually that they go unnoticed during a lifetime. Scales of size and space also vary greatly among the phenomena studied in Earth science.

Earth science is often perceived as science that is performed outdoors—and rightly so. A great deal of an Earth scientist's study is based on observations and experiments conducted in the field. But Earth science is also conducted in the laboratory, where, for example, the study of various Earth materials provides insights into many basic processes, and the creation of complex computer models allows for the simulation of our planet's complicated climate system. Frequently, Earth scientists require an understanding of and must apply their knowledge about principles from physics, chemistry, and biology. Geology, oceanography, meteorology, and astronomy are sciences that seek to expand our knowledge of the natural world and our place in it.

Figure 1.1 Volcanic eruption Molten lava from Hawaii's Kilauea Volcano is spilling into the Pacific Ocean. Internal processes are those that occur beneath Earth's surface. Sometimes they lead to the formation of major features at the surface. (Photo by Russ Bishop/Alamy Stock Photo)

Geology

In this book, Units 1–4 focus on the science of **geology**, a word that literally means "study of Earth." Geology is traditionally divided into two broad areas: physical and historical.

Physical geology examines the materials composing Earth and seeks to understand the many processes that operate beneath and upon its surface. Earth is a dynamic, ever-changing planet. Internal forces create earthquakes, build mountains, and produce volcanic structures (**Figure 1.1**). At the surface, external processes break rock apart and sculpt a broad array of landforms. The erosional effects of water, wind, and ice result in a great diversity of landscapes. Because rocks and minerals form in response to Earth's internal and external processes, their interpretation is basic to an understanding of our planet.

In contrast to physical geology, the aim of *historical geology* is to understand the origin of Earth and the development of the planet through its 4.6-billion-year history (**Figure 1.2**). 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.

Oceanography

Earth is often called the "water planet" or the "blue planet." Such terms relate to the fact that more than 70 percent of Earth's surface is covered by the global ocean. If we are to understand Earth, we must learn about its oceans. Unit 5, *The Global Ocean*, is devoted to **oceanography**.

Oceanography is actually not a separate and distinct science. Rather, it involves the application of all sciences in a comprehensive and interrelated study of the oceans in all their aspects and relationships. Oceanography integrates chemistry, physics, geology, and biology. It includes the study of the composition and movements of seawater, as well as coastal processes, seafloor topography, and marine life.

Meteorology

The continents and oceans are surrounded by an atmosphere. Unit 6, *Earth's Dynamic Atmosphere*, examines the mixture of gases that is held to the planet by gravity and thins rapidly with altitude. Acted on by the combined effects of Earth's motions and energy from the Sun, and influenced by Earth's land and sea surface, the formless and invisible atmosphere reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. **Meteorology** is the study of the atmosphere and the processes that produce weather and climate. Like oceanography, meteorology involves the application of other sciences in an integrated study of the thin layer of air that surrounds Earth.

▲ **SmartFigure 1.2**
Arizona's Grand Canyon The erosional work of the Colorado River along with other external processes created this natural wonder. For someone studying historical geology, hiking down the South Kaibab Trail in Grand Canyon National Park is a trip through time. These rock layers hold clues to millions of years of Earth history. (Photo by Michael Collier)

MOBILE FIELD TRIP
https://goo.gl/kECNV1

▲ **Figure 1.3 Earthquake in Ecuador** On April 16, 2016, a magnitude 7.8 earthquake struck coastal Ecuador. It was the strongest quake in that region in 40 years. There were nearly 700 fatalities and more than 7000 people injured. Natural hazards are *natural processes*. They become hazards only when people try to live where the processes occur. (Photo by Meridth Kohut/Bloomberg via Getty Images)

Astronomy

Unit 7, *Earth's Place in the Universe*, demonstrates that an understanding of Earth requires that we relate our planet to the larger universe. Because Earth is related to all the other objects in space, the science of **astronomy**—the study of the universe—is very useful in probing the origins of our own environment. Because we are so closely acquainted with the planet on which we live, it is easy to forget that Earth is just a tiny object in a vast universe. Indeed, Earth is subject to the same physical laws that govern the many other objects populating the great expanses of space. Thus, to understand explanations of our planet's origin, it is useful to learn something about the other members of our solar system. Moreover, it is helpful to view the solar system as a part of the great assemblage of stars that comprise our galaxy, which is but one of many galaxies.

Earth Science Is Environmental Science

Earth science is an environmental science that explores many important relationships between people and the natural environment. Many of the problems and issues addressed by Earth science are of practical value to people.

Natural Hazards Natural hazards are a part of living on Earth. Every day they adversely affect literally millions of people worldwide and are responsible for staggering damages. Among the hazardous Earth processes studied by Earth scientists are volcanoes, floods, tsunamis, earthquakes, landslides, and hurricanes. Of course, these hazards are *natural* processes. They become hazards only when people try to live where these processes occur.

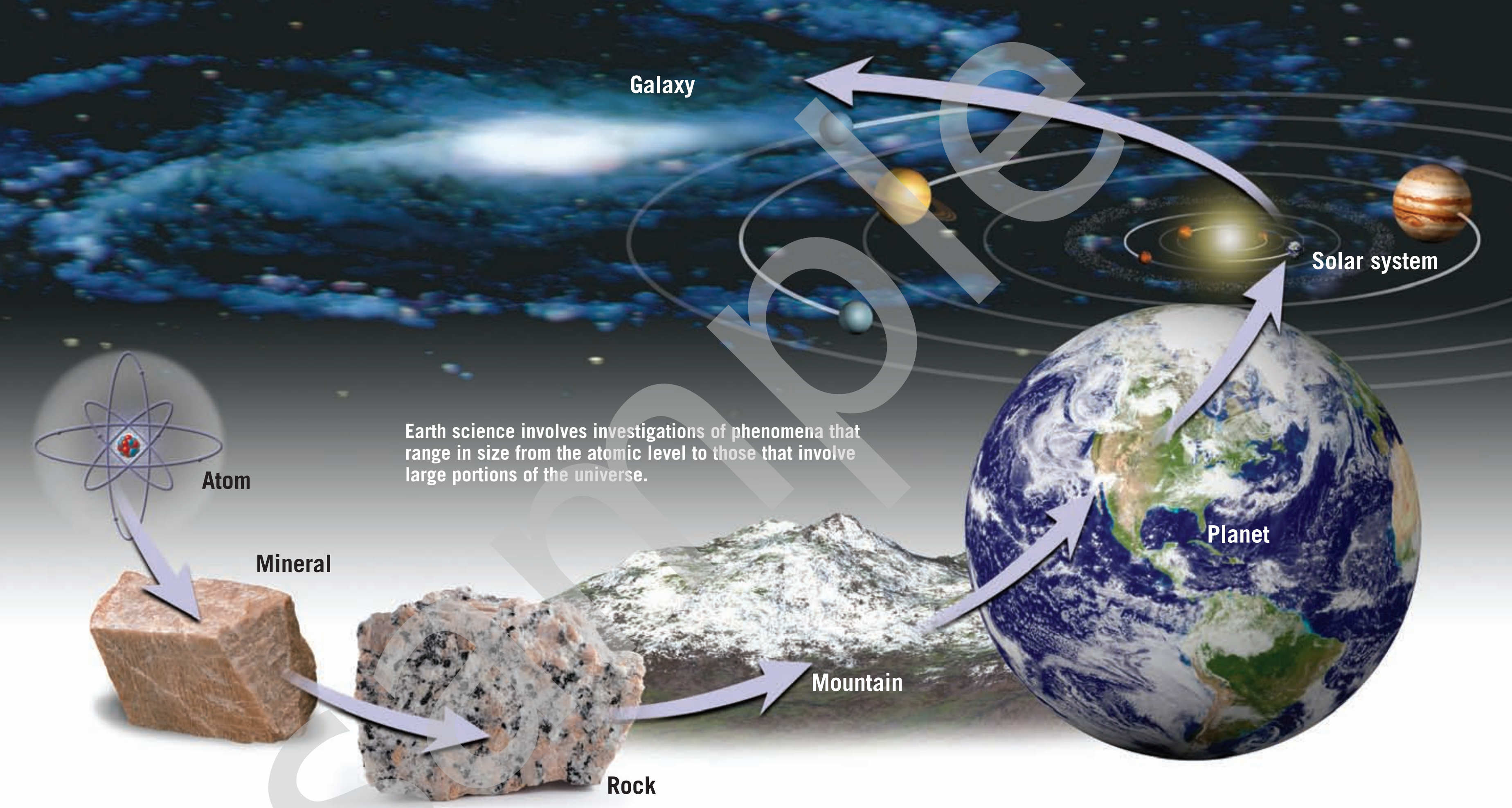
For most of history, most people lived in rural areas. However, today more people live in cities than in rural areas. This global trend toward urbanization concentrates millions of people into places that are vulnerable to natural hazards. Coastal sites are becoming more vulnerable because development often destroys natural defenses such as wetlands and sand dunes. In addition, there is a growing threat associated with human influences on the Earth system, such as sea level rise that is linked to global warming.* Other urban areas are exposed to seismic (earthquake) and volcanic hazards where inappropriate land use and poor construction practices, coupled with rapid population growth, increase vulnerability (**Figure 1.3**).

Resources Resources represent another important focus that is of great practical value to people. They include water and soil, a great variety of metallic and nonmetallic minerals, and energy. Together they form the very foundation of modern civilization. Earth science deals with the formation and occurrence of these vital resources and also with maintaining supplies and with the environmental impact of their extraction and use.

People Influence Earth Processes Not only do Earth processes have an impact on people, but we humans can dramatically influence Earth processes as well. Human activities alter the composition of the atmosphere, triggering air pollution episodes and causing global climate change (**Figure 1.4**). River flooding is natural, but the

*The idea of the Earth system is explored later in the chapter. Global climate change and its effects are a focus of Chapter 20.

▼ **Figure 1.4 People influence the atmosphere** China is plagued by frequent severe air pollution episodes. Fuel combustion from power plants, factories, and motor vehicles provide a high percentage of the pollutants. Meteorological factors determine whether pollutants remain trapped in the city or are dispersed. (Photo by AFP/Stringer/Getty Images)



▲ **Figure 1.5** **From atoms to galaxies** Earth science studies phenomena on many different scales.

magnitude and frequency of flooding can be changed significantly by human activities such as clearing forests, building cities, and constructing 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 often has the opposite effect.

At many places throughout this book, you will have opportunities to examine different aspects of our relationship with the physical environment. Moreover, significant parts of some chapters provide the basic knowledge and principles needed to understand environmental problems.

Scales of Space and Time in Earth Science

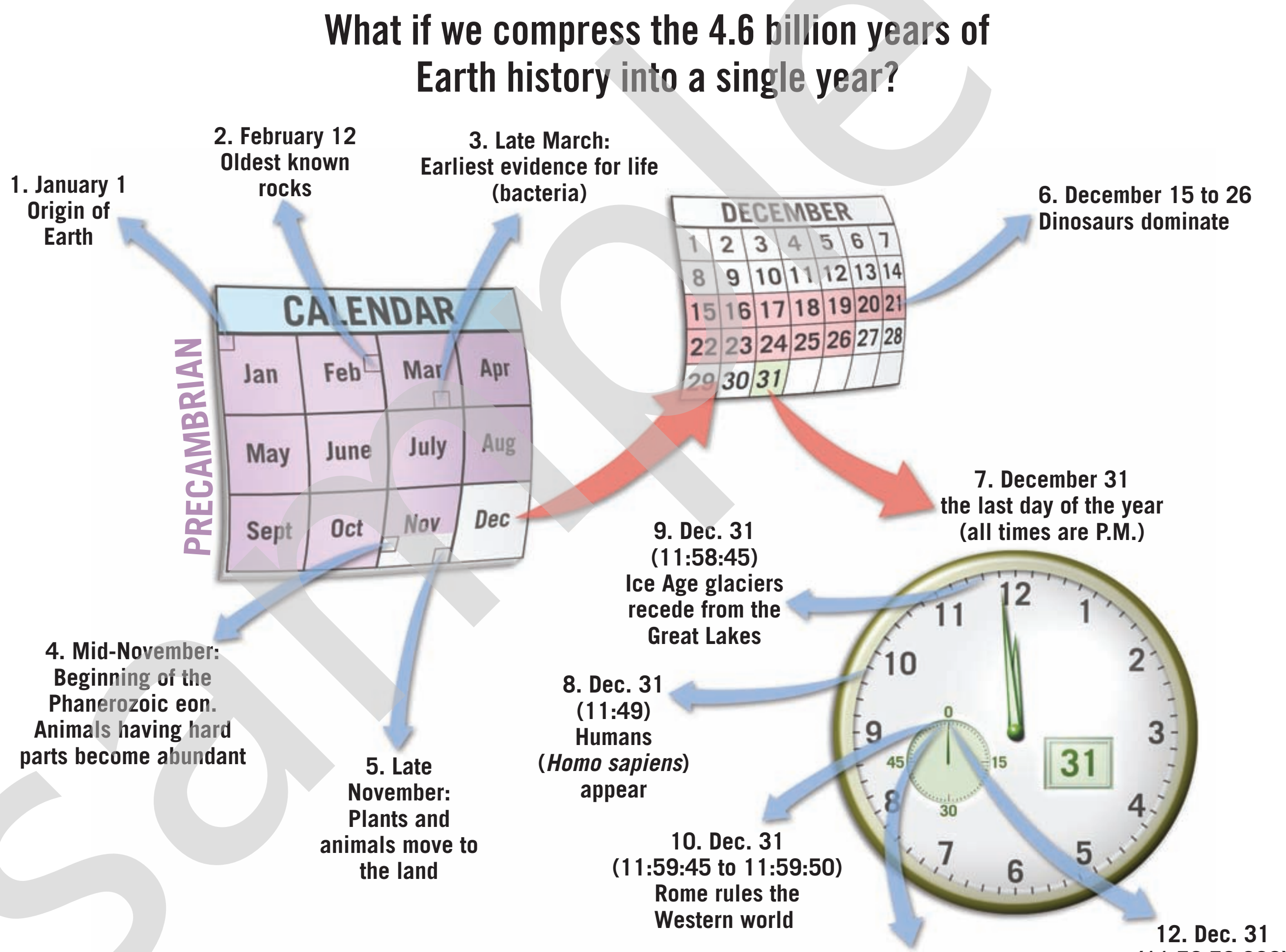
When we study Earth, we must contend with a broad array of space and time scales (**Figure 1.5**). Some phenomena are relatively easy for us to imagine, such as the size and duration of an afternoon thunderstorm or the dimensions of a sand dune. Other phenomena are so vast or so small that they are difficult to imagine. The number of stars and distances in our galaxy (and beyond!) or the internal arrangement of atoms in a mineral crystal are examples of such phenomena.

Some of the events we study occur in fractions of a second. Lightning is an example. Other processes extend over spans of tens or hundreds of millions of years. For example, the lofty Himalaya Mountains began forming nearly 50 million years ago, and they continue to develop today.

The concept of **geologic time**, the span of time since the formation of Earth, is new to many nonscientists. People are accustomed to dealing with increments of time that are measured in hours, days, weeks, and years. Our 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*.

Those who study Earth science 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, an 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 our planet because many processes are so gradual that vast spans of time are needed before significant changes occur. How long



▶ **SmartFigure 1.6**
Magnitude of geologic time

TUTORIAL
https://goo.gl/V1WFRd

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!

The preceding analogy is just one of many that have been conceived in an attempt to convey the magnitude of geologic time. Although helpful, all of them, no matter how clever, only begin to help us comprehend the vast expanse of Earth history. **Figure 1.6** provides another interesting way of viewing the age of Earth.

Over the past 200 years or so, Earth scientists have developed the *geologic time scale* of Earth history. It divides the 4.6-billion-year history of Earth into many different units and provides a meaningful time frame within which the events of the geologic past are arranged (see Figure 11.25, page 374). The principles used to develop the geologic time scale are examined in some detail in Chapter 11.

CONCEPT CHECKS 1.1

1. List and briefly describe the sciences that collectively make up Earth science.
2. List at least four different natural hazards. Aside from natural hazards, describe another important connection between people and Earth science.
3. List two examples of size/space scales in Earth science that are at opposite ends of the spectrum.
4. How old is Earth?
5. If you compress geologic time into a single year, how much time has elapsed since Columbus arrived in the New World?

1.2 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 investigation that leads to producing knowledge, based on making careful observations and on creating explanations that make sense of the observations. Developing an understanding of how science is performed and how scientists work is an important theme 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, as well as learn about the evolution and development of some major scientific theories.

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then to use that knowledge to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by understanding the circumstances and processes that produce certain cloud types, meteorologists are often able to predict the approximate time and place of their formation and the intensity of the associated weather.

The development of new scientific knowledge involves some basic logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect data through observation and measurement (**Figure 1.7**). The data collected often help answer well-defined questions about the natural world. Because some error is inevitable, the accuracy of a particular measurement

A.

B.

C.

Figure 1.7 Observation and measurement Gathering data and making careful observations are basic parts of scientific inquiry. **A.** This array of instruments automatically records and transmits basic weather data. (Photo by NASA/Science Source) **B.** The Earth sciences frequently involve fieldwork. (Photo by Robbie Shone/Science Source) **C.** In the lab, this researcher is using a special microscope to study the mineral composition of rock samples that were collected during fieldwork. (Photo by Jon Wilson/Science Source) or observation is always open to question. Nevertheless, these data are essential to science and serve as a springboard for the development of scientific hypotheses and theories.

Hypothesis

Once facts have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happened 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 is unable to devise multiple hypotheses, others in the scientific community will almost always develop alternative explanations. A spirited debate frequently ensues. As a result, extensive research is conducted by proponents of opposing hypotheses, and the results are made available to the wider scientific community in scientific journals.

Before a hypothesis can become an accepted part of scientific knowledge, it must repeatedly 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 by being compared against objective observations of nature. 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 the 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 language, we might say, "That's 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.

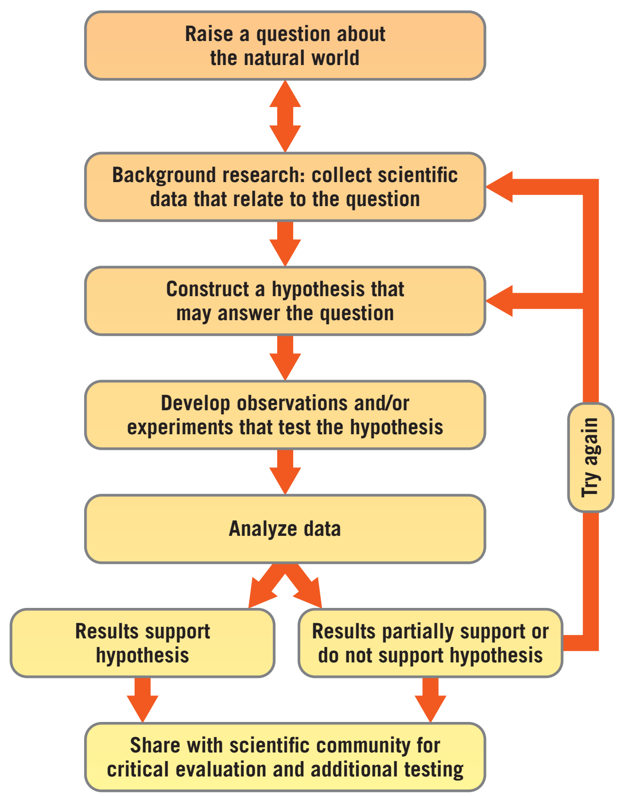
Some theories that are extensively documented and extremely well supported are comprehensive in scope and may incorporate several well-tested hypotheses. For example, the theory of plate tectonics provides the framework for understanding the origin of mountains, earthquakes, and volcanic activity. In addition, plate tectonics explains the evolution of the continents and the ocean basins through time—ideas that are explored in some detail in Chapters 4 through 7.

Scientific Methods

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

There is no fixed path for scientists to follow that leads unerringly to scientific knowledge. However, many scientific investigations involve the steps outlined in **Figure 1.8**. 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.

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



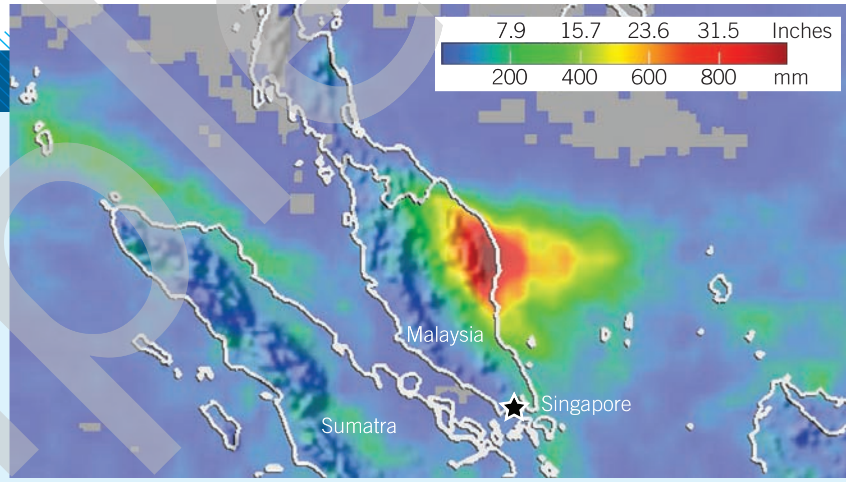
▲ **Figure 1.8 Steps frequently followed in scientific investigations** The diagram depicts the steps involved in the process many refer to as the *scientific method*.

EYE ON EARTH 1.1

This image shows rainfall data for December 7–13, 2004, in Malaysia. More than 800 millimeters (32 inches) of rain fell along the east coast of the peninsula (darkest red area). The extraordinary rains caused extensive flooding. The data for this image are from NASA's *Tropical Rainfall Measuring Mission* (*TRMM*). This is just one of hundreds of satellites that provide scientists with all kinds of data about our planet.

QUESTION 1 *Suggest some advantages that satellites provide to scientists in terms of gaining information about Earth.*

QUESTION 2 *Gathering data is a basic part of scientific inquiry. Aside from satellites, list at least two ways that Earth scientists gather data.*



NASA Headquarters

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, it should always be remembered that even the most compelling scientific theories are still simplified explanations of the natural world.

In this book, you will discover the results of centuries of scientific work. You will see the end product of millions of observations, thousands of hypotheses, and hundreds of theories. We have distilled all of this to give you a "briefing" on Earth science.

Bear in mind that our knowledge of Earth is changing daily, as thousands of scientists worldwide make satellite observations, analyze drill cores from the seafloor, measure earthquakes, develop computer models to predict climate, examine the genetic codes of organisms, and discover new facts about our planet's long history. This new knowledge often updates hypotheses and theories. Expect to see many new discoveries and changes in scientific thinking in your lifetime.

CONCEPT CHECKS 1.2

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

1.3 Early Evolution of Earth

Outline the stages in the formation of our solar system.

This section describes the most widely accepted views on the origin of our solar system. The theory summarized here represents the most consistent set of ideas available to explain what we know about our solar system today. **GEOgraphics 1.1** provides a useful perspective on size and scale in the solar system.

The Universe Begins

Our scenario begins about 13.7 billion years ago, with the *Big Bang*, an almost incomprehensible event in which space itself, along with all the matter and energy of the universe, exploded in an instant from tiny to huge dimensions. As the universe continued to expand, subatomic particles condensed to form hydrogen and helium gas, which later cooled and clumped to form the first stars and galaxies. It was in one of these galaxies, the Milky Way, that our solar system, including planet Earth, took form.

The Solar System Forms

Earth is one of eight planets that, along with dozens of moons and numerous smaller bodies, revolve around the Sun. The orderly nature of our solar system helped scientists determine 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

GEOGRAPHICS 1.1

Solar System: Size and Scale

The Sun is the center of a revolving system trillions of miles across, consisting of eight 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!

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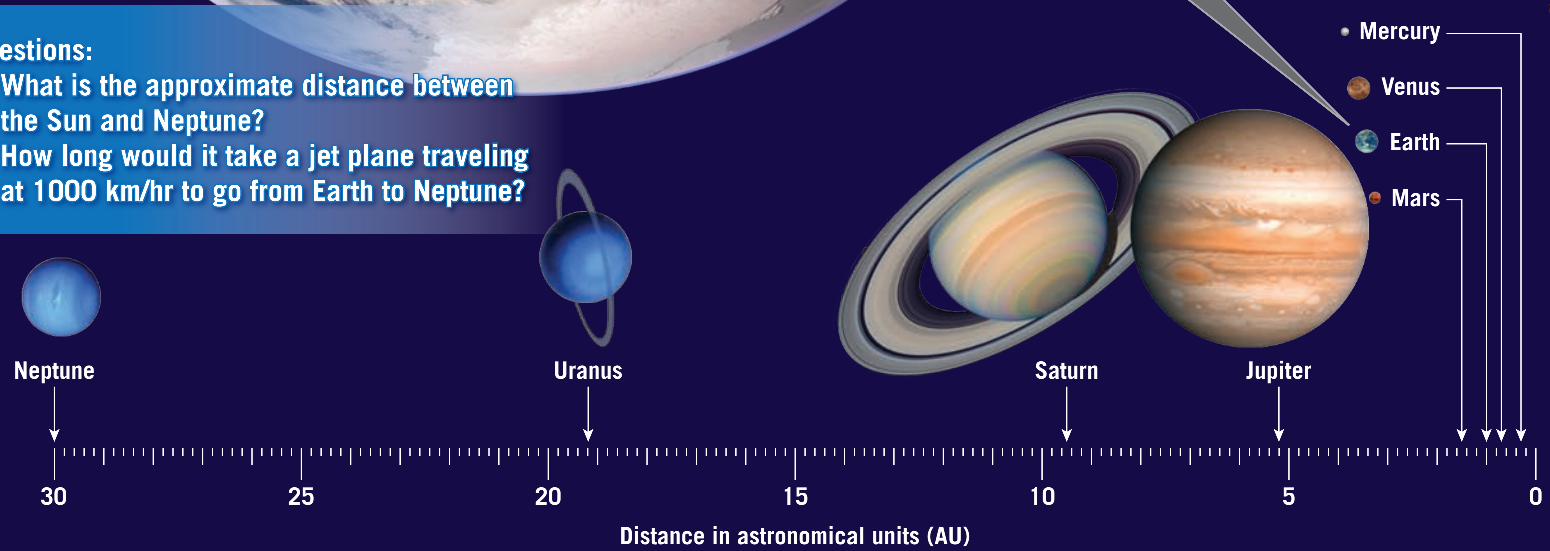
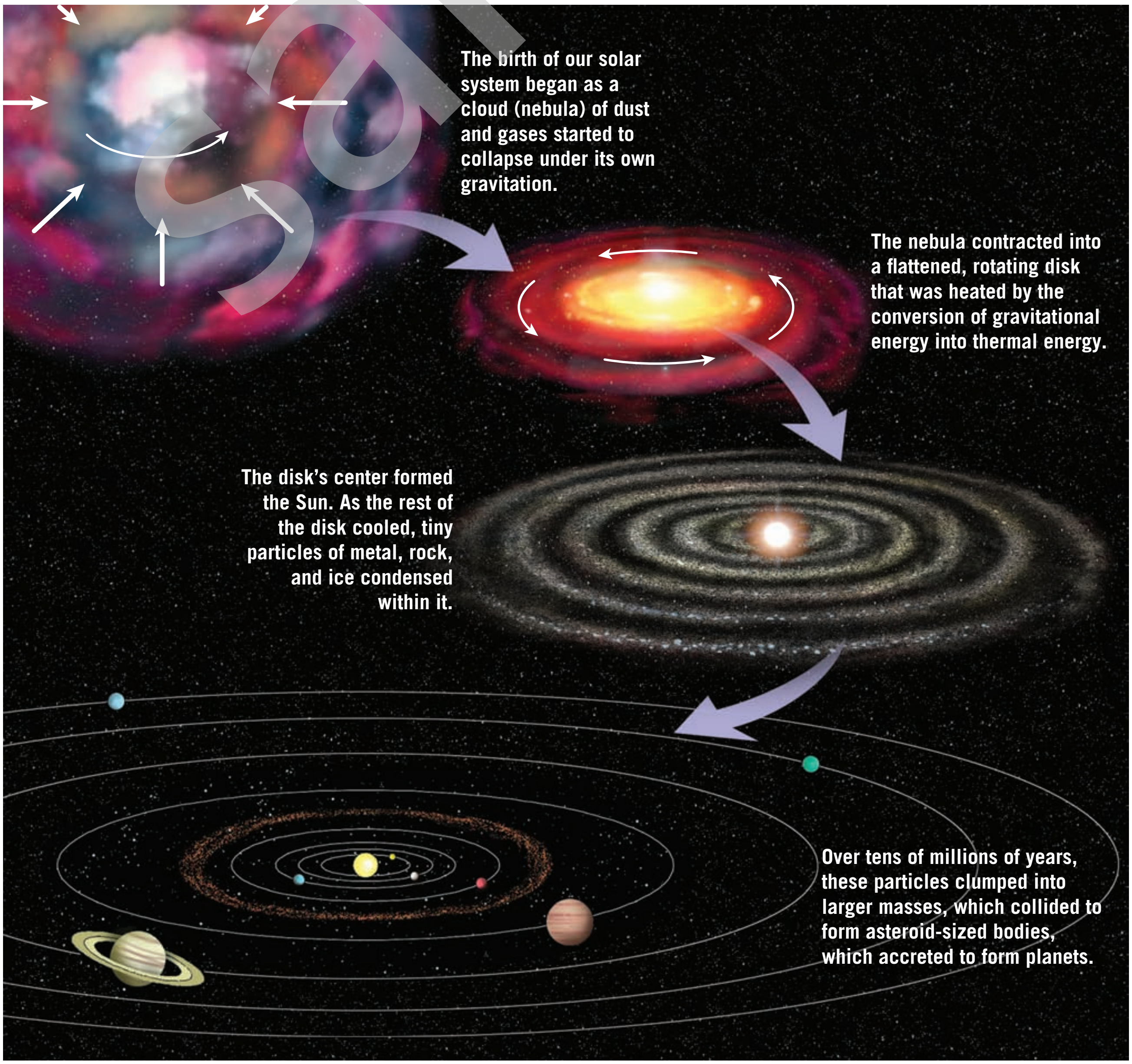
Questions:
1. What is the approximate distance between the Sun and Neptune?
2. How long would it take a jet plane traveling at 1000 km/hr to go from Earth to Neptune?



from an enormous rotating cloud called the solar nebula (**Figure 1.9**). Besides the hydrogen and helium atoms generated during the Big Bang, the solar nebula consisted of microscopic dust grains and other matter ejected ultimately from long-dead stars. (Nuclear fusion in stars converts hydrogen and helium into the other elements found in the universe.)

Nearly 5 billion years ago, something—perhaps a shock wave from an exploding star (*supernova*)—caused this nebula to start collapsing in response to its own gravitation. As it collapsed, it evolved from a huge, vaguely rotating cloud to a much smaller, fast-spinning disk. The cloud flattened into a disk for the same reason that it is easier to move along with a crowd of circling ice skaters than to cross their path. The orbital plane within the cloud that started out with the largest amount of matter gradually, through collisions and other interactions, incorporated gas and particles that originally had other orbits until all the matter orbited in one plane. The disk spun faster as it shrank, much as ice skaters spin faster when they draw their arms toward their bodies. Most of the cloud's matter ended up in the center of the disk, where it formed the *protosun* (pre-Sun). Astronomers have observed many such disks around newborn stars in neighboring regions of our galaxy.

The protosun and inner disk were heated by the gravitational energy of infalling matter. In the inner disk, temperatures became high enough to cause the dust grains to evaporate. However, at distances beyond the orbit of Mars, the temperatures probably remained



SmartFigure 1.9
Nebular theory The nebular theory proposes the formation of the solar system.

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Figure 1.10 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. (Image courtesy of European Space Agency)

quite low. At −200°C (−328°F), the tiny particles in the outer portion of the nebula were likely covered with a thick layer of frozen water, carbon dioxide, ammonia, and methane. The disk also contained appreciable amounts of the lighter gases hydrogen and helium.

The Inner Planets Form

The formation of the Sun marked the end of the period of contraction and thus the end of gravitational heating. Temperatures in the region where the inner planets now reside began to decline. The decrease in temperature caused 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 1.9). 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 1.10**). Not all of these clumps of matter were incorporated into the planetesimals. Those rocky and metallic pieces that remained in orbit are called asteroids and meteors. Meteors become *meteorites* if they impact Earth's surface.

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

The Outer Planets Develop

At the same time that the inner planets were forming, the larger, outer planets (Jupiter, Saturn, Uranus, and Neptune), along with their extensive satellite systems, were also developing. Because of low temperatures far from the Sun, the material from which these planets formed contained a high percentage of ices—water, carbon dioxide, ammonia, and methane—as well as rocky and metallic debris. The accumulation of ices accounts in part 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.

CONCEPT CHECKS 1.3

1. Name and briefly outline the theory that describes the formation of our solar system.
2. List the inner planets and the outer planets. Describe basic differences in size and composition.

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 1.11** 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, the most conspicuous features of Earth in Figure 1.11A 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 1.11B 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 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. All four spheres are represented in the chapter-opening photo.

The interactions among Earth's spheres are incalculable. Figure 1.12 provides 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.

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

A.

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

B.

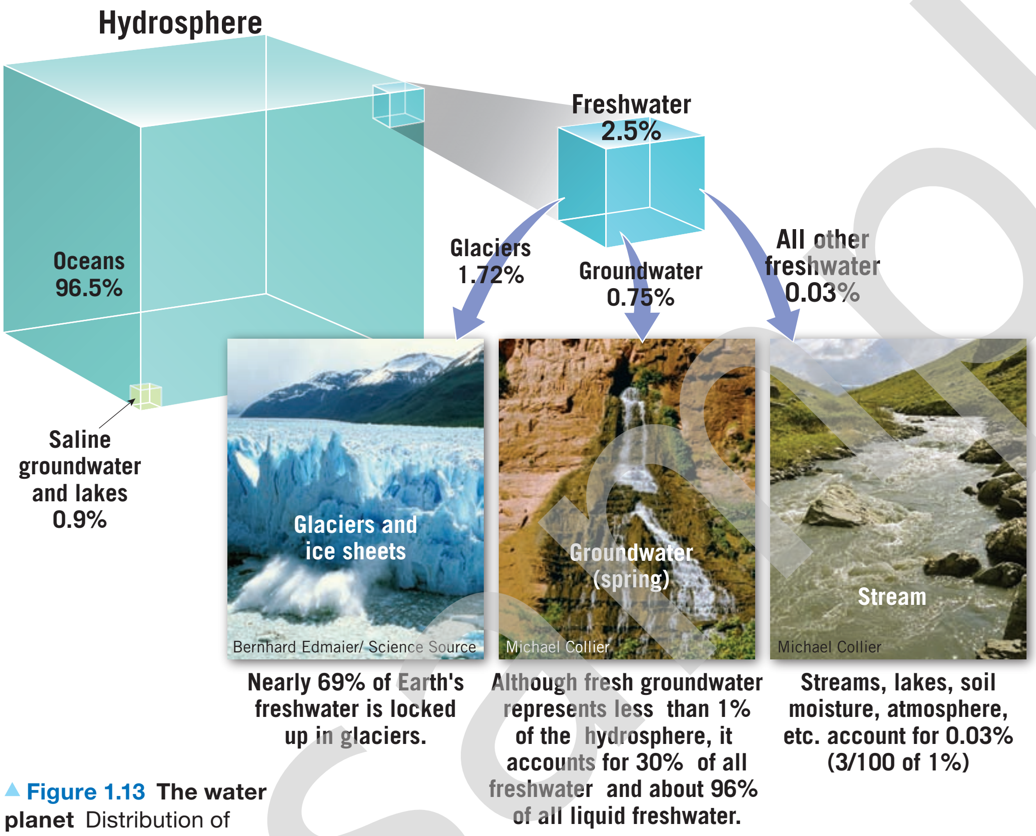
▲ **SmartFigure 1.11 Two classic views of Earth from space** The accompanying video commemorates the 45th anniversary of *Apollo 8*'s historic flight by re-creating the moment when the crew first saw and photographed Earth rising from behind the Moon. (NASA)

VIDEO
https://goo.gl/AQKqaa

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

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



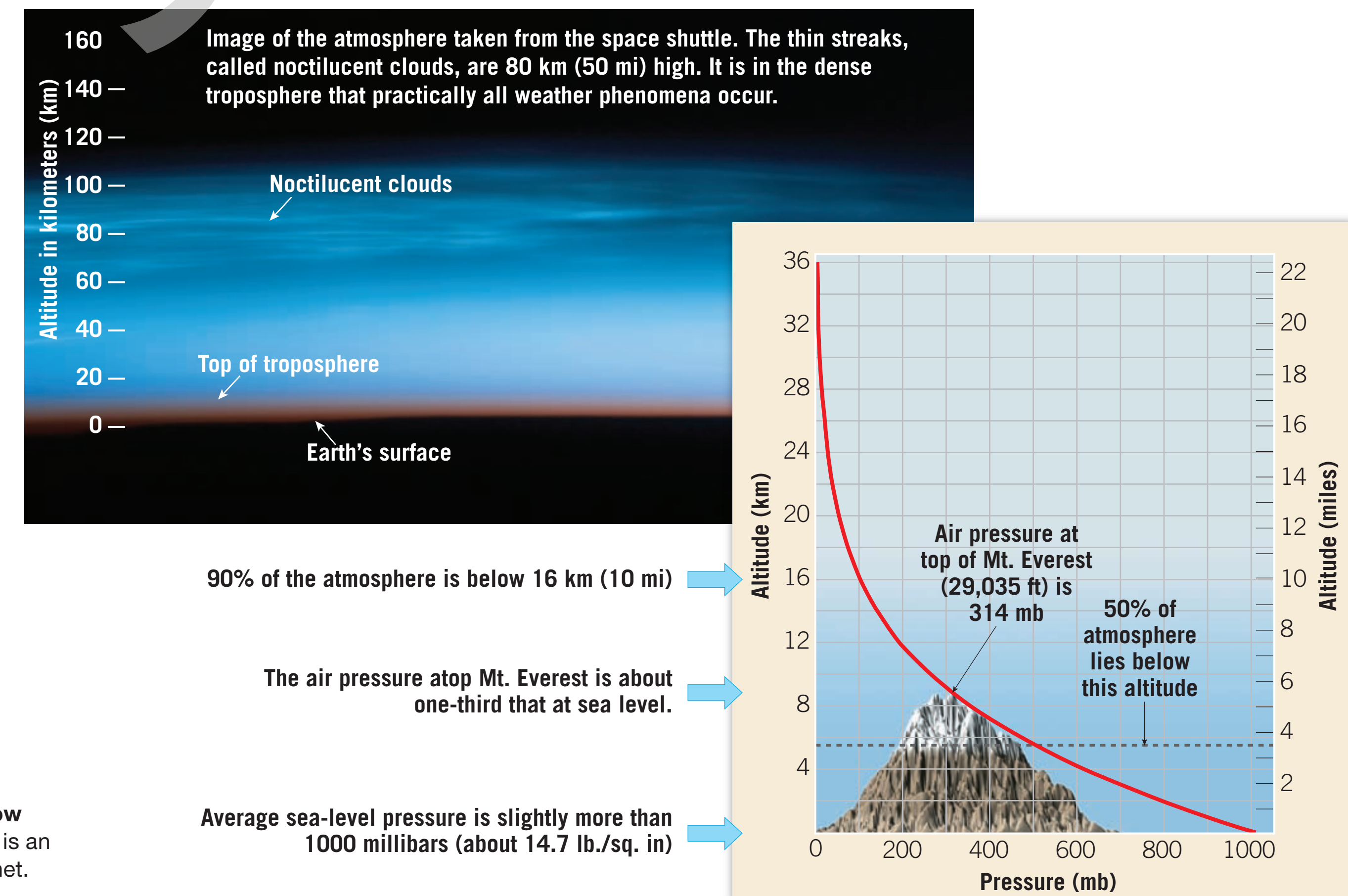
▲ **Figure 1.13 The water planet** Distribution of water in the hydrosphere.

97 percent of Earth's water (**Figure 1.13**). 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.

Even though freshwater constitutes only a small fraction of Earth's hydrosphere, it plays an outsized role in Earth's external processes. Streams, glaciers, and groundwater sculpt many of our planet's varied landforms, and freshwater is vital for life on land.

Atmosphere

Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (**Figure 1.14**). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth (about 6400 kilometers [4000 miles]), the atmosphere is a very shallow layer. Despite its modest dimensions, this thin blanket of air is an integral part of the planet. It not only provides the air we breathe but also protects us from the Sun's intense heat and dangerous ultraviolet radiation. The energy exchanges that continually



▶ **Figure 1.14 A shallow layer** The atmosphere is an integral part of the planet. (NASA)

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 1.14. 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)?*

interlight/Shutterstock

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 1.15). Ocean life is concentrated in the sunlit upper waters. Most life on land is also concentrated near the surface, with tree roots and burrowing animals reaching 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, as in Figure 1.15B. On land, some bacteria thrive in rocks as deep as 4 kilometers (2.5 miles) and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth's surface.

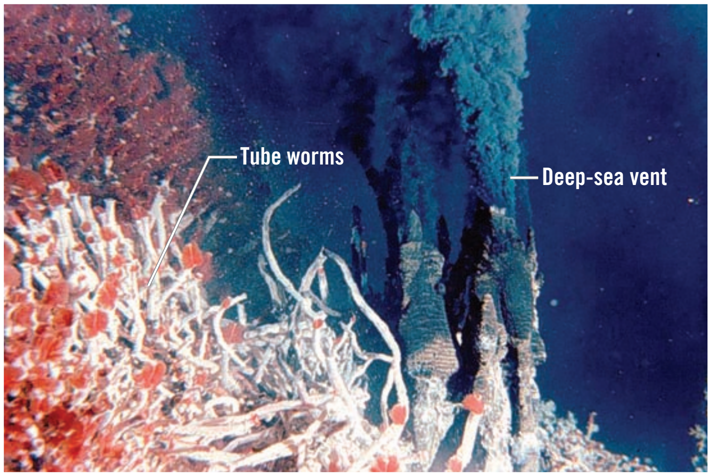
Plants and animals depend on the physical environment for the basics of life. However, organisms do not just respond to their physical environment. Through countless interactions, life-forms help maintain and alter the physical environment. Without life, the makeup and nature of the geosphere, hydrosphere,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

Geosphere

Lying beneath the atmosphere and the ocean is the solid Earth or **geosphere**, extending from the surface to the center of the planet at a depth of nearly

Figure 1.15 The biosphere The biosphere, one of Earth's four spheres, includes all life. **A.** Tropical rain forests are teeming with life and occur in the vicinity of the equator. (Photo by AGE Fotostock/SuperStock) **B.** Some life occurs in extreme environments such as the absolute darkness of the deep ocean. (Photo by Fisheries and Oceans Canada/Verena Tunnicliffe/Newscom)

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

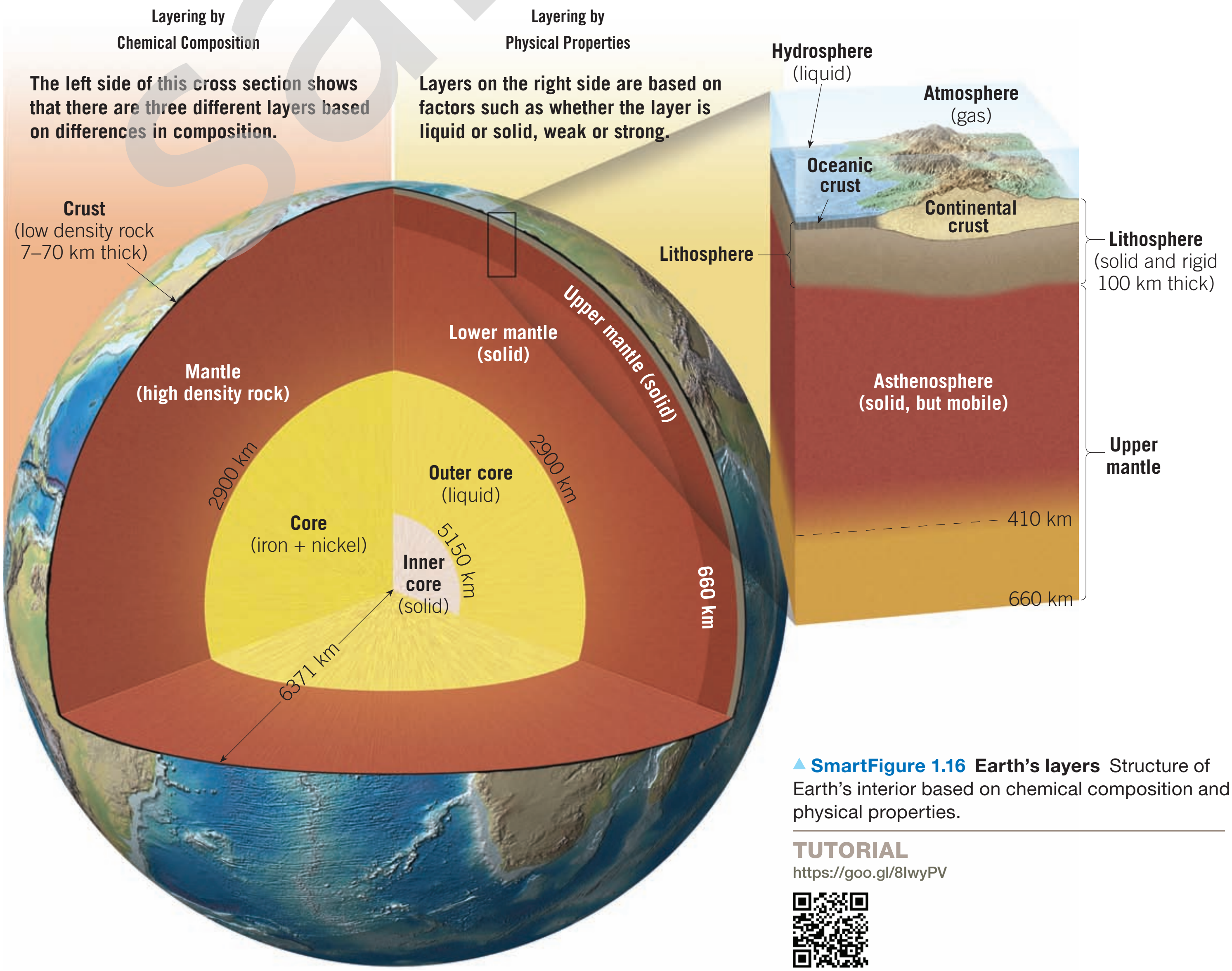


B. Microorganisms are nourished by hot, mineral-rich fluids spewing from vents on the deep-ocean floor. The microbes support larger organisms such as tube worms.

6400 kilometers (4000 miles)—by far the largest of Earth's spheres. Much of our study of the solid Earth focuses on the more accessible surface and near-surface features, but it is worth noting that many of these features are linked to the dynamic behavior of Earth's interior. Earth's interior is layered. As Figure 1.16 shows, we can think of this layering as being due to differences in both *chemical composition* and *physical properties*. On the basis of chemical composition, Earth has three layers: a dense inner sphere called the **core**; the less dense **mantle**; and the **crust**, which is the light and very thin outer skin of Earth. The crust is not a layer of uniform thickness. It is thinnest beneath the oceans and thickest where continents exist. Although the crust may seem insignificant when compared with the other layers of the geosphere, which are much thicker, it was created by the same general processes that formed Earth's present structure. Thus, the crust is important in understanding the history and nature of our planet.

The layering of Earth in terms of physical properties reflects the way Earth's materials behave when various forces and stresses are applied. The term **lithosphere** refers to the rigid outer layer that includes the crust and uppermost mantle. Beneath the rigid rocks that compose the lithosphere, the rocks of the **asthenosphere** are weak and able to slowly flow in response to the uneven distribution of heat deep within Earth.

The two principal divisions of Earth's surface are the continents and the ocean basins. The most obvious difference between these two provinces is their relative vertical levels. The average elevation of the continents above sea level is about 840 meters (2750 feet), whereas the average depth of the oceans is about 3800 meters (12,500 feet). Thus, the continents stand on average 4640 meters (about 4.6 kilometers, or nearly 3 miles) above the level of the ocean floor.



▲ SmartFigure 1.16 **Earth's layers** Structure of Earth's interior based on chemical composition and physical properties.

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◀ **Figure 1.17 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)

Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered rock debris (geosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between solid particles.

Earth System Science

A simple example of the interactions among different parts of the Earth system occurs every winter, as moisture evaporates from the Pacific Ocean and subsequently falls as rain in the mountains of Washington, Oregon, and California, 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 1.17**).

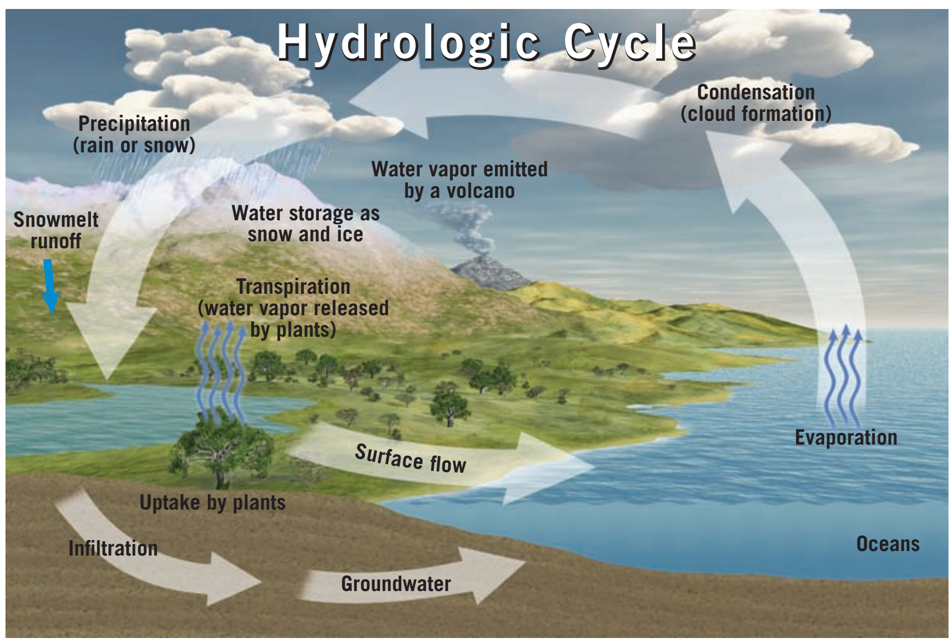
Scientists have recognized that in order to more fully understand our planet, they must learn how its individual components (land, water, air, and life-forms) are interconnected. This endeavor, called **Earth system science**, aims to study Earth as a *system* composed of numerous interacting parts, 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 many 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 be a participant in the 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 called 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 loop, or subsystem, is the *hydrologic cycle*. It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and geosphere (**Figure 1.18**). 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 sinks in and then is taken up by plants or becomes groundwater, and some flows across the surface toward the ocean.

▼ **Figure 1.18 The hydrologic cycle** Water readily changes state from liquid, to gas (vapor), to solid at the temperatures and pressures occurring on Earth. This cycle traces the movements of water among Earth's four spheres. It is one of many subsystems that collectively make up the Earth system.



Viewed over long time spans, the rocks of the geosphere are constantly forming, changing, and re-forming. The loop that involves the processes by which one rock changes to another is called the *rock cycle* and is discussed at some length in Chapter 3. The cycles of the Earth system are not independent of one another. To the contrary, there are many places where the cycles come in contact and interact.

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

Where the surface is covered by lava flows or a thick layer of volcanic ash, existing soils are buried. This causes the soil-forming processes to begin anew to transform the new surface material into soil (**Figure 1.19**). 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, and new settings for life, such as a lake formed by a lava dam, would be created. The potential climate change could also impact sensitive life-forms.

Time and Space Scales The Earth system is characterized by processes that vary on spatial scales from fractions of millimeters to thousands of kilometers. Time scales for

▲ **Figure 1.19 Change is a geologic constant** When Mount St. Helens erupted in May 1980 (inset photo), 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; inset photo by USGS)

Earth's processes range from milliseconds to billions of years. As we learn about Earth, it becomes increasingly clear that despite significant separations in distance or time, many processes are connected, and a change in one component can influence the entire system.

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

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

The organization of this text involves traditional groupings of chapters that focus on closely related topics. Nevertheless, the theme of *Earth as a system* keeps recurring through *all* major units of this text. It is a thread that weaves through the chapters and helps tie them together.

CONCEPT CHECKS 1.4

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 The Face of Earth

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

The two principal divisions of Earth's surface are the **ocean basins** and the **continents** (Figure 1.20). A significant difference between these two areas is their relative elevation, and it results primarily from 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 (4.3 miles) thick and have an average density of about 3.0 g/cm^3.
- *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^3.

The thicker and 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 visible, 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 1.20).

During the past 70 years, oceanographers have used modern depth-sounding equipment and satellite technology to map significant portions of the ocean floor. These studies have led them to identify three major regions: *continental margins*, *deep-ocean basins*, and *oceanic (mid-ocean) ridges*.

Continental Margin 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

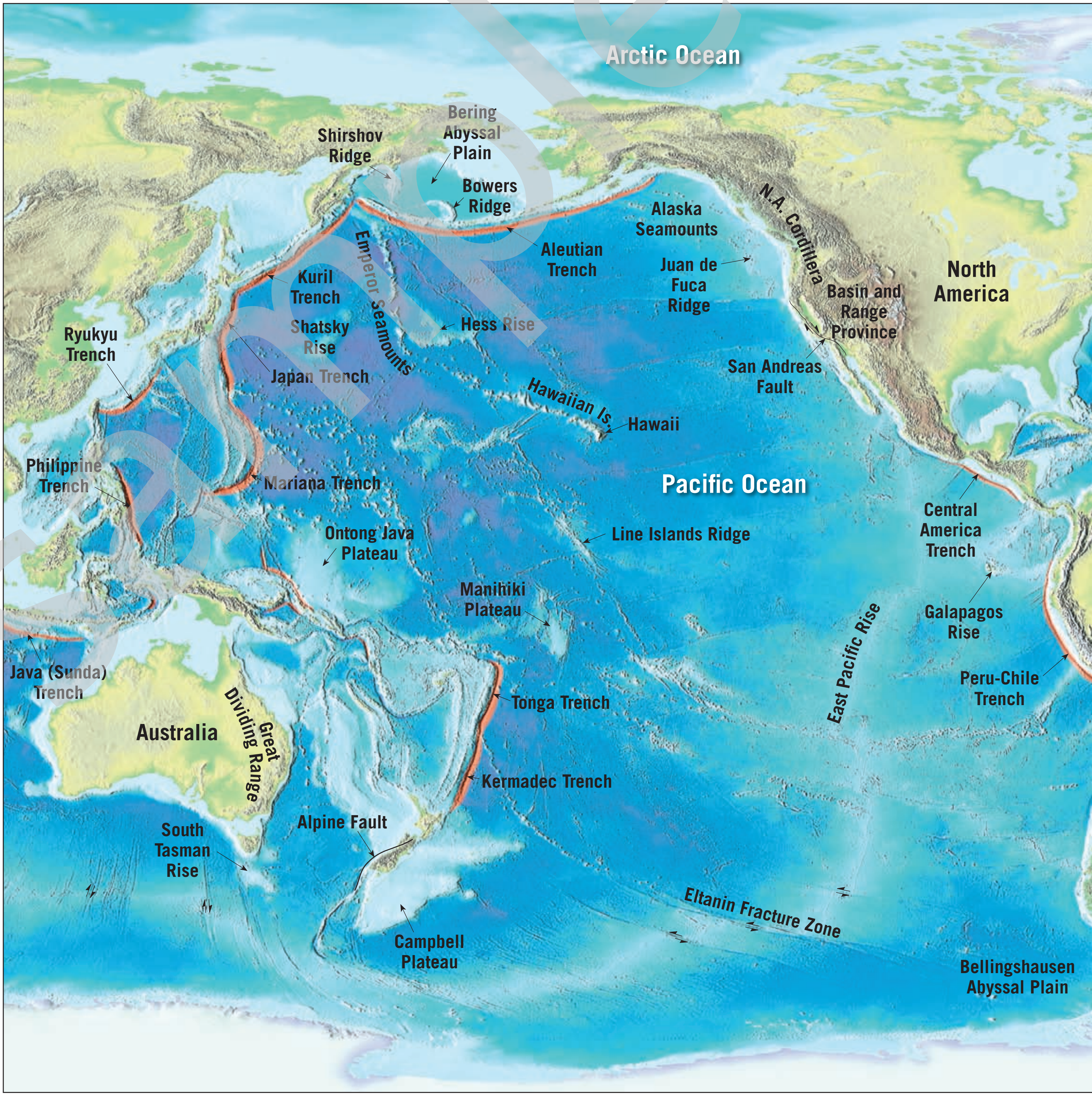
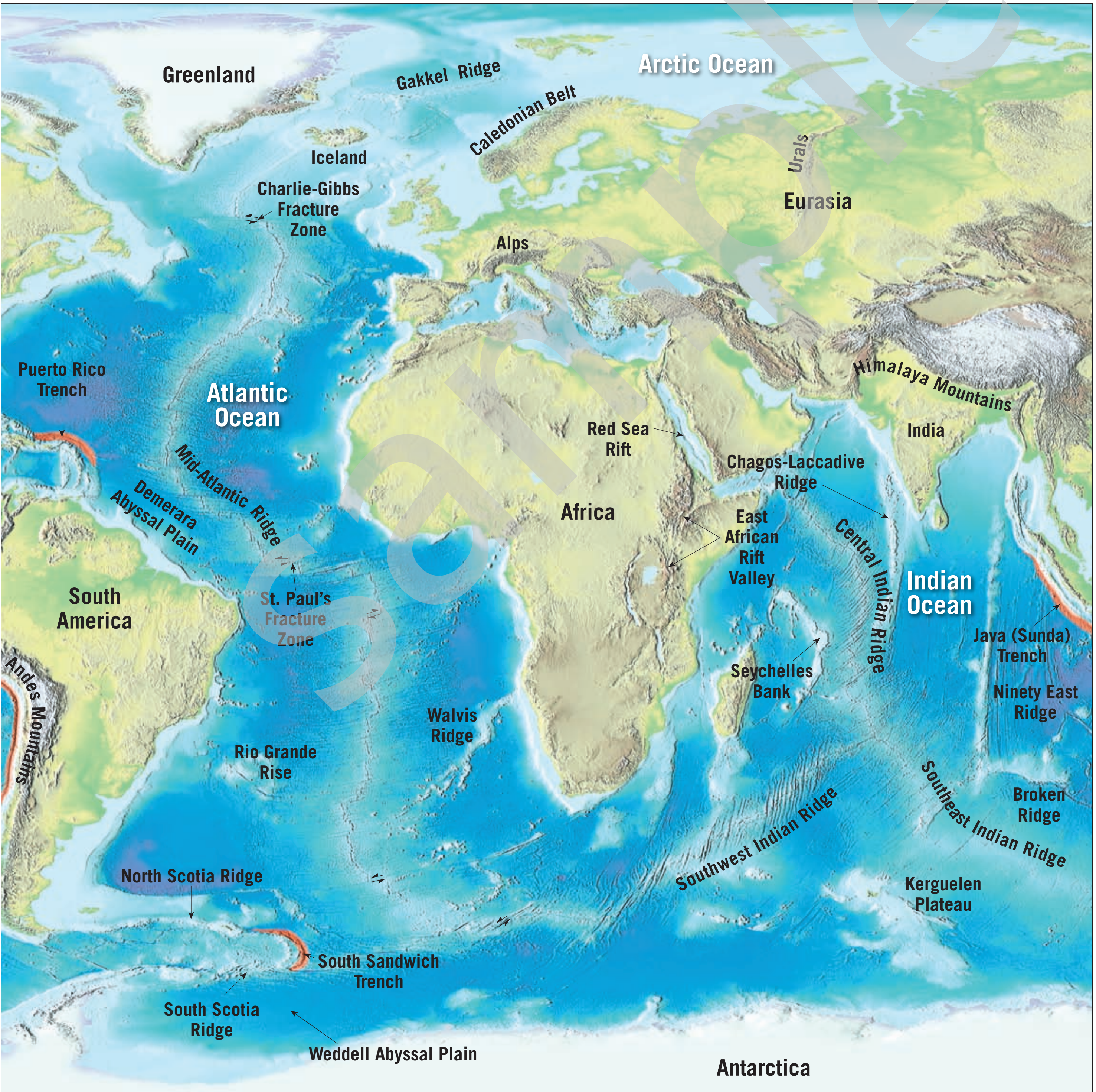


Figure 1.20 **The face of Earth** Major surface features of the geosphere.

platform, 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 1.20 shows that the width of the continental shelf is variable. 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**, which is a relatively steep drop-off that extends from the outer edge of the continental shelf, called the *shelf break*, to the floor of the deep ocean (see Figure 1.20). 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**. The continental rise



consists of a thick wedge of sediment that moved downslope from the continental shelf and accumulated on the deep-ocean floor.

Deep-Ocean Basins Between the continental margins and oceanic ridges are **deep-ocean basins**. Parts of these regions consist of incredibly flat features called **abyssal plains**. The ocean floor also contains extremely deep depressions that are occasionally 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 1.20 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

EYE ON EARTH 1.3

This photo shows the picturesque coastal bluffs and rocky shoreline along a portion of the California coast, south of San Simeon State Park.

QUESTION 1 *This area, like other shorelines, is described as an interface. What does that mean?*

QUESTION 2 *Does the shoreline represent the boundary between the continent and ocean basin? Explain.*

Michael Collier

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 1.20, the Mid-Atlantic Ridge and the East Pacific Rise are parts of this system. This broad elevated feature forms a continuous belt that winds for more than 70,000 kilometers (43,000 miles) around the globe, in a manner similar to the seam of a baseball. Rather than consist of highly deformed rock, as do most of the mountains on the continents, the oceanic ridge system consists of layer upon layer of igneous rock that has been fractured and uplifted.

Being familiar with the topographic (or relief) 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 in the next chapter, as we begin to investigate the dynamic processes that shaped our planet in the geologic past and will continue to shape it in the future.

Major Features of the Continents

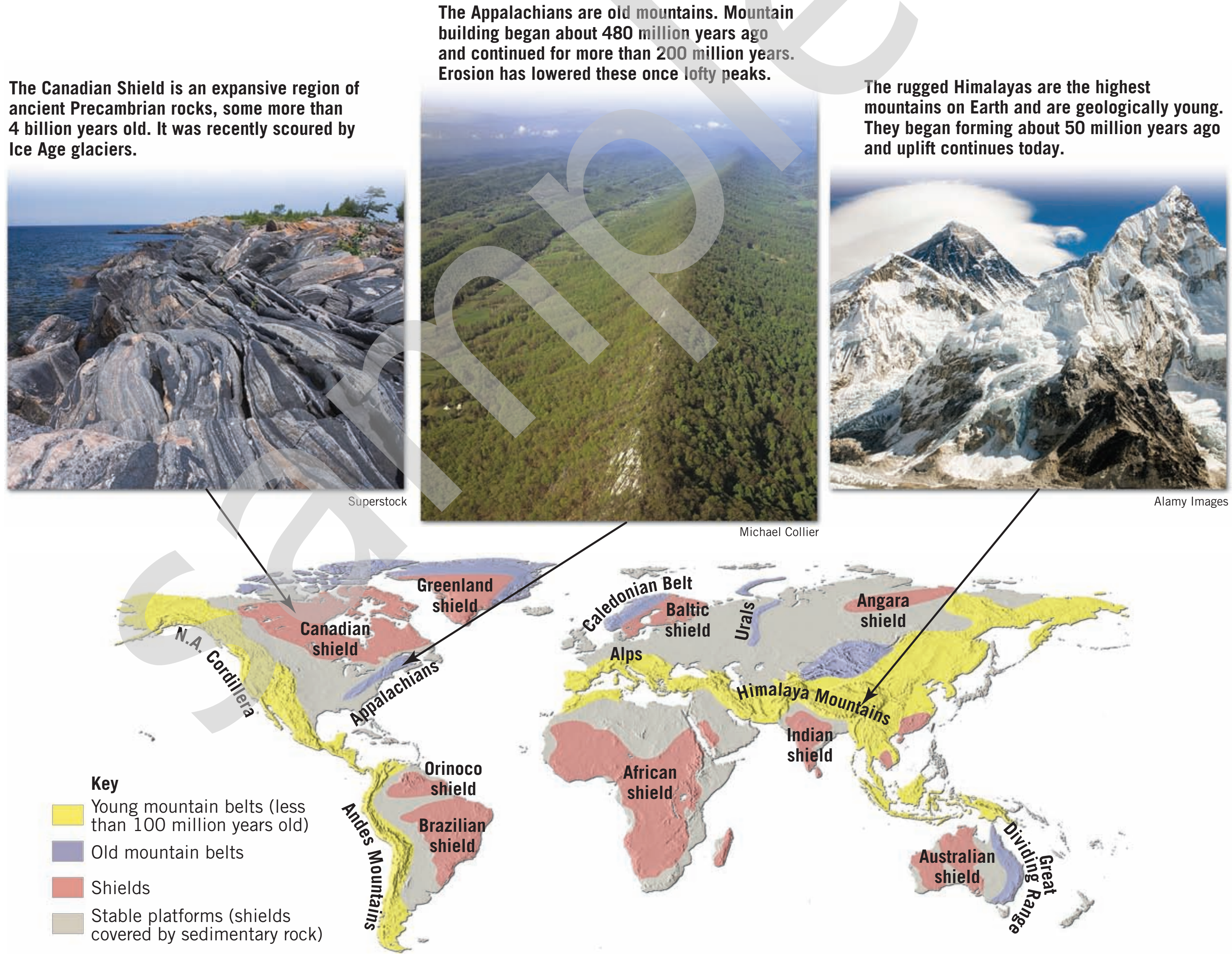
The major features of the continents can be grouped into two distinct categories: uplifted regions of deformed rocks that make up present-day mountain belts and extensive flat, stable areas that have eroded nearly to sea level. Notice in **Figure 1.21** that the young mountain belts tend to be long, narrow features at the margins of continents and that the flat, stable areas are typically located in the interiors of the continents.

Mountains The most prominent features of the continents are linear **mountain belts**. Although the distribution of mountains appears to be random, this is not the case. The youngest mountain belts (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 1.20). 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, as a result of millions of years of weathering and erosion.

The Stable Interior Unlike the young mountain belts, which 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. Typically these regions were involved in mountain-building episodes much earlier in Earth's history.

Within the stable interiors are areas known as **shields**, which are expansive, flat regions composed



▲ **SmartFigure 1.21 The continents** Distribution of mountain belts, stable platforms, and shields. (Photo by Radius Images/ SuperStock, Image Source/Alamy Stock Photo)

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largely of deformed igneous and metamorphic rocks. Notice in Figure 1.21 that the Canadian Shield is exposed in much of the northeastern part of North America. Radiometric dating of various shields has revealed that they are truly ancient regions. All contain Precambrian-age rocks that are 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, in which 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.

CONCEPT CHECKS 1.5

1. Compare and contrast continents and ocean basins.
2. Name the three major regions of the ocean floor. What are some physical 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

Introduction to Earth Science

1.1 What Is Earth Science?

List and describe the sciences that collectively make up Earth science. Discuss the scales of space and time in Earth science.

KEY TERMS: Earth science, geology, oceanography, meteorology, astronomy, geologic time

- Earth science includes geology, oceanography, meteorology, and astronomy.
- There are two broad subdivisions of geology. Physical geology studies Earth materials and the internal and external processes that create and shape Earth's landscape. Historical geology examines Earth's history.
- The other Earth sciences seek to understand the oceans, the atmosphere's weather and climate, and Earth's place in the universe.
- Earth science must deal with processes and phenomena that vary in size from the subatomic scale of matter to the nearly infinite scale of the universe.
- The time scales of phenomena studied in Earth science range from tiny fractions of a second to many billions of years.
- Geologic time, the span of time since the formation of Earth, is about 4.6 billion years, a number that is difficult to comprehend.

1.2 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

- Scientists make careful observations, construct tentative explanations for those observations (hypotheses), and then test those hypotheses with field investigations, laboratory work, and/or computer modeling.
- In science, a theory is a well-tested and widely accepted explanation that the scientific community agrees best fits certain observable facts.
- As failed 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 change in our model of the world.

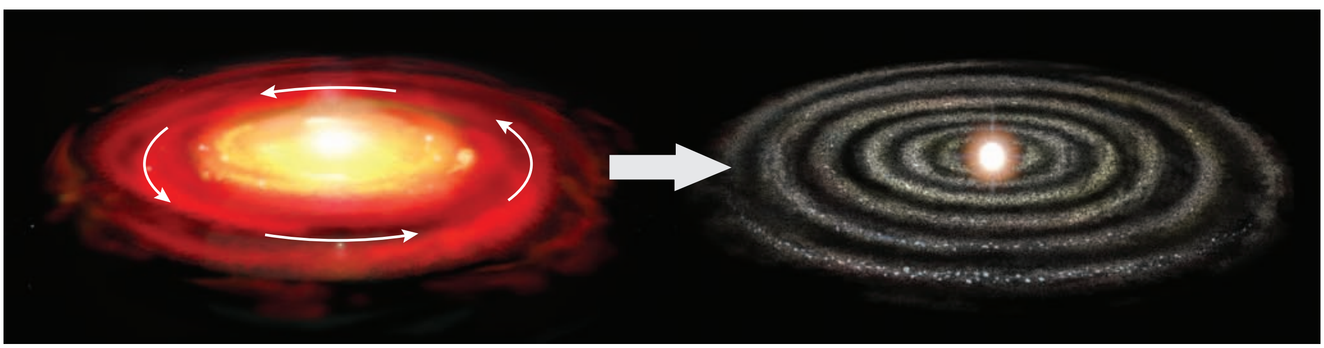
1.3 Early Evolution of Earth

Outline the stages in the formation of our solar system.

KEY TERMS: nebular theory

- The nebular theory describes the formation of the solar system. The planets and Sun began forming about 5 billion years ago from a large cloud of dust and gases.
- As the cloud contracted, it rotated faster and assumed a disk shape. Material that was gravitationally pulled toward the center became the protosun. Within the rotating disk, solid matter gradually cohered to form objects called planetesimals, which grew as they 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 large quantities of the light elements in the disk. Because of the very cold temperatures existing far from the Sun, the large outer planets include huge amounts of lighter materials. These substances account for the comparatively large sizes and low densities of the outer planets.

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



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: Earth system, hydrosphere, atmosphere, biosphere, geosphere, core, mantle, crust, lithosphere, asthenosphere, 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 thin 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, about 97 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, which powers the internal processes that produce volcanoes, earthquakes, and mountains.

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


Michael Collier

1.5 The Face of Earth

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

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 continents and ocean basins. A significant difference between them, their relative elevations, results primarily from differences in their respective densities and thicknesses.
- Continents have relatively flat, stable core 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 younger mountain belts, linear zones of intense deformation and metamorphism.
- The ocean basins are rimmed by shallow continental shelves, which are essentially flooded portions of the continents. The deep ocean includes vast abyssal plains and narrow, very deep ocean trenches. Seamounts and lava plateaus interrupt the abyssal plain in some places.

? 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**

1 After entering a dark room, you turn on a wall switch, but the light does not come on. Suggest at least three hypotheses that might explain this observation. How would you determine which one of your hypotheses (if any) is correct?

2 The length of recorded history for humankind is about 5000 years. Clearly, most people view this span as being very long. How does it compare to the length of geologic time? Calculate the percentage or fraction of geologic time that is represented by recorded history. To make calculations easier, round the age of Earth to the nearest billion.

3 Refer to the graph in Figure 1.14 to answer the following questions.
- **a.** 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?
- **b.** 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?

4 Examine Figure 1.13 to answer these questions.
- **a.** Where is most of Earth's freshwater stored?
- **b.** Where is most of Earth's liquid freshwater found?

5 Jupiter, the largest planet in our solar system, is 5.2 astronomical units (AU) from the Sun. How long would it take to go from Earth to Jupiter if you traveled as fast as a jet (1000 kilometers per hour)? Do the same calculation for Neptune, which is 30 AU from the Sun. Referring to GEOgraphics 1.1 on page 12 will be helpful.

6 These rock layers consist of materials such as sand, mud, and gravel that, over a span of millions of years, were deposited by rivers, waves, wind, and glaciers. Each layer was buried by subsequent deposits and eventually compacted and cemented into solid rock. Later, the region was uplifted, and erosion exposed the layers seen here.
- **a.** 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?
- **b.** Explain the logic you used.

(Photo by M. Timothy O'Keefe/Alamy Stock Photo)

EXAMINING THE EARTH SYSTEM

1 This scene is in British Columbia's Mount Robson Provincial Park. The park is named for the highest peak in the Canadian Rockies.

a. List as many examples as possible of features associated with each of Earth's four spheres.

b. Which, if any, of these features was created by internal processes? Describe the role of external processes in this scene.

Michael Wheatley/AGE Fotostock

2 Humans are a part of the Earth system. List at least three examples of how you, in particular, influence one or more of Earth's major spheres.

3 The accompanying photo provides an example of interactions among different parts of the Earth system. It is a view of a debris flow (popularly called a mudslide) that was triggered by extraordinary rains. Which of Earth's four spheres were involved in this natural disaster, which buried a small town on the Philippine island of Leyte? Describe how each might have contributed to or been influenced by the event.

Pat Roque/AP Photo

DATA ANALYSIS

Swift Creek Landslide

The Swift Creek landslide is located in northwestern Washington State, on the west side of Sumas Mountain. The landslide moves on average 3 to 4 meters per year, which is about 1 centimeter per day.

ACTIVITIES

Go to the Western Washington University Swift Creek Landslide Observatory (SCLO) page at http://landslide.geol.wwu.edu and click About SCLO.

1 Why are geologists, government agencies, and local residents interested in the Swift Creek landslide?

Click TimeLapse to open the video generator. Choose a start date of January 1, 2007, and an end date of January 1, 2014. For time of day select between 12pm-3pm for the best lighting. Set the framerate to Medium, for 20 frames per second. Select the camera position and click Generate. It may take about 30 seconds to generate the video.

2 Compare the Upper camera to the Lower camera. Which section of the landslide has a more constant flow rate? How can you tell?

Use the TimeLapse video generator to answer the following question. You may need to watch multiple years and examine each season separately.

3 Is the flowrate of the upper part of the landslide faster during the wet season (October–March) or the dry season (April–September)?

UNIT 1
Earth Materials

Matter and Minerals

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 List the main characteristics that an Earth material must possess to be considered a mineral and describe each characteristic.

2.2 Compare and contrast the three primary particles contained in atoms.

2.3 Distinguish among ionic bonds, covalent bonds, and metallic bonds.

2.4 List and describe the properties used in mineral identification.

2.5 List the common silicate and nonsilicate minerals and describe what characterizes each group.

2.6 Discuss Earth's mineral resources in terms of renewability. Differentiate between mineral resources and ore deposits.

The Cave of Crystals, Chihuahua, Mexico, contains giant gypsum crystals, some of the largest natural crystals ever found. (Photo by Carsten Peter/Speleoresearch & Films/National Geographic/Getty Images)

EARTH'S CRUST AND OCEANS are home to a wide variety of useful and essential minerals. Most people are familiar with the common uses of many basic metals, including aluminum in beverage cans, copper in electrical wiring, and gold and silver in jewelry. However, some people are not aware that pencil "lead" contains the greasy-feeling mineral graphite and that bath powders and many cosmetics contain the mineral talc. Moreover, many do not know that dentists use drill bits impregnated with diamonds to drill through tooth enamel. In fact, practically every manufactured product contains materials obtained from minerals.

In addition to the economic uses of rocks and minerals, every geologic process in some way depends on the properties of these basic Earth materials. Events such as volcanic eruptions, mountain building, weathering and erosion, and even earthquakes involve rocks and minerals. Consequently, a basic knowledge of Earth materials is essential to understanding all geologic phenomena.

2.1 Minerals: Building Blocks of Rocks

List the main characteristics that an Earth material must possess to be considered a mineral and describe each characteristic.

We begin our discussion of Earth materials with an overview of **mineralogy** (*mineral* = mineral, *ology* = study of) because minerals are the building blocks of rocks. Humans have used minerals for both practical and decorative purposes for thousands of years. For example, the common mineral quartz is the source of silicon for computer chips. The first Earth materials mined were flint and chert, which humans fashioned into weapons and cutting tools. As early as 3700 B.C.E. Egyptians began mining gold, silver, and copper. By 2200 B.C.E. humans had discovered how to combine copper with tin to make bronze—a strong, hard alloy. Later, a process was developed to extract iron from minerals such as hematite—a discovery that marked the decline of the Bronze Age. During the Middle Ages, mining of a variety of minerals became common, and the impetus for the formal study of minerals was in place.

In everyday conversation, the term *mineral* is used in several different ways. For example, those concerned with health and fitness extol the benefits of vitamins and minerals. The mining industry typically uses the word *mineral* to refer to anything extracted from Earth, such as coal, iron ore, or sand and gravel. The guessing game *Twenty Questions* usually begins with the question *Is it animal, vegetable, or mineral?* What criteria do geologists use to determine whether something is a mineral (**Figure 2.1**)?

▼ **Figure 2.1 Quartz crystals** A collection of well-developed quartz crystals found near Hot Springs, Arkansas. (Photo by Jeffrey A. Scovil)

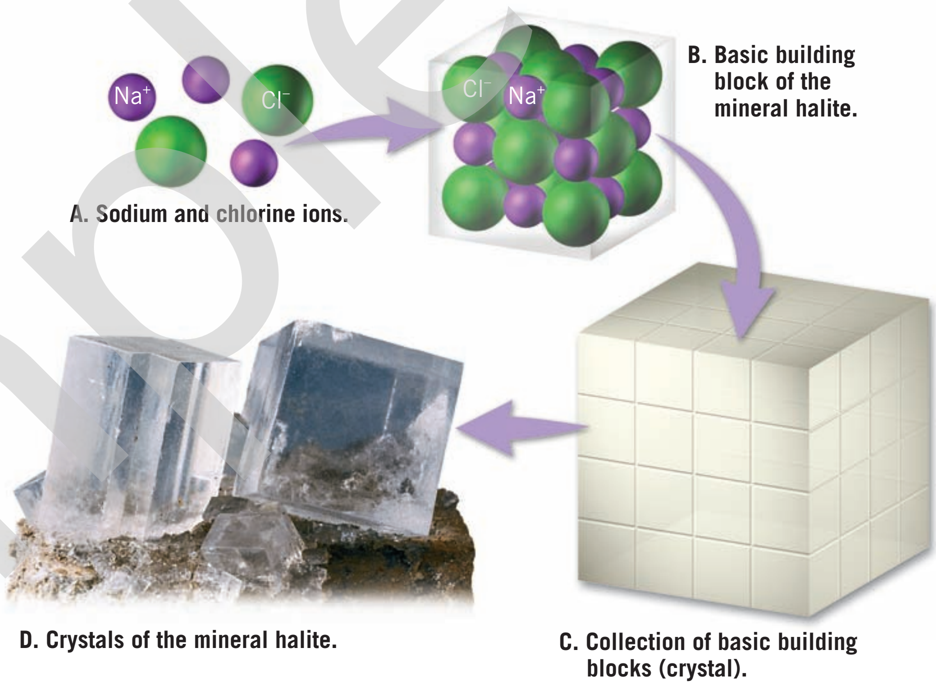
Defining a Mineral

Geologists define **mineral** as *any naturally occurring inorganic solid that possesses an orderly crystalline structure and a definite chemical composition that allows for some variation*. Thus, Earth materials that are classified as minerals exhibit the following characteristics:

1. **Naturally occurring.** Minerals form by natural geologic processes. Synthetic materials, meaning those produced in a laboratory or by human intervention, are not considered minerals.
2. **Generally inorganic.** Inorganic crystalline solids, such as ordinary table salt (halite), that are found naturally in the ground are considered minerals. Organic compounds (that is, the kinds of carbon-containing compounds that are made by living things) are generally not considered minerals. Sugar, a crystalline solid like salt but extracted from

sugarcane or sugar beets, is a common example of an organic compound. Many marine animals secrete inorganic compounds, such as calcium carbonate (calcite), in the form of shells and coral reefs. If these materials are buried and become part of the rock record, geologists consider them minerals.

3. **Solid substance.** Only solid crystalline substances are considered minerals. Ice (frozen water) fits this criterion and is considered a mineral, whereas liquid water and water vapor do not.
4. **Orderly crystalline structure.** Minerals are crystalline substances, made up of atoms (or ions) that are arranged in an orderly, repetitive manner (**Figure 2.2**). This orderly packing of atoms is reflected in regularly shaped objects called *crystals*. Some naturally occurring solids, such as volcanic glass (obsidian), lack a repetitive atomic structure and are not considered minerals.
5. **Definite chemical composition that allows for some variation.** Most minerals are chemical compounds having compositions that can be expressed by a chemical formula. For example, the common mineral quartz has the formula SiO_2, which indicates that quartz consists of silicon (Si) and oxygen (O) atoms, in a 1:2 ratio. This proportion of silicon to oxygen is true for any sample of pure quartz, regardless of its origin. However, the compositions of some minerals can vary *within specific, well-defined limits*. This occurs because certain elements can substitute for others of similar size without changing the mineral's internal structure.



▲ **Figure 2.2 Arrangement of sodium and chloride ions in the mineral halite** The arrangement of atoms (ions) into basic building blocks that have a cubic shape results in regularly shaped cubic crystals. (Photo by Dennis Tasa)

CONCEPT CHECKS 2.1

1. List five characteristics of a mineral.
2. Based on the definition of mineral, which of the following—gold, liquid water, synthetic diamonds, ice, and wood—are *not* classified as minerals?
3. Define the term *rock*. How do rocks differ from minerals?

What Is a Rock?

In contrast to minerals, rocks are more loosely defined. Simply, a **rock** is any solid mass of mineral or mineral-like matter that occurs naturally as part of our planet. Most rocks, like the sample of granite shown in **Figure 2.3**, are aggregates of several different minerals. The term *aggregate* implies that the minerals are joined in such a way that their individual properties are retained. Note that the different minerals that make up granite can be easily identified. However, some rocks are composed almost entirely of one mineral. A common example is the sedimentary rock *limestone*, which is an impure mass of the mineral calcite.

In addition, some rocks are composed of nonmineral matter. These include the volcanic rocks *obsidian* and *pumice*, which are noncrystalline glassy substances, and *coal*, which consists of solid organic debris.

Although this chapter deals primarily with the nature of minerals, keep in mind that most rocks are simply aggregates of minerals. Because the properties of rocks are determined largely by the chemical composition and crystalline structure of the minerals contained within them, we will first consider these Earth materials.

▼ **SmartFigure 2.3 Most rocks are aggregates of minerals** Shown here is a hand sample of the igneous rock granite and three of its major constituent minerals. (Photos by E. J. Tarbuck)

TUTORIAL
https://goo.gl/k5qL1I

2.2 Atoms: Building Blocks of Minerals

Compare and contrast the three primary particles contained in atoms.

When minerals are carefully examined, even under optical microscopes, the innumerable tiny particles of their internal structures are not visible. Nevertheless, scientists have discovered that all matter, including minerals, is composed of minute building blocks called **atoms**—the smallest particles that constitute specific elements and cannot be split by chemical means. Atoms, in turn, contain even smaller particles—*protons* and *neutrons* located in a central **nucleus** that is surrounded by *electrons* (**Figure 2.4**).

Properties of Protons, Neutrons, and Electrons

Protons and **neutrons** are very dense particles with almost identical masses. By contrast, **electrons** have a negligible mass, about 1/2000 that of a proton. To visualize this difference, imagine a scale on which a proton or neutron has the mass of a baseball, whereas an electron has the mass of a single grain of rice.

Both protons and electrons share a fundamental property called *electrical charge*. Protons have an electrical charge of +1, and electrons have a charge of –1. Neutrons, as the name suggests, have no charge. The charges of protons and electrons are equal in magnitude but opposite in polarity, so when these two particles are paired, the charges cancel each other out. Since matter typically contains equal numbers of positively charged protons and negatively charged electrons, most substances are electrically neutral.

Illustrations sometimes show electrons orbiting the nucleus in a manner that resembles the planets of our solar system orbiting the Sun (see Figure 2.4A). However, electrons do not actually behave this way. A more realistic depiction would show electrons as a cloud of negative charges surrounding the nucleus (see Figure 2.4B). Studies of the arrangements of electrons show that they move about the nucleus in regions called *principal shells*, each with an associated energy level. In addition, each shell can hold a specific number of electrons, with the outermost shell generally containing **valence electrons**. These electrons can be transferred to or shared with other atoms to form chemical bonds.

Most of the atoms in the universe (except hydrogen and helium) were created inside massive stars by nuclear fusion and then released into interstellar space during hot, fiery supernova explosions. As this ejected material cooled, the newly formed nuclei attracted electrons to complete their atomic structure. At the temperatures found at Earth's surface, free atoms (those not bonded to other atoms) generally have a full complement of electrons—one for each proton in the nucleus.

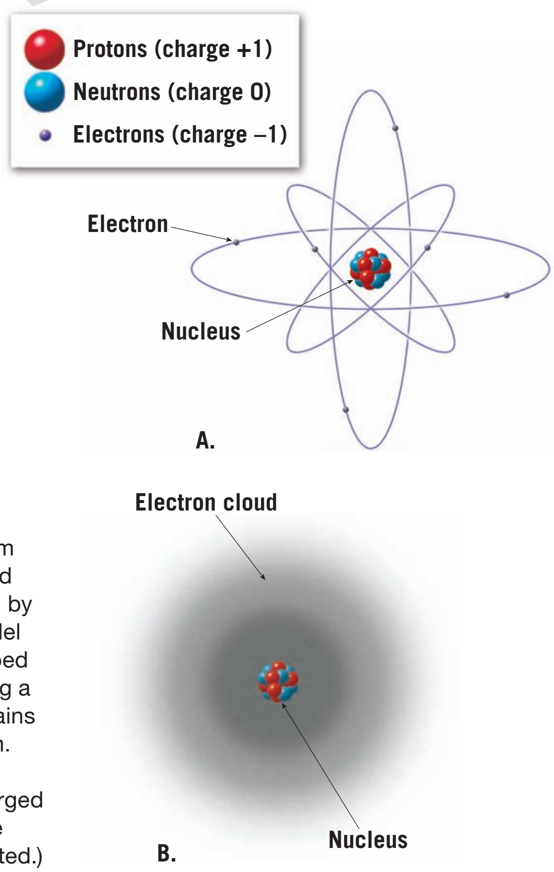
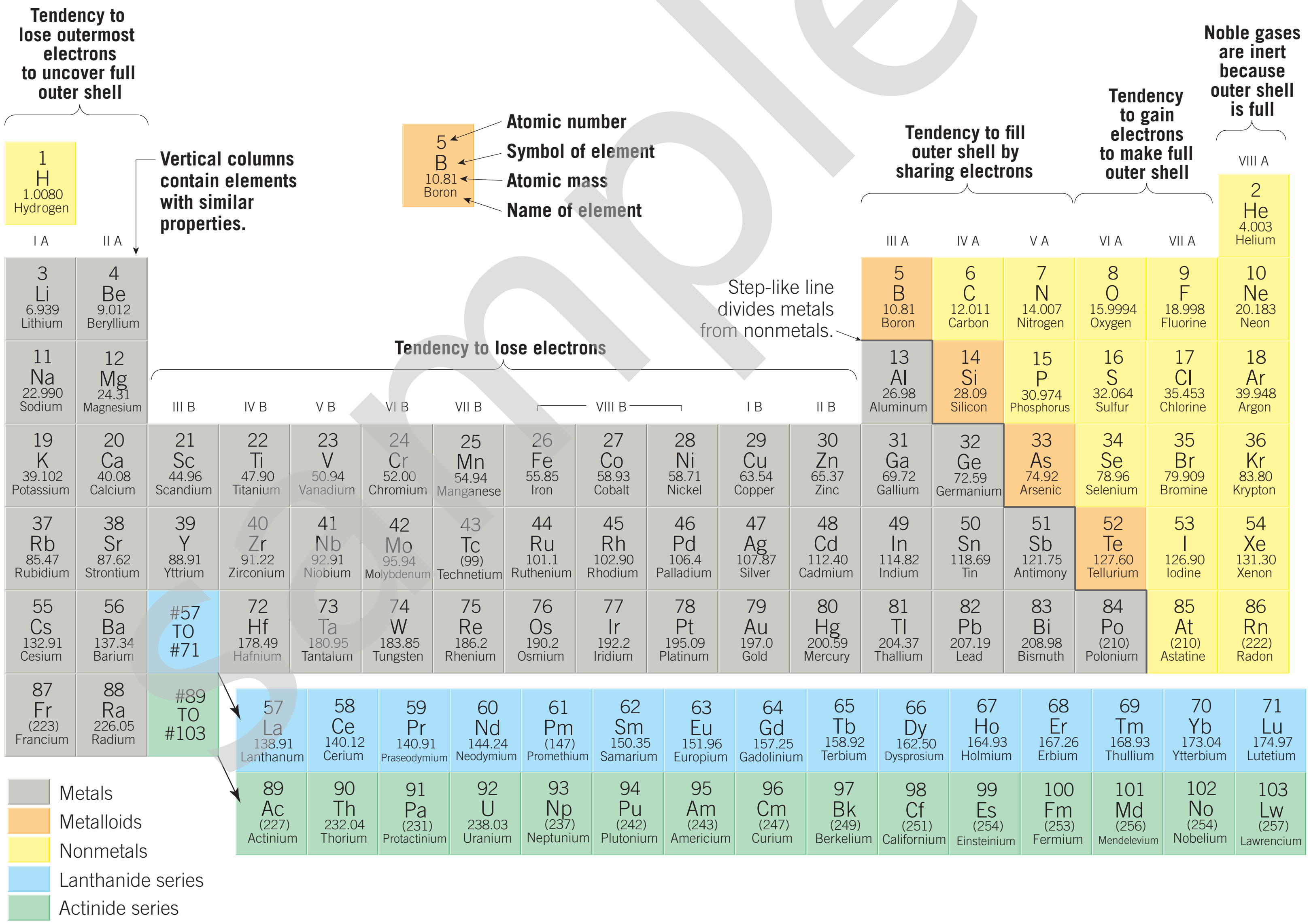


Figure 2.4 Two models of an atom A. Simplified view of an atom having a central nucleus composed of protons and neutrons, encircled by high-speed electrons. **B.** This model of an atom shows spherically shaped electron clouds (shells) surrounding a central nucleus. The nucleus contains virtually all of the mass of the atom. The remainder of the atom is the space occupied by negatively charged electrons. (The relative sizes of the nuclei shown are greatly exaggerated.)

Elements: Defined by Their Number of Protons

The simplest atoms have only 1 proton in their nuclei, whereas others have more than 100. The number of protons in the nucleus of an atom, called the **atomic number**, determines the atom's chemical nature. All atoms with the same number of protons have the same chemical and physical properties; collectively they constitute an **element**. There are about 90 naturally occurring elements, and several more have been synthesized in the laboratory. You are probably familiar with the names of many elements, including carbon, nitrogen, and oxygen. All carbon atoms have 6 protons, whereas all nitrogen atoms have 7 protons, and all oxygen atoms have 8.

The **periodic table**, shown in **Figure 2.5**, is a tool scientists use to organize the known elements. In it, the elements with similar properties line up in columns, referred to as *groups*. Each element is assigned a one- or two-letter symbol. The atomic number and atomic mass for each element are also included in the periodic table.



▲ **Figure 2.5 Periodic table of the elements**

▼ **Figure 2.6 Examples of minerals composed of a single element** (Photos by Dennis Tasa)

A. Gold on quartz **B. Sulfur** **C. Copper**

and calcite ($CaCO_3$). However, a few minerals, such as diamonds, sulfur, and native gold and copper, are made entirely of atoms of only one element (**Figure 2.6**). (A metal is called "native" when it is found in its pure form in nature; see GEOgraphics 2.1.)

Atoms of the naturally occurring elements are the basic building blocks of Earth's minerals. Most elements join with other elements to form **chemical compounds**. Therefore, most minerals are chemical compounds composed of atoms of two or more elements. These include the minerals quartz (SiO_2), halite ($NaCl$),

CONCEPT CHECKS 2.2

1. Make a simple sketch of an atom and label its three main particles. Explain how these particles differ from one another.
2. What is the significance of valence electrons?

GEOGRAPHICS 2.1

Gold

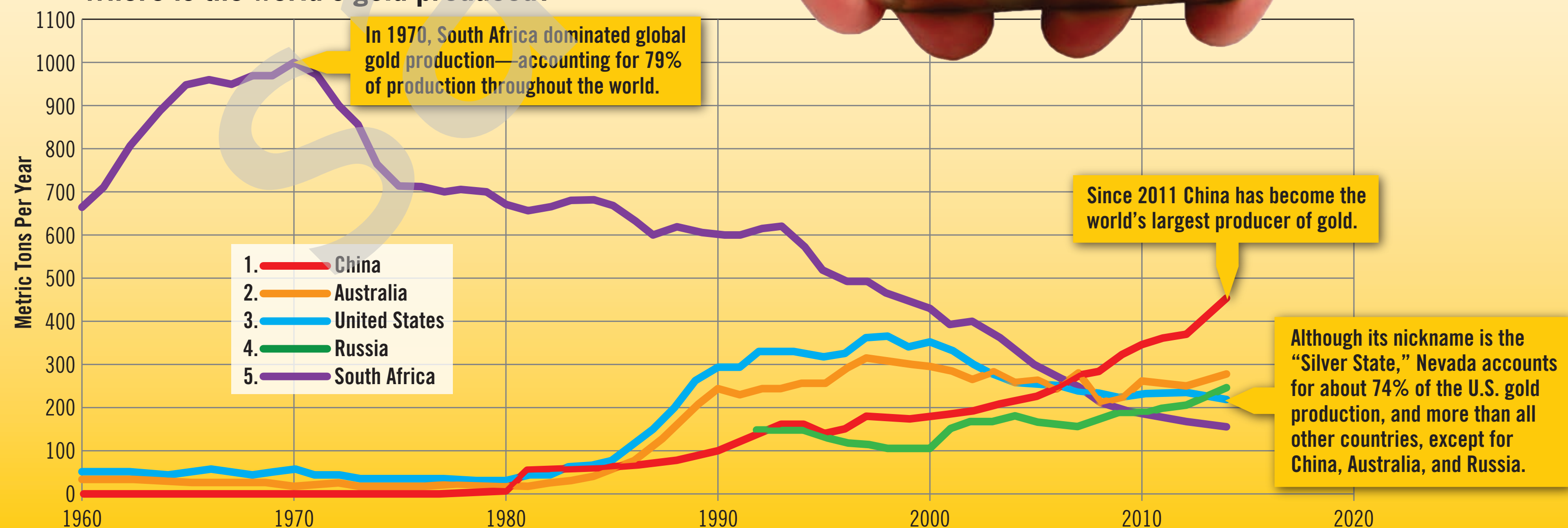
Gold has been treasured since long before recorded history for its beauty.

How valuable is gold? **$41,280**

Shutterstock

In early 2015, the value of one troy ounce of gold was about US$1,290. Based on that value, a 1000-gram (32-ounce) bar of gold, like the one shown, was worth $41,280. In 1970, the price of gold was less than $40 per troy ounce!

Where is the world's gold produced?



(Photo by D7INAMI7S/Shutterstock)

2.3 Why Atoms Bond

Distinguish among ionic bonds, covalent bonds, and metallic bonds.

Under the temperature and pressure conditions found on Earth, most elements do not occur in the form of individual atoms; instead, their atoms bond with other atoms. (A group of elements known as the noble gases are an exception.) Some atoms bond to form *ionic compounds*, some form *molecules*, and still others form *metallic substances*. Why does this happen? Experiments show that electrical forces hold atoms together and bond them to each other. These electrical attractions lower the total energy of the bonded atoms, and this, in turn, generally makes them more stable. Consequently, atoms that are bonded in compounds tend to be more stable than atoms that are free (not bonded).

The Octet Rule and Chemical Bonds

As noted earlier, valence (outer-shell) electrons are generally involved in chemical bonding. **Figure 2.7** shows a shorthand way of representing the number of valence electrons for some selected elements. Notice that the elements in Group I have one valence electron each, those in Group II have two valence electrons each, and so on, up to eight valence electron in Group VIII.

The noble gases have very stable electron arrangements with eight valence electrons (except helium, which has two) and, therefore, tend to lack chemical reactivity. Many other

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Native gold

Because gold does not easily react with other elements, it often occurs as a native element in nuggets found in stream deposits or as grains in igneous rocks.

Shutterstock

What are the uses of gold?

About 50% of gold is used in jewelry. Another 40% is used for currency and investment, and about 10% is used in industry, including electronic devices such as cell phones and televisions. Gold is also used in gourmet foods and cocktails as a decorative ingredient. Because metallic gold is one of the least reactive materials, it has no taste, provides no nutritional value, and leaves the human body unaltered.

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Questions:

1. What is the chemical symbol for gold?
2. What is the term for the property of tenacity, which allows gold to be easily hammered into different shapes?

?

Electron Dot Diagrams for Some Representative Elements

I	II	III	IV	V	VI	VII	VIII
H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca	Ga	Ge	As	Se	Br	Kr

▲ **Figure 2.7** **Dot diagrams for certain elements** Each dot represents a valence electron found in the outermost principal shell.

atoms gain, lose, or share electrons during chemical reactions, ending up with electron arrangements of the noble gases. This observation led to a chemical guideline known as the **octet rule**: *Atoms tend to gain, lose, or share electrons until they are surrounded by eight valence electrons.* Although there are exceptions to the octet rule, it is a useful *rule of thumb* for understanding chemical bonding.

When an atom's outer shell does not contain eight electrons, it is likely to chemically bond to other atoms to achieve an octet in its outer shell. A **chemical bond** is a transfer or sharing of electrons that allows each atom to attain a full valence shell of electrons. Some atoms do this by transferring all their valence electrons to other atoms so that an inner shell becomes the full valence shell.

When the valence electrons are transferred between the elements to form ions, the bond is an *ionic bond*. When the electrons are shared between the atoms, the bond is a *covalent bond*. When the valence electrons are shared among all the atoms in a substance, the bonding is *metallic*.

Ionic Bonds: Electrons Transferred

Perhaps the easiest type of bond to visualize is the **ionic bond**, in which one atom gives up one or more valence electrons to another atom to form **ions**—*positively and negatively charged atoms*. The atom that loses electrons becomes a positive ion, and the atom that gains electrons becomes a negative ion. Oppositely charged ions are strongly attracted to one another and join to form *ionic compounds*.

Consider the ionic bonding that occurs between sodium (Na) and chlorine (Cl) to produce the solid ionic compound sodium chloride—the mineral halite (common table salt). Notice in **Figure 2.8A** that a sodium atom gives up its single valence electron to chlorine and, as a result, becomes a positively charged sodium ion (Na^+). Chlorine, on the other hand, gains one electron and becomes a negatively charged chloride ion (Cl^-). We know that ions having unlike charges attract. Thus, an ionic bond is an attraction of oppositely charged ions to one another that produces an electrically neutral ionic compound.

Figure 2.8B illustrates the arrangement of sodium and chlorine ions in ordinary table salt. Notice that salt consists of alternating sodium and chlorine ions, positioned so that each positive ion is attracted to and surrounded on all sides by negative ions and vice versa. This arrangement maximizes the attraction between ions with opposite charges while minimizing the repulsion between ions with identical charges. Thus, ionic compounds consist of an orderly arrangement of oppositely charged ions assembled in a definite ratio that provides overall electrical neutrality.

The properties of a chemical compound are dramatically different from the properties of the various elements comprising it. For example, sodium is a soft silvery metal that is extremely reactive and poisonous. If you were to consume even a small amount of elemental sodium, you would need immediate medical attention. Chlorine, a green poisonous gas, is so toxic that it was used as a chemical weapon during World War I. Together, however, these elements produce sodium chloride, the edible flavor enhancer that we call table salt. Thus, when elements combine to form compounds, their properties change significantly.

Covalent Bonds: Electron Sharing

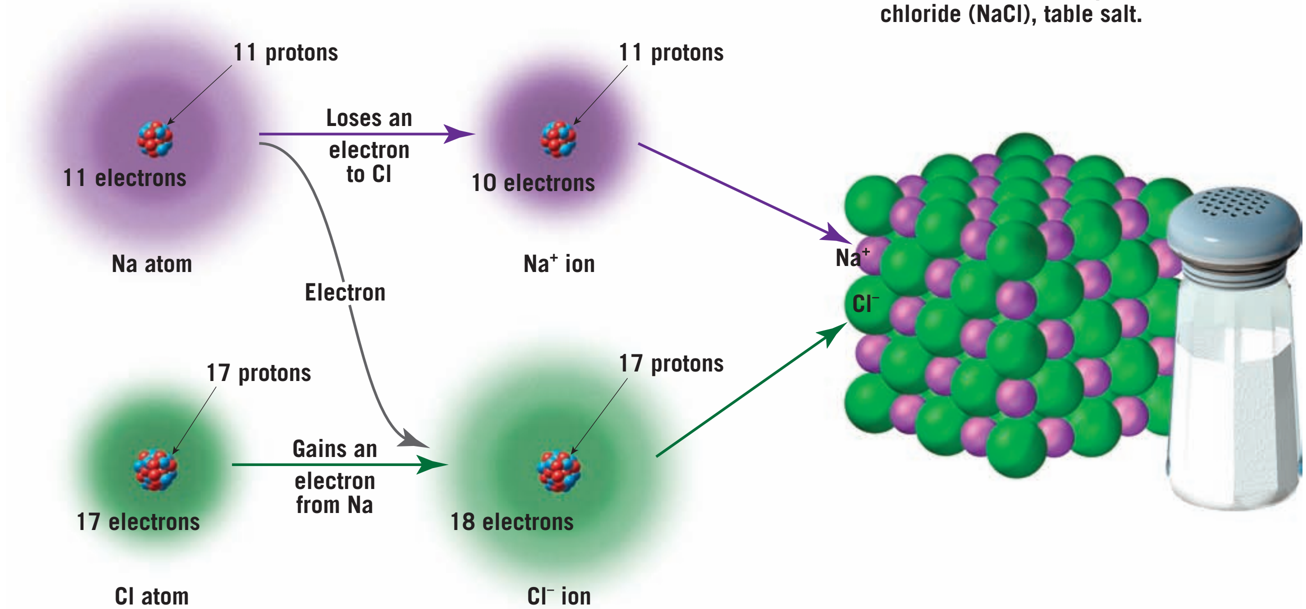
Sometimes the forces that hold atoms together cannot be understood on the basis of the attraction of oppositely charged ions. One example is the hydrogen molecule (H_2), in which the two hydrogen atoms are held together tightly and no ions are present. The strong attractive force that holds two hydrogen atoms together results from a **covalent bond**, a chemical bond formed by the *sharing* of one or more valance electrons between a pair of atoms. (Hydrogen is one of the exceptions to the octet rule: Its single shell is full with just two electrons.)

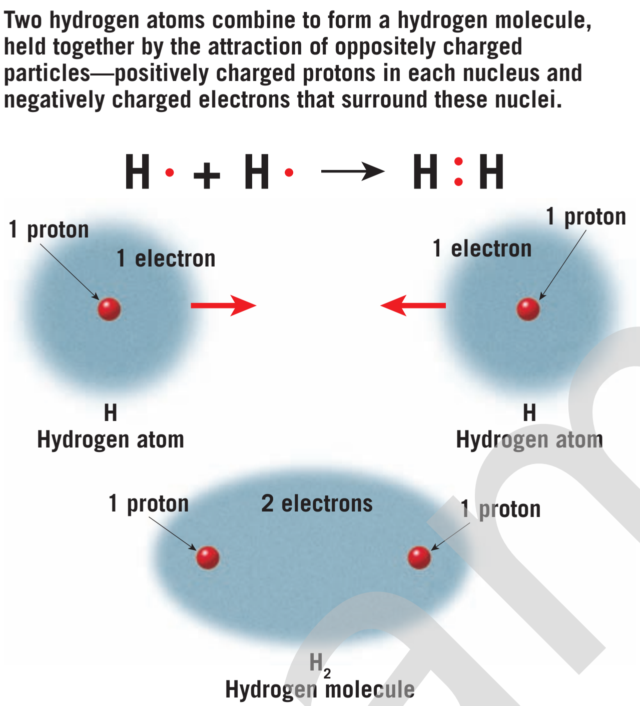
Imagine two hydrogen atoms (each with one proton and one electron) approaching one another, as shown in **Figure 2.9**. Once they meet, the electron configuration changes so that both electrons primarily occupy the space between the atoms. In other words, the two electrons are shared by both hydrogen atoms and are attracted simultaneously by the positive charge of the proton in the

Figure 2.8 Formation of the ionic compound sodium chloride

A. The transfer of an electron from a sodium (Na) atom to a chlorine (Cl) atom leads to the formation of a Na^+ ion and a Cl^- ion.

B. The arrangement of Na^+ and Cl^- in the solid ionic compound sodium chloride (NaCl), table salt.





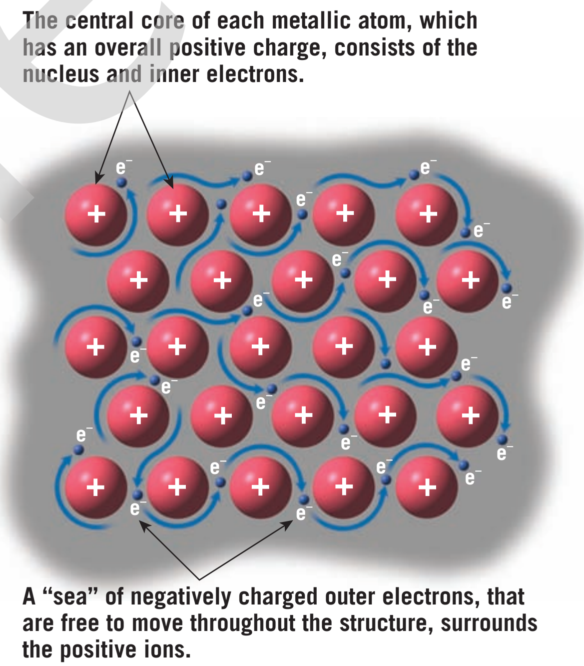
▲ **Figure 2.9 Formation of a covalent bond** When hydrogen atoms bond, the negatively charged electrons are shared by both hydrogen atoms and attracted simultaneously by the positive charge of the proton in the nucleus of each atom.

nucleus of each atom. In this situation the hydrogen atoms do not form ions; instead, the force that holds these atoms together arises from the attraction of oppositely charged particles—positively charged protons in the nuclei and negatively charged electrons that surround these nuclei.

Metallic Bonds: Electrons Free to Move

A few minerals, such as native gold, silver, and copper, are made entirely of metal atoms packed tightly together in an orderly way. The bonding that holds these atoms together results from each atom contributing its valence electrons to a common pool of electrons, which freely move throughout the entire metallic structure. The contribution of one or more valence electrons leaves an array of positive ions immersed in a "sea" of valence electrons, as shown in **Figure 2.10**.

The attraction between this sea of negatively charged electrons and the positive ions produces the **metallic bonds** that give metals their unique properties. Metals are good conductors of electricity because the valence electrons are free to move from one atom to another. Metals are also *malleable*, which means they can be hammered into thin sheets, and *ductile*, which means they can be drawn into thin wires. By contrast, ionic and covalent solids tend to be *brittle* and fracture when stress is applied. Consider the difference between dropping a metal frying pan and a ceramic plate onto a concrete floor.



▲ **Figure 2.10 Metallic bonding** Metallic bonding is the result of each atom contributing its valence electrons to a common pool of electrons that are free to move throughout the entire metallic structure. The attraction between the "sea" of negatively charged electrons and the positive ions produces the metallic bonds that give metals their unique properties.

CONCEPT CHECKS 2.3

1. What is the difference between an atom and an ion?
2. How does an atom become a positive ion? A negative ion?
3. Briefly distinguish between ionic, covalent, and metallic bonding and discuss the role that electrons play in each.

EYE ON EARTH 2.1

The accompanying image shows one of the world's largest open-pit gold mine, located near Kalgoorlie, Australia. Known as the Super Pit, it originally consisted of a number of small underground mines that were consolidated into a single, open-pit mine. Each year, about 28 metric tons of gold are extracted from the 15 million metric tons of rock shattered by blasting and then transported to the surface.

QUESTION 1 *What is one environmental advantage of underground mining over open-pit mining?*

QUESTION 2 *For those employed at this mine, what change in working conditions would have occurred as it evolved from an underground mine to an open-pit mine?*

(Photo by McPhoto/Bickwinkel/AGE Fotostock)

2.4 Properties of Minerals

List and describe the properties used in mineral identification.

Minerals have definite crystalline structures and chemical compositions that give them unique sets of physical and chemical properties shared by all specimens of that mineral, regardless of when or where they formed. For example, two samples of the mineral quartz will be equally hard and equally dense, and they will break in a similar manner. However, the physical properties of individual samples may vary within specific limits due to ionic substitutions, inclusions of foreign elements (impurities), and defects in the crystalline structure.

Some mineral properties, called **diagnostic properties**, are particularly useful in identifying an unknown mineral. The mineral halite, for example has a salty taste. Because so few minerals share this property, a salty taste is considered a diagnostic property of halite. Other properties of certain minerals, particularly color, vary among different specimens of the same mineral. These properties are referred to as **ambiguous properties**.

▲ SmartFigure 2.12 **Color variations in minerals** Some minerals, such as fluorite, shown above, exhibit a variety of colors. (Photo by E. J. Tarbuck)

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Optical Properties

Of the many diagnostic properties of minerals, their optical characteristics such as luster, color, streak, and ability to transmit light are most frequently used for mineral identification.

A. This freshly broken sample of galena displays a metallic luster.

Metallic

B. This sample of galena is tarnished and has a submetallic luster.

Submetallic

▲ Figure 2.11 **Metallic versus submetallic luster** (Photos courtesy of E. J. Tarbuck)

Luster

The appearance or quality of light reflected from the surface of a mineral is known as **luster**. Minerals that are shiny like a metal, regardless of color, are said to have a *metallic luster* (Figure 2.11A). Some metallic minerals, such as native copper and galena, develop a dull coating or tarnish when exposed to the atmosphere. Because they are not as shiny as samples with freshly broken surfaces, these samples are often said to exhibit a *submetallic luster* (Figure 2.11B).

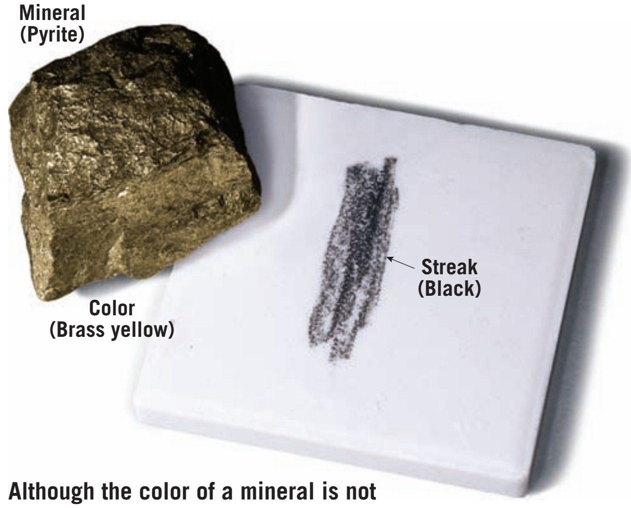
Most minerals have a *nonmetallic luster* and are described using various adjectives. For example, some minerals are described as being *vitreous*, or *glassy*. Other nonmetallic minerals are described as having a *dull*, or *earthy*, *luster* (a dull appearance like soil) or a *pearly luster* (such as a pearl or the inside of a clamshell). Still others exhibit a *silky luster* (like satin cloth) or a *greasy luster* (as though coated in oil).

Color

Although **color** is generally the most conspicuous characteristic of any mineral, it is considered a diagnostic property of only a few minerals. Slight impurities in the common minerals fluorite and quartz, for example, give them a variety of tints, including pink, purple, yellow, white, gray, and even black (Figure 2.12). Other minerals, such as tourmaline, also exhibit a variety of hues, with multiple colors sometimes occurring in the same sample. Thus, the use of color as a means of identification is often ambiguous or even misleading.

Streak

The color of a mineral in powdered form, called **streak**, is often useful in identification. A mineral's streak is obtained by rubbing it across a *streak plate* (a piece of unglazed porcelain) and observing the color of the mark it leaves (Figure 2.13). Although a mineral's color may vary



Although the color of a mineral is not always helpful in identification, the streak, which is the color of the powdered mineral, can be very useful.

▲ SmartFigure 2.13 **Streak** (Photo by Dennis Tasa)

VIDEO
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from sample to sample, its streak is usually consistent in color. (Note that not all minerals produce a streak when rubbed across a streak plate. Quartz, for example, is harder than a porcelain streak plate and therefore leaves no streak.)

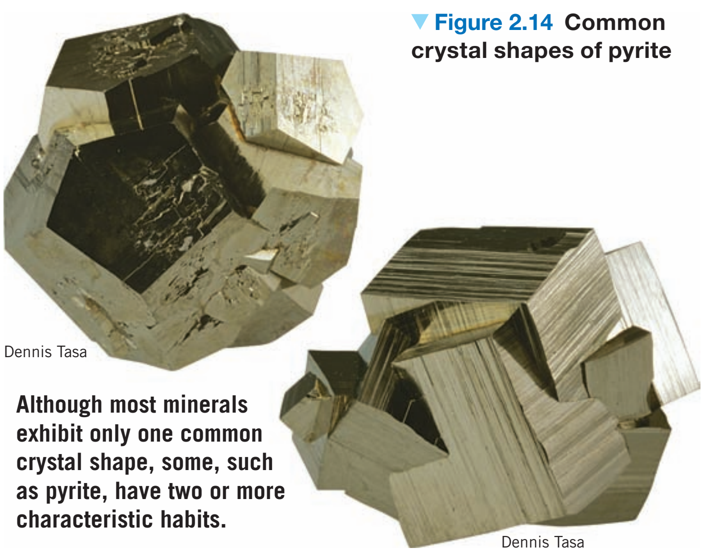
Streak can also help distinguish between minerals with metallic luster and those with nonmetallic luster. Metallic minerals generally have a dense, dark streak, whereas minerals with nonmetallic luster typically have a light-colored streak.

Ability to Transmit Light Another optical property used to identify minerals is the ability to transmit light. When no light is transmitted through a mineral sample, that mineral is described as *opaque*; when light, but not an image, is transmitted, the mineral is said to be *translucent*. When both light and an image are visible through the sample, the mineral is described as *transparent*.

Crystal Shape, or Habit

Mineralogists use the term **crystal shape,** or **habit**, to refer to the common or characteristic shape of individual crystals or aggregates of crystals. Some minerals tend to grow equally in all three dimensions, whereas others tend to be elongated in one direction or flattened if growth in one dimension is suppressed. The crystals of a few minerals can have a regular polygonal shape that is helpful in identification. For example, magnetite crystals sometimes occur as octahedrons, garnets often form dodecahedrons, and halite and fluorite crystals tend to grow as cubes or near-cubes. Most minerals have just one common crystal shape, but a few, such as the pyrite samples shown in **Figure 2.14**, have two or more characteristic crystal shapes.

In addition, some mineral samples consist of numerous intergrown crystals exhibiting characteristic shapes that are useful for identification. Terms commonly used to describe these and other crystal habits include *equant* (equidimensional), *bladed*, *fibrous*, *tabular*, *cubic*, *prismatic*, *platy*, *blocky*, and *banded*. Some of these habits are pictured in **Figure 2.15**.



▼ Figure 2.14 Common crystal shapes of pyrite

Although most minerals exhibit only one common crystal shape, some, such as pyrite, have two or more characteristic habits.

A. Fibrous **B. Bladed** **C. Banded** **D. Cubic crystals**

▲ SmartFigure 2.15 Some common crystal habits A. Thin, rounded crystals that break into fibers. **B.** Elongated crystals that are flattened in one direction. **C.** Minerals that have stripes or bands of different color or texture. **D.** Groups of crystals that are cube shaped.

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Mineral Strength

How easily minerals break or deform under stress is determined by the type and strength of the chemical bonds that hold the crystals together. Mineralogists use terms including *hardness*, *cleavage*, *fracture*, and *tenacity* to describe mineral strength and how minerals break when stress is applied.

Hardness One of the most useful diagnostic properties is **hardness**, a measure of the resistance of a mineral to abrasion or scratching. This property is determined by rubbing a mineral of unknown hardness against one of known hardness or vice versa. A numerical value of hardness can be obtained by using the **Mohs scale** of hardness, which consists of 10 minerals arranged in order from 1 (softest) to 10 (hardest), as shown in **Figure 2.16A**. It should be noted that the Mohs scale is a relative ranking and does not imply that a mineral with a hardness of 2, such as gypsum, is twice as hard as mineral with a hardness of 1, like talc. In fact, gypsum is only slightly harder than talc, as **Figure 2.16B** indicates.

In the laboratory, common objects used to determine the hardness of a mineral can include a human fingernail, which has a hardness of about 2.5, a copper penny (3.5), and a piece of glass (5.5). The mineral gypsum, which has

SmartFigure 2.16
Hardness scales A. The Mohs scale of hardness, with the hardnesses of some common objects. **B.** Relationship between the Mohs relative hardness scale and an absolute hardness scale.

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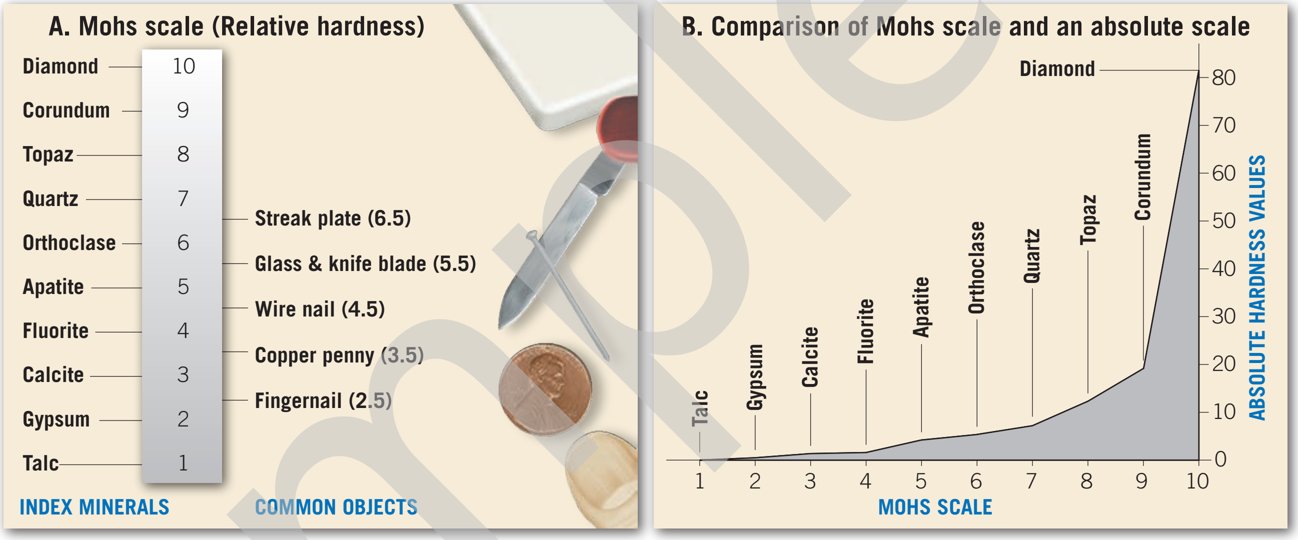

a hardness of 2, can be easily scratched with a fingernail. On the other hand, the mineral calcite, which has a hardness of 3, will scratch a fingernail but will not scratch glass. Quartz, one of the hardest common minerals, will easily scratch glass. Diamonds, hardest of all, scratch anything, including other diamonds.

Cleavage In the crystal structure of many minerals, some atomic bonds are weaker than others. It is along these weak bonds that minerals tend to break when they are stressed. **Cleavage** (*kleiben* = carve) is the tendency of a mineral to break (cleave) along planes of weak bonding. Not all minerals have cleavage, but those that do can be identified by the relatively smooth, flat surfaces that are produced when the mineral is broken.

The simplest type of cleavage is exhibited by the micas (**Figure 2.17**). Because these minerals have very weak bonds in one direction, they cleave to form thin, flat sheets. Some minerals have excellent cleavage in one, two, three, or more directions, whereas others exhibit fair or poor cleavage, and still others have no cleavage at all. When minerals break evenly in more than one direction, cleavage is described by *the number of cleavage directions and the angle(s) at which they meet* (**Figure 2.18**).

Each cleavage surface that has a different orientation is counted as a different direction of cleavage. For example, some minerals, such as halite, cleave to form six-sided cubes. Because a cube is defined by three different sets of parallel planes that intersect at 90-degree angles, cleavage for the mineral halite is described as *three directions of cleavage that meet at 90 degrees*.

Do not confuse cleavage with crystal shape. When a mineral exhibits cleavage, it breaks into pieces that all have the same geometry. By contrast, the smooth-sided quartz crystals shown in Figure 2.1 do not have cleavage. If broken, they fracture into shapes that do not resemble one another or the original crystals.

SmartFigure 2.17
Micas exhibit perfect cleavage The thin sheets shown here exhibit one plane of cleavage. (Photo by Chip Clark/Fundamental Photographs)

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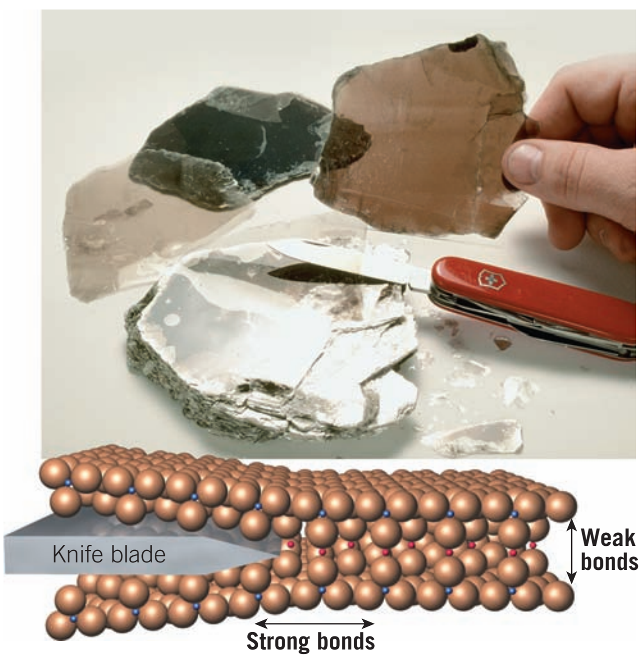

Fracture Minerals having chemical bonds that are equally, or nearly equally, strong in all directions exhibit a property called **fracture** (**Figure 2.19A**). When minerals fracture, most produce uneven surfaces and are described as exhibiting *irregular fracture*. However, some minerals, including quartz, sometimes break into smooth, curved surfaces resembling broken glass. Such breaks are called *conchoidal fractures* (**Figure 2.19B**). Still other minerals exhibit fractures that produce splinters or fibers referred to as *splintery fracture* and *fibrous fracture*, respectively.

Tenacity The term **tenacity** describes how a mineral responds to stress—for instance, whether it tends to break in a brittle fashion or bend elastically. As mentioned earlier, nonmetallic minerals such as quartz and minerals that are ionically bonded, such as fluorite and halite, tend to be *brittle* and fracture or exhibit cleavage when struck. By contrast, native metals, such as copper and gold, are *malleable*, which means they can be hammered without breaking. In addition, minerals that can be cut into thin shavings, including gypsum and talc, are described as *sectile*. Still others, notably the micas, are *elastic* and bend and snap back to their original shape after stress is released.

A. **Cleavage in one direction.** Example: Muscovite

B. **Cleavage in two directions at 90° angles.** Example: Feldspar

C. **Cleavage in two directions not at 90° angles.** Example: Hornblende

D. **Cleavage in three directions at 90° angles.** Example: Halite

E. **Cleavage in three directions not at 90° angles.** Example: Calcite

F. **Cleavage in four directions.** Example: Fluorite

◀ SmartFigure 2.18 **Cleavage directions exhibited by minerals** (Photos by E. J. Tarbuck and Dennis Tasa)

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Density and Specific Gravity

Density, an important property of matter, is defined as mass per unit volume. Mineralogists often use a related measure called **specific gravity** to describe the density of minerals. Specific gravity is a number representing the ratio of a mineral's weight to the weight of an equal volume of water.

Most common minerals have a specific gravity between 2 and 3. For example, quartz has a specific gravity of 2.65. By contrast, some metallic minerals, such as pyrite, native copper, and magnetite, are more than twice as dense and thus have more than twice the specific gravity of quartz. Galena, an ore from which lead is extracted, has a specific gravity of roughly 7.5, whereas 24-karat gold has a specific gravity of approximately 20.

With a little practice, you can estimate the specific gravity of a mineral by hefting it in your hand. Does this mineral feel about as "heavy" as similarly sized rocks you have handled? If the answer is "yes," the specific gravity of the sample will likely be between 2.5 and 3.

Other Properties of Minerals

In addition to the properties discussed thus far, some minerals can be recognized by other distinctive properties. For example, halite is ordinary salt, so it can be quickly identified through taste. Talc and graphite both have distinctive feels: Talc feels soapy, and graphite feels greasy. Further, the streaks of many sulfur-bearing minerals smell like rotten eggs. A few minerals, such as magnetite, have high iron content and can be picked up with a magnet, while some varieties (such as lodestone) are themselves natural magnets and will pick up small iron-based objects such as pins and paper clips (see Figure 2.32F, page 50).

Moreover, some minerals exhibit special optical properties. For example, when a transparent piece of calcite is placed over printed text, the letters appear twice. This optical property is known as *double refraction* (**Figure 2.20**).

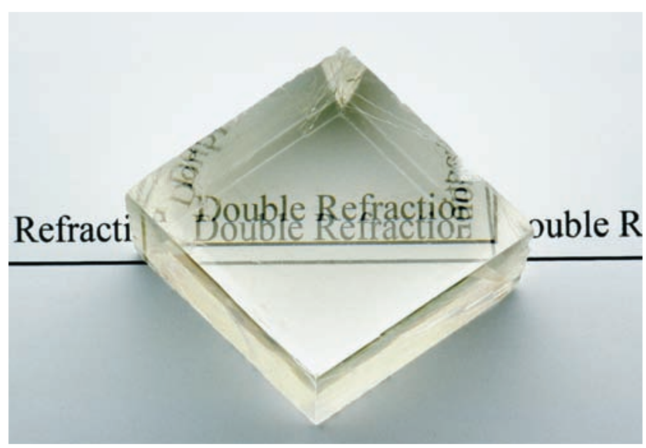
One very simple chemical test to detect carbonate minerals involves placing a drop of dilute hydrochloric

▼ Figure 2.20 **Double refraction** This sample of calcite exhibits double refraction. (Photo by Chip Clark/Fundamental Photographs)

A. **Irregular fracture (Quartz)**

B. **Conchoidal fracture (Quartz)**

▼ Figure 2.19 **Irregular versus conchoidal fracture** (Photos by E. J. Tarbuck)



EYE ON EARTH 2.2

Glass bottles, like most other manufactured products, contain substances obtained from minerals extracted from Earth's crust and oceans. The primary ingredient in commercially produced glass bottles is the mineral quartz. Glass also contains lesser amounts of the mineral calcite. (Photo by Chris Brignell/Shutterstock)

QUESTION 1 *In what mineral group does quartz belong?*

QUESTION 2 *Glass beer bottles are usually clear, green, or brown. Based on what you know about how the mineral quartz is colored, what do glass manufacturers do to make bottles green and brown?*

QUESTION 3 *Why did some brewers color their glass bottles, rather than use clear glass. (Hint:Search the Internet.)*

SmartFigure 2.21 Calcite reacting with a weak acid (Photo by Chip Clark/ Fundamental Photographs)

VIDEO
https://goo.gl/5L3gns

acid from a dropper bottle onto a freshly broken mineral surface. Samples containing carbonate minerals will effervesce (fizz) as carbon dioxide gas is released (Figure 2.21). This test is especially useful in identifying calcite, a common carbonate mineral.

CONCEPT CHECKS 2.4

1. Define *luster*.
2. Why is color not always a useful property in mineral identification? Give an example of a mineral that supports your answer.
3. What differentiates cleavage from fracture?
4. What is meant by a mineral's *tenacity*? List three terms that describe tenacity.
5. Describe a simple chemical test useful in identifying the mineral calcite.

2.5 Mineral Groups

List the common silicate and nonsilicate minerals and describe what characterizes each group.

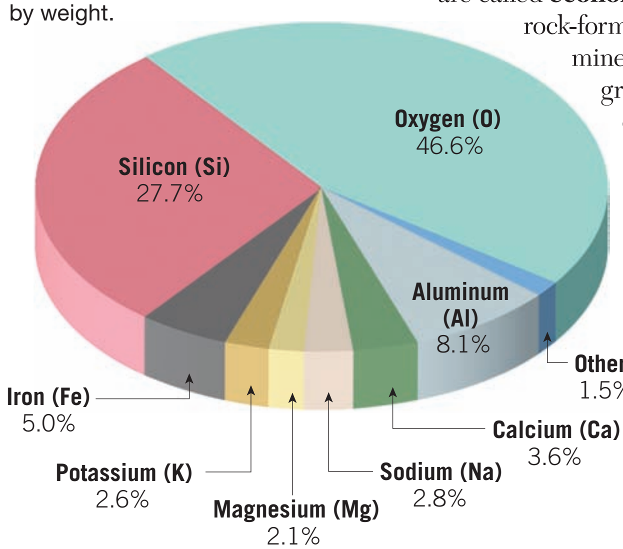
More than 4000 minerals have been named, and several new ones are identified each year. Fortunately for students who are beginning to study minerals, no more than a few dozen are abundant. Collectively, these few make up most of the rocks of Earth's crust and are therefore generally known as the **rock-forming minerals**.

Although less abundant, many other minerals are used extensively in the manufacture of products; these are called **economic minerals**. However, rock-forming minerals and economic minerals are not mutually exclusive groups. When found in large deposits, some rock-forming minerals are economically significant. One example is calcite, a mineral that is the primary component of the sedimentary rock limestone. Among calcite's many uses is cement production.

It is worth noting that *only eight elements* make up the vast majority of the rock-forming minerals and represent more than 98 percent (by weight) of the continental crust (Figure 2.22). These elements, in order of most to least abundant, are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg). As shown in Figure 2.22, oxygen and silicon are by far the most common elements in Earth's crust. Furthermore, these two elements readily combine to form the basic "building block" for the most common mineral group, the **silicates**. More than 800 silicate minerals are known, and they account for more than 90 percent of Earth's crust.

Because other mineral groups are far less abundant in Earth's crust than the silicates, they are often grouped together in the category **nonsilicates**. Although not as common as silicates, some nonsilicate minerals are very important economically. They provide us with iron and aluminum to build automobiles, gypsum for plaster and drywall for home construction, and copper wire that carries electricity and connects us to the Internet. In addition to their economic importance, these groups include minerals that are major constituents in sediments and sedimentary rocks.

Figure 2.22 The eight most abundant elements in Earth's continental crust The numbers represent percentages by weight.



Silicate Minerals

Every silicate mineral contains oxygen and silicon atoms. Except for a few silicate minerals such as quartz, most silicate minerals also contain one or more additional elements in their crystalline structure. These elements give rise to the great variety of silicate minerals and their varied properties.

All silicates have the same fundamental building block, the **silicon–oxygen tetrahedron** (SiO_4^{4-}). This structure consists of four oxygen ions that are covalently bonded to a comparatively smaller silicon ion, forming a tetrahedron—a pyramid shape with four identical faces (**Figure 2.23**). In some minerals, the tetrahedra are joined into chains, sheets, or three-dimensional networks by sharing oxygen atoms (**Figure 2.24**). These larger silicate structures are then connected to one another by other elements. The primary elements that join silicate structures are iron (Fe), magnesium (Mg), potassium (K), sodium (Na), and calcium (Ca).

Major groups of silicate minerals and common examples are given in Figure 2.24. The *feldspars* are by far the most plentiful group, comprising about 51 percent of Earth's crust. *Quartz*, the second-most-abundant mineral in the continental crust, is the only common mineral made completely of silicon and oxygen.

Notice in Figure 2.24 that each mineral *group* has a particular silicate *structure*. A relationship exists between this internal structure of a mineral and the *cleavage* it exhibits. Because the silicon–oxygen bonds are strong, silicate minerals tend to cleave between the silicon–oxygen structures rather than across them. For example, the micas have a sheet structure and thus tend to cleave into flat plates (see the muscovite in Figure 2.17). Quartz has equally strong silicon–oxygen bonds in all directions; therefore, it has no cleavage but fractures instead.

How do silicate minerals form? Most of them crystallize from molten rock as it cools. This cooling can occur at or near Earth's surface (low temperature and pressure) or at great depths (high temperature and pressure). The *environment* during crystallization and the *chemical composition of the molten rock* mainly determine which minerals are produced. For example, the silicate mineral olivine crystallizes at high temperatures (about 1200°C [2200°F]), whereas quartz crystallizes at much lower temperatures (about 700°C [1300°F]).

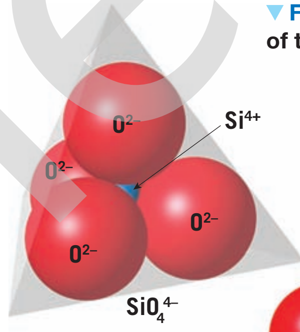
In addition, some silicate minerals form at Earth's surface from the weathered (disintegrated) products of other silicate minerals. Clay minerals are an example. Still other silicate minerals are formed under the extreme pressures associated with mountain building. Each silicate mineral, therefore, has a structure and a chemical composition that *indicate the conditions under which it formed*. Thus, by carefully examining the mineral makeup of rocks, geologists can often determine the circumstances under which the rocks formed.

We will now examine some of the most common silicate minerals, which are divided into two major groups based on their chemical composition.

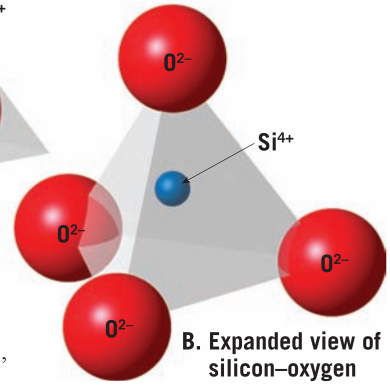
Common Light Silicate Minerals

The **light silicate minerals** are generally light in color and are noticeably less dense than the dark silicates. These differences are mainly attributable to the presence or absence of iron and magnesium, which are "heavy" elements. The light silicates contain varying amounts of aluminum, potassium, calcium, and sodium rather than iron and magnesium.

Figure 2.23 **Two representations of the silicon–oxygen tetrahedron**



A. Silicon–oxygen tetrahedron



B. Expanded view of silicon–oxygen tetrahedron

Feldspar Group *Feldspar minerals* are by far the most plentiful silicate group in Earth's crust, comprising about 51 percent of the crust (**Figure 2.25**). Their abundance can be partially explained by the fact that they can form under a wide range of temperatures and pressures. Two different feldspar structures exist (**Figure 2.26**). One group of feldspar minerals contains potassium ions in its structure and is therefore termed **potassium feldspar** (Figure 2.26A,B). The other group, called **plagioclase feldspar**, contains both sodium and calcium ions that freely substitute for one another, depending on the environment during crystallization (Figure 2.26C,D). Despite these differences, all feldspar minerals have similar physical properties. They have two planes of cleavage meeting at or near 90-degree angles, are relatively hard (6 on the Mohs scale), and have a luster that ranges from glassy to pearly. As a component in igneous rocks, feldspar crystals can be identified by their rectangular shape and rather smooth, shiny faces.

Potassium feldspar is usually light cream, salmon pink, or occasionally blue-green in color. The plagioclase feldspars, on the other hand, range in color from gray to blue-gray or sometimes black. However, color should not be used to distinguish these groups, as the only way to distinguish the feldspars by looking at them is through the presence of a multitude of fine parallel lines, called *striations*. Striations are found on some cleavage planes of plagioclase feldspar but are not present on potassium feldspar (see Figure 2.26B,D).

Quartz **Quartz** (SiO_2) is the second-most-abundant mineral in the continental crust and the only common silicate mineral that consists entirely of silicon and oxygen. In quartz, a three-dimensional framework is developed through the complete sharing of oxygen by adjacent silicon atoms (see Figure 2.24). Thus, all the bonds in quartz are of the strong silicon–oxygen type. Consequently, quartz is hard, resists weathering, and does not have cleavage.

When broken, quartz generally exhibits conchoidal fracture. When pure, quartz is clear and, if allowed to

SmartFigure 2.24
Common silicate minerals Note that the complexity of the silicate structure increases from the top of the chart to the bottom. (Photos by Dennis Tasa and E. J. Tarbuck)

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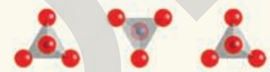
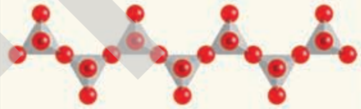
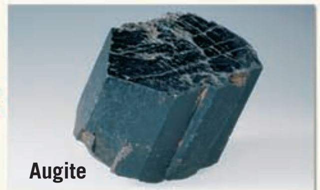
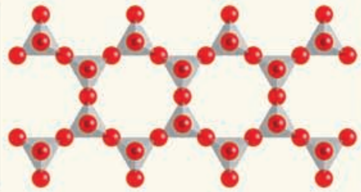
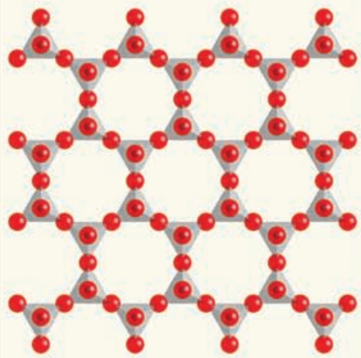
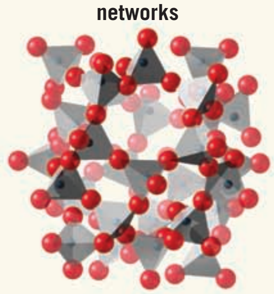
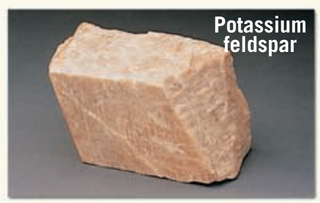
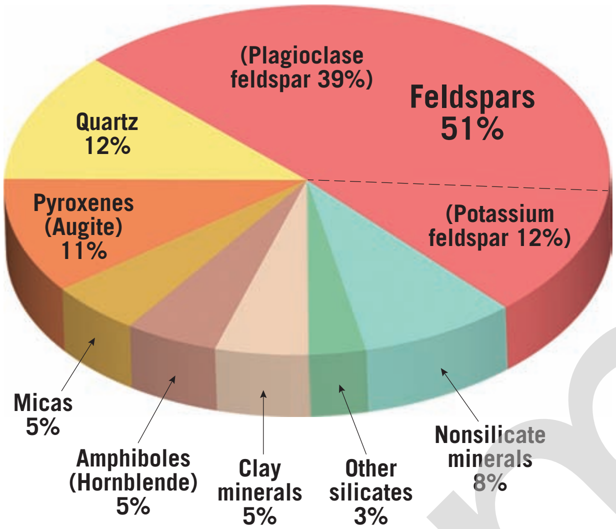
Common Silicate Minerals and Mineral Groups

Mineral/Formula	Cleavage	Silicate Structure	Example
Olivine group $(Mg,Fe)_2SiO_4$	None	Single tetrahedra 	
Pyroxene group (Augite) $(Mg,Fe,Ca,Na)AlSiO_3$	Two planes at 90°	Single chains 	
Amphibole group (Hornblende) $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$	Two planes at 60° and 120°	Double chains 	
Micas: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	One plane	Sheets 	
Micas: **Muscovite** $KAl_2(AlSi_3O_{10})(OH)_2$			
Feldspars: **Potassium feldspar (Orthoclase)** $KAlSi_3O_8$	Two planes at 90°	Three-dimensional networks 	
Feldspars: **Plagioclase** $(Ca,Na)AlSi_3O_8$			
Quartz SiO_2	None		

grow without interference, will develop hexagonal crystals that develop pyramid-shaped ends. However, like most other clear minerals, quartz is often colored by inclusions of various ions (impurities) and often forms without developing good crystal faces. The most common varieties of quartz are milky (white), smoky (gray), rose (pink), amethyst (purple), citrine (yellow to brown), and rock crystal (clear) (**Figure 2.27**).



▲ **Figure 2.25 Mineral composition of Earth's crust** Feldspar minerals make up about 51 percent of Earth's crust, and all silicate minerals combined make up about 92 percent of Earth's crust.

◀ **Figure 2.26 Some common feldspar minerals A.** Characteristic crystal form of potassium feldspar. **B.** Most salmon-colored feldspar belongs to the potassium feldspar subgroup. (though some are light cream in color). **C.** Sodium-rich plagioclase feldspar tends to be light in color with a pearly luster. **D.** Calcium-rich plagioclase feldspar tends to be gray, blue-gray, or black in color. Labradorite, the sample shown here, exhibits striations on one of its crystal faces. (Photos by Dennis Tasa and E. J. Tarbuck)

Muscovite **Muscovite** is a common member of the mica family. It is light in color and has a pearly luster (see Figure 2.17). Like other micas, muscovite has excellent cleavage in one direction. In thin sheets, muscovite is clear, a property that accounts for its use as window "glass" during the Middle Ages. Because muscovite is very shiny, it can often be identified by the sparkle it gives a rock. If you have ever looked closely at beach sand, you may have seen the glimmering brilliance of the mica flakes scattered among the other sand grains.

Clay Minerals **Clay** is a term used to describe a category of complex minerals that, like the micas, have a sheet structure. Unlike other common silicates, most clay minerals originate as products of the chemical breakdown (chemical weathering) of other silicate minerals. Thus, clay minerals make up a large percentage of the surface material we call soil. (Weathering and soils are discussed in detail in Chapter 8.) Because of soil's importance to agriculture, and because of its role as a supporting material for buildings, clay minerals are extremely important to humans. In addition, clays account for nearly half the volume of sedimentary rocks. Clay minerals are generally very fine grained, which makes them difficult to identify unless they are studied microscopically. Clays are most common in shales, mudstones, and other sedimentary rocks.

One of the most common clay minerals is *kaolinite* (**Figure 2.28**), which is used in the manufacture of fine china and as a coating for high-gloss paper, such as that used in this textbook. Further, some clay minerals absorb large amounts of water, which allows them to swell to several times their normal size. These clays have been used commercially in a variety of ingenious ways, including as an additive to thicken milkshakes in fast-food restaurants.

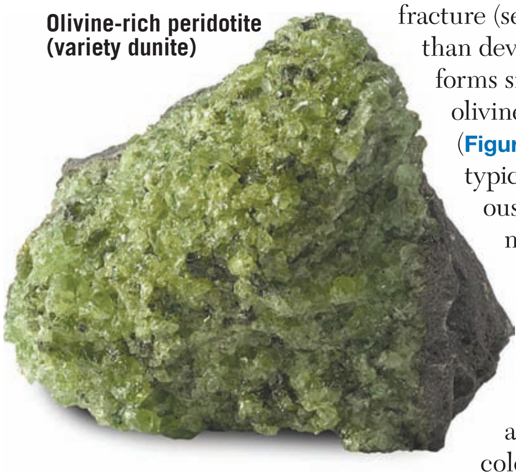
▲ **Figure 2.27 Quartz, the second-most-common mineral in Earth's crust, has many varieties A.** Smoky quartz is commonly found in coarse-grained igneous rocks. **B.** Rose quartz owes its color to small amounts of titanium. **C.** Milky quartz often occurs in veins, which occasionally contain gold. **D.** Amethyst, a purple variety of quartz often used in jewelry, is the birthstone for February. (Photos by Dennis Tasa and E. J. Tarbuck)

Common Dark Silicate Minerals

Dark silicate minerals contain ions of iron and/or magnesium in their structure. Because of their iron content, these silicates are dark in color and have a greater specific gravity than the light silicates.

Olivine Group **Olivine**, a family of high-temperature silicate minerals, are black to olive green in color and have a glassy luster and a conchoidal

▼ **Figure 2.28 Kaolinite** Kaolinite is a common clay mineral formed by weathering of feldspar minerals. (Photo by Dennis Tasa)



▲ **Figure 2.29 Olivine** Commonly black to olive green in color, olivine has a glassy luster and is often granular in appearance. Olivine is commonly found in the igneous rock basalt. (Photo by Dennis Tasa)

fracture (see Figure 2.24, upper-right). Rather than develop large crystals, olivine commonly forms small, rounded crystals that give olivine-rich rocks a granular appearance (**Figure 2.29**). Olivine and related forms are typically found in basalt, a common igneous rock of the oceanic crust and volcanic areas on the continents; they are thought to constitute up to 50 percent of Earth's upper mantle.

Pyroxene Group The *pyroxenes* are a group of diverse minerals that are important components of dark-colored igneous rocks. The most common member, **augite**, is a black, opaque mineral with two directions of cleavage that meet at nearly a 90-degree angle. Augite is one of the dominant minerals in basalt (**Figure 2.30A**).

Amphibole Group **Hornblende** is the most common member of a chemically complex group of minerals called *amphiboles* (**Figure 2.30B**). Hornblende is usually dark green to black in color, and except for its cleavage angles, which are about 60 degrees and 120 degrees, it is very similar in appearance to augite. In a rock, hornblende often forms elongated crystals. This helps distinguish it from pyroxene, which forms rather blocky crystals. Hornblende is found in igneous rocks, where it often makes up the dark portion of an otherwise light-colored rock (see Figure 2.3).

Biotite **Biotite** is a dark, iron-rich member of the mica family (see Figure 2.24). Like other micas, biotite possesses a sheet structure that gives it excellent cleavage in one direction. Biotite also has a shiny black appearance that helps distinguish it from the other dark ferromagnesian minerals. Like hornblende, biotite is a common constituent of igneous rocks, including the rock granite.

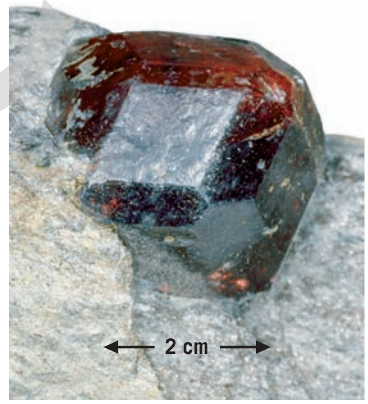
▼ **Figure 2.30 Augite and hornblende** These dark-colored silicate minerals are common constituents of a variety of igneous rocks. (Photos by E. J. Tarbuck)

Garnet **Garnet** is similar to olivine in that its structure is composed of individual tetrahedra linked by metallic ions. Also like olivine, garnet has a glassy luster, lacks cleavage, and exhibits conchoidal fracture. Although the colors of garnet are varied, this mineral is most often brown to deep red. Well-developed garnet crystals have 12 diamond-shaped faces and are most commonly found in metamorphic rocks (**Figure 2.31**).

Important Nonsilicate Minerals

Although the nonsilicates make up only about 8 percent of Earth's crust, some nonsilicate minerals, such as gypsum, calcite, and halite, occur as constituents in sedimentary rocks in significant amounts. Many nonsilicates are also economically important.

▶ **Figure 2.31 Well-formed garnet crystal** Garnets come in a variety of colors and are commonly found in mica-rich metamorphic rocks. (Photo by E. J. Tarbuck)



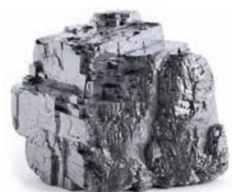
Nonsilicate minerals are typically divided into groups based on the negatively charged ion or complex ion that the members have in common. For example, the *oxides* contain negative oxygen ions (O^{2-}), which bond to one or more kinds of positive ions. Thus, within each mineral group, the basic structure and type of bonding is similar. As a result, the minerals in each group have similar physical properties that are useful in mineral identification. **Figure 2.32** lists some of the major nonsilicate mineral groups and includes a few examples of each.

Some of the most common nonsilicate minerals belong to one of three classes of minerals: the carbonates (CO_3^{2-}), the sulfates (SO_4^{2-}), and the halides (Cl^{1-}, F^{1-}, Br^{1-}). The carbonate minerals, which are much simpler structurally than the silicates, are composed of the carbonate ion (CO_3^{2-}) and one or more kinds of positive ions. The two most common carbonate minerals are **calcite**, $CaCO_3$ (calcium carbonate), and **dolomite**, $CaMg(CO_3)_2$ (calcium/magnesium carbonate) (Figure 2.32A,B). Calcite and dolomite are usually found together as the primary constituents in the sedimentary rocks limestone and dolostone. When calcite is the dominant mineral, the rock is called *limestone*, whereas *dolostone* results from a predominance of dolomite. Limestone is used in road aggregate and as a building stone, and it is the main ingredient in Portland cement.

Two other nonsilicate minerals frequently found in sedimentary rocks are **halite** and **gypsum** (Figure 2.32C, I). Both of these minerals are commonly found in thick layers that are the last vestiges of ancient seas that have long since evaporated (**Figure 2.33**). Like limestone, both halite and gypsum are important nonmetallic resources. Halite is the mineral name for common table salt (NaCl). Gypsum ($CaSO_4 \cdot 2H_2O$), which is calcium sulfate with water bound into the structure, is the mineral from which plaster and other similar building materials are composed.

Most nonsilicate mineral classes contain members that are prized for their economic value. This includes the oxides, whose members *hematite* and *magnetite* are important ores of iron (see Figure 2.32E,F). Also significant are the sulfides, which are basically compounds of sulfur (S) and one or more metals.

Common Nonsilicate Mineral Groups

Mineral Group (key ion(s) or element(s))	Mineral Name	Chemical Formula	Economic Use	Examples
Carbonates (CO_3^{2-})	Calcite Dolomite	$CaCO_3$ $CaMg(CO_3)_2$	Portland cement, lime Portland cement, lime	 A. Calcite  B. Dolomite
Halides $(Cl^{1-}, F^{1-}, Br^{1-})$	Halite Fluorite Sylvite	$NaCl$ CaF_2 KCl	Common salt Used in steel making Used as fertilizer	 C. Halite  D. Fluorite
Oxides (O^{2-})	Hematite Magnetite Corundum Ice	Fe_2O_3 Fe_3O_4 Al_2O_3 H_2O	Ore of iron, pigment Ore of iron Gemstone, abrasive Solid form of water	 E. Hematite  F. Magnetite
Sulfides (S^{2-})	Galena Sphalerite Pyrite Chalcopyrite Cinnabar	PbS ZnS FeS_2 $CuFeS_2$ HgS	Ore of lead Ore of zinc Sulfuric acid production Ore of copper Ore of mercury	 G. Galena  H. Chalcopyrite
Sulfates (SO_4^{2-})	Gypsum Anhydrite Barite	$CaSO_4 \cdot 2H_2O$ $CaSO_4$ $BaSO_4$	Plaster Plaster Drilling mud	 I. Gypsum  J. Anhydrite
Native elements (single elements)	Gold Copper Diamond Graphite Sulfur Silver	Au Cu C C S Ag	Trade, jewelry Electrical conductor Gemstone, abrasive Pencil lead Sulfa drugs, chemicals Jewelry, photography	 K. Copper  L. Sulfur

▲ **Figure 2.32 Important nonsilicate mineral groups** (Photos by Dennis Tasa and E. J. Tarbuck)

Figure 2.33 Thick bed of halite exposed in an underground mine In this halite (salt) mine in Grand Saline, Texas, note the person for scale. (Photo by Tom Bochsler/Pearson Education)

Important sulfide minerals include galena (lead), sphalerite (zinc), and chalcopyrite (copper). In addition, native elements—including gold, silver, and carbon (diamonds)—are economically important, as are a host of other nonsilicate minerals—fluorite (flux in making steel), corundum (gemstone, abrasive), and uraninite (a uranium source). See GEOGraphics 2.2 for more information on gemstones.

CONCEPT CHECKS 2.5

1. List the eight most common elements in Earth's crust.
2. Sketch the silicon–oxygen tetrahedron and label its parts.
3. What is the most abundant mineral in Earth's crust?
4. What is the most common carbonate mineral?
5. List six common nonsilicate minerals and their economic uses.

2.6 Minerals: A Nonrenewable Resource

Discuss Earth's mineral resources in terms of renewability. Differentiate between mineral resources and ore deposits.

Earth's crust and oceans are the source of a wide variety of useful and valuable materials. From the first use of rocks such as flint and obsidian to make tools thousands of years ago, the use of Earth materials has expanded, resulting in more complex societies and our modern civilization. The mineral and energy resources we extract from Earth's crust are the raw materials from which we make all the products we use.

Natural resources are typically grouped into broad categories according to (1) their ability to be regenerated (renewable or nonrenewable) or (2) their origin or type. Here we will consider mineral resources. However, other natural resources are indispensable to humans, including air, water, and solar energy.

Figure 2.34 Solar energy is renewable The Ivanpah Solar Electric Generating System is a solar thermal plant located in California's Mojave Desert, southwest of Las Vegas. It consists of 173,500 heliostats (mirrors that move so they reflect sunlight at a target), each with two mirrors that focus solar energy on boilers located on one of three centralized towers. The boilers, in turn, generate steam, which turns turbines that generate electricity. (Photo by Steve Proehl/Getty Images/Corbis Documentary)

Renewable Versus Nonrenewable Resources

Resources classified as **renewable** can be replenished over relatively short time spans. Common examples are corn used for food and for making ethanol, natural fibers such as cotton for clothing, and forest products for lumber and paper. Energy from flowing water, wind, and the Sun are also considered renewable (Figure 2.34).

By contrast, many other basic resources are classified as **nonrenewable**. Important metals such as iron, aluminum, and copper fall into this category, as do our most widely used fuels: petroleum, natural gas, and coal. Although these and other resources form continuously, the processes that create them are so slow that significant deposits take millions of years to accumulate. Thus, for all practical purposes, Earth contains fixed quantities of these substances. The present supplies will be depleted as they are mined or pumped from the ground. Although some nonrenewable resources, such as the aluminum we use for containers, can be recycled, others, such as the oil burned for fuel, cannot.

Mineral Resources and Ore Deposits

Today, practically every manufactured product contains materials obtained from minerals. Figure 2.32 lists some of the most economically important mineral groups. **Mineral resources** are occurrences of useful minerals that are formed in such quantities that eventual extraction is reasonably certain. Mineral resources include deposits of metallic minerals that can be presently extracted profitably, as well as known deposits that are not yet economically or technologically recoverable. Materials used for such purposes as building stone, road aggregate, abrasives, ceramics, and fertilizers are not usually called mineral resources; rather, they are classified as *industrial rocks and minerals*.

An **ore deposit** is a naturally occurring concentration of one or more metallic minerals that can be extracted economically. In common usage, the term *ore* is also applied to some nonmetallic minerals such as fluorite and sulfur. Recall that more than 98 percent of Earth's crust is composed of only eight elements, and except for oxygen and silicon, all other elements make up a relatively small fraction of common crustal rocks (see Figure 2.22). Indeed, the natural concentrations of many elements are exceedingly small. A deposit containing the average concentration of an element such as gold has no economic value because the cost of extracting it greatly exceeds the value of the gold that could be recovered.

In order to have economic value, an ore deposit must be highly concentrated. For example, copper makes up about 0.0068 percent of the crust. For a deposit to be considered a copper ore, it must contain a concentration of copper that is about 100 times this amount, or about 0.68 percent. Aluminum, on the other hand, represents about 8.1 percent of the crust and can be extracted profitably when it is found in concentrations 3 or 4 times that amount.

It is important to understand that due to economic or technological changes, a deposit may either become profitable to extract or lose its profitability. If the demand for a metal increases and its value rises sufficiently, the status of a previously unprofitable deposit can be upgraded from a mineral to an ore. Technological advances that allow a resource to be extracted more efficiently and, thus, more profitably than before may also trigger a change of status.

Conversely, changing economic factors can turn what was once a profitable ore deposit into an unprofitable mineral deposit. This situation was illustrated at the copper mining operation located at Bingham Canyon, Utah, one of the largest open-pit mines on Earth (**Figure 2.35**). Mining was halted there in 1985 because outmoded equipment had driven the cost of extracting the copper beyond the current selling price. In 1989 new owners responded by replacing an antiquated 1000-car railroad with modern conveyor belts and large dump trucks for efficiently transporting the ore and waste. The new equipment reduced extraction costs by nearly 30 percent, ultimately returning the copper mine operation to profitability. Today the Bingham Canyon mine produces nearly 18 percent of the refined copper in the United States. In addition to producing about 300,000 metric tons of copper, the Bingham Canyon mine produces about 400,000 troy ounces of gold, 4 million troy ounces of silver, and 25 million pounds of molybdenum.

Over the years, geologists have been keenly interested in learning how natural processes produce localized concentrations of essential minerals. One well-established fact is that occurrences of valuable mineral resources are closely related to the rock cycle. That is, the mechanisms that generate igneous, sedimentary, and metamorphic rocks, including the processes of weathering and erosion, play a major role in producing concentrated accumulations of useful elements.

Moreover, with the development of the theory of plate tectonics, geologists have added another tool for understanding the processes by which one rock is transformed into another. As these rock-forming processes are examined in the following chapters, we consider their role in producing some of our important mineral resources.

CONCEPT CHECKS 2.6

1. List three examples of renewable resources and three examples of nonrenewable resources.
2. Compare and contrast a *mineral resource* and an *ore deposit*.
3. Explain how a mineral deposit that previously could not be mined profitably might be upgraded to an ore deposit.

▼ **Figure 2.35 Aerial view of Bingham Canyon copper mine near Salt Lake City, Utah** Although the amount of copper in the rock is less than 0.5 percent, the huge volume of material removed and processed each day (over 400,000 metric tons) yields enough metal to be profitable. In addition to copper, this mine produces gold, silver, and molybdenum. (Photo by Michael Collier)

GEOGRAPHICS 2.2

Gemstones

Precious stones have been prized since antiquity. Although most gemstones are varieties of a particular mineral, misinformation abounds regarding gems and their mineral makeup.

Important Gemstones

Gemstones are classified in one of two categories: precious or semiprecious. Precious gems are rare and generally have hardnesses that exceed 9 on the Mohs scale. Therefore, they are more valuable and thus more expensive than semiprecious gems.

GEM	MINERAL NAME	PRIZED HUES
PRECIOUS		
Diamond	Diamond	Colorless, pinks, blues
Emerald	Beryl	Greens
Ruby	Corundum	Reds
Sapphire	Corundum	Blues
Opal	Opal	Brilliant hues
SEMIPRECIOUS		
Alexandrite	Chrysoberyl	Variable
Amethyst	Quartz	Purples
Cat's-eye	Chrysoberyl	Yellows
Chalcedony	Quartz (agate)	Banded
Citrine	Quartz	Yellows
Garnet	Garnet	Red, greens
Jade	Jadeite or nephrite	Greens
Moonstone	Feldspar	Transparent blues
Peridot	Olivine	Olive greens
Smoky quartz	Quartz	Browns
Spinel	Spinel	Reds
Topaz	Topaz	Purples, reds
Tourmaline	Tourmaline	Reds, blue-greens
Turquoise	Turquoise	Blues
Zircon	Zircon	Reds

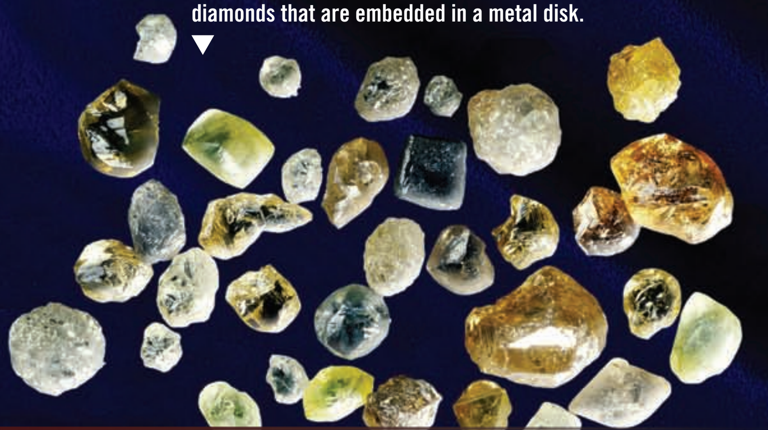
Reuters

The Famous Hope Diamond

The deep-blue Hope Diamond is a 45.52-carat gem that is thought to have been cut from a much larger 115-carat stone discovered in India in the mid-1600s. The original 115-carat stone was cut into a smaller gem that became part of the crown jewels of France and was in the possession of King Louis XVI and Marie Antoinette before they attempted to escape France. Stolen during the French Revolution in 1792, the gem is thought to have been recut to its present size and shape. In the 1800s, it became part of the collection of Henry Hope (hence its name) and is on display at the Smithsonian in Washington, DC.

What Constitutes a Gemstone?

When found in their natural state, most gemstones are dull and would be passed over by most people as "just another rock." Gems must be cut and polished by experienced professionals before their true beauty is displayed. Cutting and polishing is accomplished using abrasive material, most often tiny fragments of diamonds that are embedded in a metal disk.

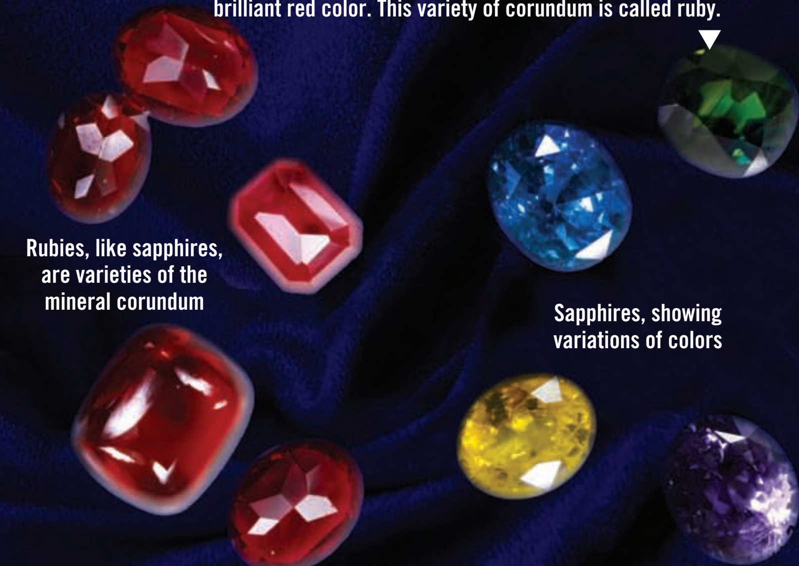


Charles D. Winters/ Photo Researchers, Inc.

? Question:
Why are diamonds used as an abrasive material to cut and polish gemstones?

Naming Gemstones

Most precious stones are given names that differ from their parent mineral. For example, sapphire is one of two gems that are varieties of the same mineral, corundum. Trace elements can produce vivid sapphires of nearly every color. Tiny amounts of titanium and iron in corundum produce the most prized blue sapphires. When the mineral corundum contains a sufficient quantity of chromium, it exhibits a brilliant red color. This variety of corundum is called ruby.



Rubies, like sapphires, are varieties of the mineral corundum

Sapphires, showing variations of colors

Dorling Kindersley

Greg C. Grace/ Alamy

2 CONCEPTS IN REVIEW
Matter and Minerals

2.1 Minerals: Building Blocks of Rocks

List the main characteristics that an Earth material must possess to be considered a mineral and describe each characteristic.

KEY TERMS: mineralogy, mineral, rock

- In Earth science, the word mineral refers to naturally occurring inorganic solids that possess an orderly crystalline structure and a characteristic chemical composition. The study of minerals is called mineralogy.
- Minerals are the building blocks of rocks. Rocks are naturally occurring masses of minerals or mineral-like matter such as natural glass or organic material.

2.2 Atoms: Building Blocks of Minerals

Compare and contrast the three primary particles contained in atoms.

KEY TERMS: atom, nucleus, proton, neutron, electron, valence electron, atomic number, element, periodic table, chemical compound

- Minerals are composed of atoms of one or more elements. All atoms consist of the same three basic components: protons, neutrons, and electrons.
- The atomic number represents the number of protons found in the nucleus of an atom of a particular element. For example, an oxygen atom has eight protons, so its atomic number is eight. Protons and neutrons have approximately the same size and mass, but protons are positively charged, whereas neutrons have no charge.
- Electrons weigh only about 1/2000 as much as protons or neutrons. They occupy the space around the nucleus, where they form what can be thought of as a cloud that is structured into several distinct energy levels called principal shells. The electrons in the outermost principal shell, called valence electrons, are responsible for the bonds that hold atoms together to form chemical compounds.
- Elements that have the same number of valence electrons tend to behave similarly. The periodic table is organized so that elements with the same number of valence electrons form a column, called a group.

? Use the periodic table (see Figure 2.5) to identify the geologically important elements that have the following numbers of protons: (A) 14, (B) 6, (C) 13, (D) 17, and (E) 26.

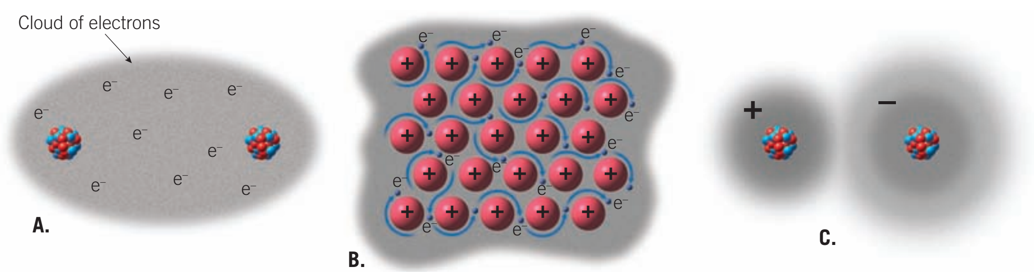
2.3 Why Atoms Bond

Distinguish among ionic bonds, covalent bonds, and metallic bonds.

KEY TERMS: octet rule, chemical bond, ionic bond, ion, covalent bond, metallic bond

- When atoms are attracted to other atoms, they can form chemical bonds, which generally involve the transfer or sharing of valence electrons. The most stable arrangement for most atoms is to have eight electrons in the outermost principal shell. This concept is called the octet rule.
- To form ionic bonds, atoms of one element give up one or more valence electrons to atoms of another element, forming positively and negatively charged atoms called ions. The ionic bond results from the attraction between oppositely charged ions.
- Covalent bonds form when adjacent atoms share valence electrons.
- In metallic bonds, the sharing is more extensive: The shared valence electrons can move freely through the substance.

? Which of the accompanying diagrams (A, B, or C) best illustrates ionic bonding? What are the distinguishing characteristics of ionic bonding and of covalent bonding?



2.4 Properties of Minerals

List and describe the properties used in mineral identification.

KEY TERMS: diagnostic property, ambiguous property, luster, color, streak, crystal shape (habit), hardness, Mohs scale, cleavage, fracture, tenacity, density, specific gravity

- The composition and internal crystalline structure of a mineral give it specific physical properties. Mineral properties useful in identifying minerals are termed *diagnostic properties.*
- Luster is a mineral's ability to reflect light. The terms transparent, translucent, and opaque describe the degree to which a mineral can transmit light. Color can be unreliable for mineral identification, as impurities can "stain" minerals with diverse colors. A more reliable identifier is streak, the color of the powder generated by scraping a mineral against a porcelain streak plate.
- Crystal shape, also called crystal habit, is often useful for mineral identification.