Earth Science
Earth Science

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Illustrated by
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To Our Grandchildren
Shannon, Amy, Andy, Ali, and Michael
Allison and Lauren
Each is a bright promise for the future

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Preface

Earth Science, 13th 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 with little background in science. Usually these students are taking an Earth science class to meet a portion of their college or university’s general requirements.

In addition to being informative and up-to-date, Earth Science, 13th 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 to This Edition

• **An enhanced active learning approach.** Each chapter begins with Focus on Concepts—a series of questions that alert students to important ideas in the chapter. Within the chapter, each major section concludes with Concept Checks that allow students to monitor their understanding and comprehension of significant facts and ideas. Each chapter concludes with a new section called Give It Some Thought. These questions and problems challenge learners by involving them in activities that require higher-order thinking skills that include the synthesis, analysis, and application of material in the chapter.

• **MasteringGeology™.** Used by over one million science students each year, the Mastering platform is the most effective and widely used online homework, tutorial, and assessment system for the sciences. Earth Science, 13th Edition, is supported by MasteringGeology assignable activities that include geoscience animations, Encounter Earth Google Earth multimedia activities, and GEODe activities, as well as a robust student self Study Area with many digital resources including a Pearson eText version of Earth Science. www.masteringgeology.com.

• **A stronger art program.** Dozens of figures are new or redrawn. The result is art that is clearer and easier to understand. Numerous diagrams and maps are paired with photographs for greater effectiveness. Many new and revised art pieces also have additional labels that “narrate” the process being illustrated and/or “guide” students as they examine the figure.

• **More than 150 new, high-quality photos and satellite images.** New “Geologist’s Sketch” illustrations accompany many important photographs and satellite images. Each sketch, which resembles what a geologist or other Earth scientist might put in a field notebook, helps the student identify important and sometimes subtle aspects of an image.

This author–artist collaboration helps make an already strong visual component even stronger and more effective.

• **New “Professional Profile” boxes.** Eight chapters include essays that present profiles of working Earth scientists. These special boxes are intended to give students a sense of what Earth scientists do and a perspective on a variety of careers in Earth science.

• **Revised and updated content.** A basic function of a college science textbook is to provide clear, understandable presentations that are accurate, engaging, and up-to-date. Our foremost goal is to keep Earth Science current, relevant, and highly readable for the beginning student. With this goal in mind, every part of the book was examined carefully. Significant changes were made throughout, including the chapters on minerals, running water and groundwater, plate tectonics, volcanoes, and earthquakes. Discussions on the ocean floor, global climate change, hurricanes, the solar system, stellar evolution, and the big bang theory also received considerable attention.

Distinguishing Features

Readability

The language of this book is straightforward and written to be understood. Clear, readable discussions with a minimum of technical language are the rule. Frequent headings and subheadings help students follow discussions and identify the important ideas presented in each chapter. In this edition, improved readability was achieved by examining chapter organization and flow, and writing in a more personal style. Large portions of the text were substantially rewritten in an effort to make the material more understandable.

Focus on Basic Principles and Instructor Flexibility

Although many topical issues are treated in Earth Science, 13th Edition, it should be emphasized that the main focus of this new edition remains the same as its predecessors—to promote student understanding of basic Earth science principles. Whereas student use of the text is a primary concern, the book’s adaptability to the needs and desires of the instructor is equally important. Realizing the broad diversity of Earth science courses in both content and approach, we have continued to use a relatively nonintegrated format to allow maximum flexibility for the instructor. Each of the major units stands alone; hence, they can be taught in any order. A unit can be omitted entirely without appreciable loss of continuity, and portions of some chapters may be interchanged or excluded at the instructor’s discretion.
A Strong Visual Component

Earth science is highly visual, so art and photographs play a critical role in an introductory textbook. As in previous editions, Dennis Tasa, a gifted artist and respected Earth science illustrator, has worked closely with the authors to plan and produce the diagrams, maps, graphs, and sketches that are so basic to student understanding. The result is art that is clearer and easier to understand.

Our aim is to get the maximum effectiveness from the visual component of the book. Michael Collier aided us greatly in this quest. Many of his extraordinary aerial photographs were used in the new edition. Michael is an award-winning geologist-photographer. Among his many awards is the American Geological Institute Award for Outstanding Contribution to the Public Understanding of the Geosciences. We are fortunate to have had Michael’s assistance in Earth Science, 13th Edition.

Three Important Themes

Chapter 1, “Introduction to Earth Science,” presents students with three important themes that recur throughout the book: Earth as a System, People and the Environment, and Understanding Earth.

Earth as a System

An important occurrence in modern science has been the realization that Earth is a giant multidimensional system. Our planet consists of many separate but interacting parts. A change in any one part can produce changes in any or all of the other parts—often in ways that are neither obvious nor immediately apparent. Although it is not possible to study the entire system at once, it is possible to develop an awareness and appreciation for the concept and for many of the system’s important interrelationships. Therefore, starting with the revised discussion of “Earth System Science” in Chapter 1, the theme of “Earth as a System” keeps recurring throughout all major units of the book. It is a thread that “weaves” throughout the chapters and helps tie them together. Several new and revised special interest boxes relate to “Earth as a System.” In addition, each chapter concludes with an Examining the Earth System section. The questions and problems found here are intended to develop an awareness and appreciation for some of the Earth system’s many interrelationships.

People and the Environment

Because knowledge about our planet and how it works is necessary to our survival and well-being, the treatment of environmental issues has always been an important part of Earth Science. Such discussions serve to illustrate the relevance and application of Earth science knowledge. With each new edition this focus has been given greater emphasis. This is certainly the case with this edition. The text integrates a great deal of information about the relationship between people and the natural environment and explores the application of the Earth sciences to understanding and solving problems that arise from these interactions. In addition to many basic text discussions, many of the text’s special interest boxes involve the “People and the Environment” theme.

Understanding Earth

As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Developing an understanding of how science is done and how scientists work is a third important theme that appears throughout this book, beginning with the section “The Nature of Scientific Inquiry” in Chapter 1. Students will examine some of the difficulties encountered by scientists as they attempt to acquire reliable data about our planet and some of the ingenious methods that have been developed to overcome these difficulties. Students will also explore many examples of how hypotheses are formulated and tested, as well as learn about the evolution and development of some major scientific theories. Many basic text discussions as well as a number of the special interest boxes on “Understanding Earth” provide the reader with a sense of the observational techniques and reasoning processes involved in developing scientific knowledge. The emphasis is not just on what scientists know, but how they figured it out.

For the Instructor

Pearson Prentice Hall continues to improve the instructor resources in this edition with the goal of saving you time in preparing for your classes.

MasteringGeology™ with Pearson eText

Used by over one 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, 13th Edition, MasteringGeology™ offers:

- Assignable activities that include geoscience animations, Encounter Earth Google Earth multimedia, and GEODe: Earth Science activities.
- Additional Concept Check and Give It Some Thought questions, Test Bank questions, and Reading Quizzes
- A student Study Area with geoscience animations, GEODe: Earth Science activities, In the News RSS feeds, Self Study Quizzes, Web Links, Glossary, and Flashcards
- Pearson eText for Earth Science, 13th Edition, which gives students access to the text whenever and wherever they can access the Internet, and includes powerful interactive and customization functions

www.masteringgeology.com

Instructor’s Resource Center (IRC) on DVD

The IRC on DVD puts all of your lecture resources in one easy-to-reach place:

- Three PowerPoint presentations for each chapter
- The Geoscience Animation Library
- All of the line art, tables, and photos from the text in .jpg files
- “Images of Earth” photo gallery
- Instructor’s Manual in Microsoft Word
- Test Bank in Microsoft Word
- TestGen test generation and management software
PowerPoints®
Found on the IRC are three PowerPoint files for each chapter. Cut down on your preparation time, no matter what your lecture needs.

1. Art—All of your line art, tables, and photos from the text have been preloaded into PowerPoint slides for easy integration into your presentation.
2. Lecture Outline—This set averages 35 slides per chapter and includes customizable lecture outlines with supporting art.
3. Classroom Response System (CRS) Questions—Authored for use in conjunction with any classroom response system. These systems allow you to electronically poll your class for responses to questions, pop quizzes, attendance, and more.

Animations and Images of Earth
The Pearson Prentice Hall Geoscience Animation Library includes more than 100 animations illustrating many difficult-to-visualize topics of Earth science. Created through a unique collaboration among five of Pearson Prentice Hall’s leading geoscience authors, these animations represent a significant step forward in lecture presentation aids. They are provided both as Flash files and, for your convenience, preloaded into PowerPoint slides.

Images of Earth allows you to supplement your personal and text-specific slides with an amazing collection of more than 300 geologic photos contributed by Marli Miller (University of Oregon) and other professionals in the field. The photos are available on the IRC on DVD.

Instructor’s Manual with Test Bank
Authored by Stanley Hatfield (Southwestern Illinois College), the Instructor’s Manual contains: learning objectives, chapter outlines, answers to end-of-chapter questions, and suggested short demonstrations to spic up your lecture. Authored by Jennifer Cole (Northeastern University), the Test Bank incorporates art and averages 75 multiple-choice, true/false, short answer, and critical thinking questions per chapter.

TestGen
Use this electronic version of the Test Bank to customize and manage your tests. Create multiple versions, add or edit questions, add illustrations—your customization needs are easily addressed by this powerful software.

Course Management
Pearson Prentice Hall offers instructor and student media for the 13th edition of Earth Science in formats compatible with Blackboard and other course management platforms. Contact your local Pearson representative for more information.

For the Student
The student resources to accompany Earth Science, 13th Edition, have been further refined with the goal of focusing the students’ efforts and improving their understanding of Earth science concepts.

MasteringGeology™ with Pearson eText
Used by over one 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, 13th Edition, MasteringGeology™ offers students a self Study Area containing:

- Geoscience Animation Library: More than 100 animations illustrating many difficult to understand Earth science concepts.
- GEODe: Earth Science: An interactive visual walkthrough of each chapter’s content
- In The News RSS Feeds: Current Earth science events and news articles are pulled into the site with assessment
- Pearson eText
- Optional Self-Study Quizzes
- Web Links
- Glossary
- Flashcards

Study Guide
Written by experienced educator Stanley Hatfield (Southwestern Illinois College), the Study Guide helps students identify the important points from the text, and then provides them with review exercises, study questions, self-check exercises, and vocabulary review.

For the Laboratory
Applications and Investigations in Earth Science, Seventh Edition. Written by Ed Tarbuck, Fred Lutgens, and Ken Pinzke, this full-color laboratory manual contains 23 exercises that provide students with hands-on experience in geology, oceanography, meteorology, astronomy, and Earth science skills. The lab manual is available at a discount when purchased with the text; please contact your local Pearson representative for more details.

Acknowledgments
Writing a college textbook requires the talents and cooperation of many people. We value the excellent work of Mark Watry and Teresa Tarbuck of Spring Hill College whose talents helped us improve Chapters 2, 22, and 24. They helped make these chapters more readable, engaging, and up-to-date.

Working with Dennis Tasa, who is responsible for all of the text’s outstanding illustrations and much of the developmental work on the animations and tutorials in MasteringGeology, is always special for us. We not only value his outstanding artistic talents and imagination but his friendship as well.

Sincere thanks to Michael Collier whose contributions as an aerial photographer and geologist added greatly to this project. Collaborating with Michael was a special pleasure.

Great thanks also go to those colleagues who prepared in-depth reviews. Their critical comments and thoughtful input helped guide our work and clearly strengthened the text. Special thanks to:
As always, we want to acknowledge the team of professionals at Pearson Prentice Hall. We sincerely appreciate the company's continuing strong support for excellence and innovation. All are committed to producing the best textbooks possible. Special thanks to our geology editor, Andy Dunaway, and to our conscientious project manager, Crissy Dudonis, for a job well done. The production team led by Patty Donovan at Laserworks Maine did an outstanding job. Kristin Piljay's photo research assistance was also a great help. All are true professionals with whom we are very fortunate to be associated.

Ed Tarbuck
Fred Lutgens
A new **active learning approach** in the Thirteenth Edition offers students a structured learning path and provides a reliable, consistent framework for mastering the chapter concepts.

**NEW! Focus on Concepts**
Each chapter begins with **Focus on Concepts**, which consists of a series of questions that alert students to key concepts in the chapter.

**NEW! Concept Checks**
Within each chapter, every major section concludes with **Concept Checks** that allow students to monitor their understanding and comprehension of significant facts and ideas.

**NEW! Give It Some Thought (GIST)**
These questions and problems are found at the end of each chapter. They challenge learners by involving them in activities that require higher-order thinking skills such as the synthesis, analysis, and application of material in the chapter.
NEW! Professional Earth Scientist’s Perspective

Throughout the new edition, the perspective and tools of the practicing Earth scientist are emphasized as an integral component of the concepts discussed.

NEW! Geologist Sketches

“Geologist’s Sketches” are incorporated into the text’s visual program, where particular photographs are shown alongside sketched versions of the same image. This visual feature encourages students to see the world through the eyes of a professional geologist.

NEW! Professional Profile Boxes

Professional Profile boxes are essays that present profiles of working Earth scientists, giving students detailed perspectives on a variety of careers in the field.

Thematic Approach

Three themes that recur throughout the text as boxed essays —“Earth as a System,” “People and the Environment,” and “Understanding Earth”—help to organize and connect otherwise-dissimilar concepts.

Earth as a System

People and the Environment

Understanding Earth
The Mastering platform is the most effective and widely used online tutorial, homework, and assessment system for the sciences. The Mastering system empowers students to take charge of their learning through activities aimed at different learning styles, and engages them in learning science through practice and step-by-step guidance—at their convenience, 24/7.

Assignable Content:
- *Encounter Earth* Activities
- Geoscience Animation Activities
- *GEODe* Activities
- Reading Quiz Questions
- Test Bank Questions
- Concept Check and Give It Some Thought Questions

For Student Self Study:
- Geoscience Animations
- *GEODe* Activities
- *In the News* RSS Feeds
- Optional Pearson eText
- Self-Study Quizzes
- Web Links

**Encounter Earth: Interactive Geoscience Explorations**

*Encounter Earth* activities enable students to use the dynamic features of Google Earth™ to visualize and explore geoscience concepts and answer multiple-choice and short answer questions related to core Earth science concepts. Questions include hints and specific wrong-answer feedback to help coach students towards mastery of the concepts. All explorations include corresponding Google Earth KMZ media files.
Reading Quizzes

Reading Quizzes encourage students to read the textbook before coming to class. These quizzes help students stay on track, become more engaged in lecture, and check their understanding of the content.

Geoscience Animations

Geoscience Animation Library, the world’s largest library of geoscience visualizations, includes over 100 animations that illuminate the most difficult-to-visualize topics from the physical geosciences. Animations include audio narration, a text transcript, and assignable assessments with and specific wrong-answer feedback to help guide students towards mastering the concepts.

GEODE

GEODE Activities provide interactive visual walkthroughs of each chapter’s core concepts through animations, videos, illustrations, photographs, and narration. The activities include assessment questions and specific wrong-answer feedback to test those concepts.
The Mastering platform is the most effective and widely used online tutorial, homework, and assessment system for the sciences. It helps instructors maximize class time with customizable, easy-to-assign, and automatically graded assessments that motivate students to learn outside of class and arrive prepared for lecture. These assessments can easily be customized and personalized for an instructor’s individual teaching style. The powerful gradebook provides unique insight into student and class performance even before the first test. As a result, instructors can spend class time where students need it most.

**The Mastering platform:**
- was developed by scientists for science students and instructors
- features over one million active registrations
- offers data-supported efficacy
- has a proven history with over 9 years of student use
- includes active users in all 50 states and in 30 countries
- offers 99.8% server reliability

**Gradebook**

Every assignment is automatically graded. **Shades of red** highlight vulnerable students and challenging assignments.

**Gradebook Diagnostics**

This screen gives instructors weekly diagnostics. With a single click, charts summarize the most difficult problems, vulnerable students, grade distribution, and even score improvement over the course.
Student Performance Data

At a glance, instructors can identify students who are having difficulty by using the color-coded gradebook. Instructors can also identify the most difficult problem (and step within that problem) in each assignment, or critique the detailed work of anyone who needs more help. They can even compare results on any problem and any step with a previous class, or with the national average.

Continuously Improving Content

MasteringGeology™ offers a dynamic pool of assignable content that improves with student usage. Detailed analysis of student performance statistics—including time spent, answers submitted, solutions requested, and hints used—ensures the highest quality content.

1. We conduct a thorough analysis of each question by reviewing student performance data that has been generated by real students.
2. We make enhancements to improve the clarity and accuracy of content, answer choices, and instructions for each problem.
3. We repeat the process.

This ongoing process helps students learn as students help the system improve.

Pearson eText

Pearson eText gives students access to the text whenever and wherever they can access the Internet. The eText pages look exactly like the printed text, and include powerful interactive and customization functions. Users can create notes, highlight text in different colors, create bookmarks, zoom, click hyperlinked words and phrases to view definitions, and view as a single-page or as two-pages. Pearson eText also links students to associated media files, enabling them to view an animation as they read the text and offers a full-text search and the ability to save and export notes.
Iceland's Eyjafjallajökull volcano erupting on April 17, 2010. The plume of volcanic ash spread over much of Europe and severely disrupted air traffic.

(Photo by Joanna Vestey/CORBIS)
The spectacular eruption of a volcano, the magnificent scenery of a rocky coast, and the destruction created by a hurricane are all subjects for the 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 so variable? Is climate really changing? How old is Earth, and how is it related to the other planets in the solar system? What causes ocean tides? What was the Ice Age like? Will there be another? Can a successful well be located at this site?

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.

FOCUS ON CONCEPTS
To assist you in learning the important concepts in this chapter, focus on the following questions:

- What are the sciences that collectively make up Earth science?
- What are some examples of interactions between people and the natural environment?
- How is a scientific hypothesis different from a scientific theory?
- How old is Earth?
- How did Earth and other planets in our solar system originate?
- What are Earth's four major “spheres”?
- What are the principal divisions of the solid Earth? What criteria were used to establish these divisions?
- What is the theory of plate tectonics?
- What are the major features of the continents and ocean basins?
- Why should Earth be thought of as a system?

What Is 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. 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. 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. It strives to establish an orderly chronological arrangement of the multitude of physical and biological changes that have occurred in the geologic past (Figure 1.1A). 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.

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 (Figure 1.1B).

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, 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.

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 of 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 in turn is but one of many galaxies.

Understanding Earth science is challenging because our planet is a dynamic body with many interacting parts and a complex history. Throughout its long existence, Earth has been changing. In fact, it is changing as you read this page and will continue to do so into the foreseeable future. Sometimes the changes are rapid and violent, as when severe storms, landslides, or volcanic eruptions occur. Just as often, change takes place so gradually that it goes 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 in the out of doors, and rightly so. A great deal of what Earth scientists 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 and application of knowledge and 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.

**CONCEPT CHECK 1.1**

1. List the sciences that make up Earth science.
2. Name the two broad subdivisions of geology and distinguish between them.
Earth Science, People, and the Environment

The primary focus of this book is to develop an understanding of basic Earth science principles, but along the way we explore numerous important relationships between people and the natural environment. Many of the problems and issues addressed by the Earth sciences are of practical value to people.

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. The chapter opening photo and Figure 1.2 are two examples. Among the hazardous Earth processes studied by Earth scientists are volcanoes, floods, tsunami, earthquakes, landslides, and hurricanes. Of course, these hazards are natural processes. They become hazards only when people try to live where these processes occur.

According to the United Nations, in 2008, for the first time, more people lived in cities than in rural areas. This global trend toward urbanization concentrates millions of people into megacities, many of which are vulnerable to natural hazards (Figure 1.3). 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 climate change. Other megacities are exposed to seismic (earthquake) and volcanic hazards where inappropriate land use and poor construction practices, coupled with rapid population growth, are increasing vulnerability.

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 (Figure 1.4). Together they form the very foundation of modern civilization. Earth science deals not only with the formation and occurrence of these vital resources but also with maintaining supplies and with the environmental impact of their extraction and use.

Complicating all environmental issues is rapid world population growth and everyone’s aspiration to a better standard of living. This means a ballooning demand for resources and a growing pressure for people to dwell in environments having significant natural hazards.

Not only do Earth processes have an impact on people but we humans can dramatically influence Earth processes as well. For example, river flooding is natural, but the 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

FIGURE 1.2 Crystal Beach, Texas, on September 16, 2008, three days after Hurricane Ike came ashore. At landfall the storm had sustained winds of 165 kilometers (105 miles) per hour. The extraordinary storm surge caused much of the damage pictured here. (Photo by Earl Nottingham/Associated Press)

1The idea of the Earth system is explored later in the chapter. Global climate change and its effects are a focus of Chapter 20.
Students Sometimes Ask...

What is the current world population and how fast is it growing?

It took until about the year 1800 for the world population to reach 1 billion people. In 1970, the number was about 4 billion. According to the U.S. Census Bureau, the world population in mid-2010 was approaching 6.9 billion people. The planet is currently adding people at a rate exceeding 75 million per year.

The Nature of Scientific Inquiry

As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Developing an understanding of how science is done and how scientists work is another important theme that appears 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 this knowledge to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by knowing how oil deposits form, geologists are able to predict the most favorable sites for exploration and, perhaps as important, how to avoid regions having little or no potential.

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 scientific “facts” through observation and measurement. The
types of facts or data that are collected generally seek to answer a well-defined question about the natural world. How did this mountain range form? How does rainfall vary in this area? Because some error is inevitable, the accuracy of a particular measurement or observation is always open to question. Nevertheless, these data are essential to science and serve as the springboard for the development of scientific theories (Box 1.1).

**Box 1.1**

**UNDERSTANDING EARTH**

**Studying Earth from Space**

Scientific facts are gathered in many ways, including laboratory studies and field observations and measurements. Satellite images are another valuable source of data. Such images provide perspectives that are difficult to gain from more traditional sources. Moreover, the high-tech instruments aboard many satellites enable scientists to gather information from remote regions where data are otherwise scarce.

The image in Figure 1.A was created using satellite radar data from the Antarctic Mapping Mission. It shows the movement of Antarctica’s Lambert Glacier. The smaller glaciers that join Lambert Glacier exhibit low velocities, shown in green, of 100–300 meters (330–980 feet) per year. Most of Lambert Glacier itself moves at rates between 400–800 meters (1,310–2,620 feet) per year. Near its terminus, where the ice spreads out and thins, velocities increase to 1,000–1,200 meters (3,280–3,940 feet) per year. Due to the remoteness and extreme weather conditions associated with this region, only a handful of traditional in-situ velocity measurements had previously been reported. Now that accurate satellite measurements are available, scientists have a quantitative baseline for future comparisons.

The image in Figure 1.B is from NASA’s Tropical Rainfall Measuring Mission (TRMM). TRMM’s research satellite was designed to expand our understanding of Earth’s hydrologic (water) cycle and its role in our climate system. Instruments aboard the TRMM satellite have greatly expanded our ability to collect precipitation data. In addition to data for land areas, this satellite provides precise measurements of rainfall over the oceans where conventional land-based instruments cannot see. This is especially important because much of Earth’s rain falls in ocean-covered tropical areas, and a great deal of the globe’s weather-producing energy comes from heat exchanges involved in the rainfall process. Until the TRMM, information on the intensity and amount of rainfall over the tropics was scanty. Such data are crucial to understanding and predicting global climate change.

**FIGURE 1.A** This satellite image provides detailed information about the movement of Antarctica’s Lambert Glacier. The ice velocities are determined from pairs of images obtained 24 days apart, using a technique called radar interferometry. (NASA)

**FIGURE 1.B** This map of rainfall for December 7–13, 2004, in Malaysia was constructed using TRMM data. Over 800 millimeters (32 inches) of rain fell along the east coast of the peninsula (darkest red area). The extraordinary rains caused extensive flooding and triggered many mudflows. (NASA/TRMM image)

**Hypothesis**

Once facts have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happen in the manner observed. They often do this by constructing a tentative (or untested) explanation, which is called a scientific hypothesis. It is best if an
investigator can formulate more than one hypothesis to explain a given set of observations. If an individual scientist 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 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 comparing them against objective observations of nature. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Those 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 ones have been eliminated, a hypothesis may be elevated to the status of a scientific theory. In everyday language we may 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. 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 later chapters.

**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 that scientists always follow that leads unerringly to scientific knowledge. Nevertheless, many scientific investigations involve the following steps: (1) a question is raised about the natural world; (2) scientific data are collected that relate to the question (Figure 1.5); (3) questions are posed that relate to the data and one or more working hypotheses are developed that

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may answer these questions; (4) observations and experiments are developed to test the hypotheses; (5) the hypotheses are accepted, modified, or rejected based on extensive testing; (6) data and results are shared with the scientific community for critique and further testing.

Other scientific discoveries may result from purely theoretical ideas, which stand up to extensive examination. Some researchers use high-speed computers to simulate what is happening in the "real" world. These models are useful when dealing with natural processes that occur on very long time scales or take place in extreme or inaccessible locations. Still other scientific advancements are made when a totally unexpected happening occurs during an experiment. These serendipitous discoveries are more than pure luck, for as 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 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.

But realize 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 CHECK 1.3**

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

## 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 1.6). 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. The lofty Himalaya Mountains began forming nearly 50 million years ago, and they continue to develop today.

The concept of geologic time 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 1,000-year-old artifact is ancient.

By contrast, 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 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, seven days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.6 billion!

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 (Figure 1.7). The principles used to develop the geologic time scale are examined at some length in Chapter 11.

CONCEPT CHECK 1.4

1. List two examples of size/space scales in Earth science that are at opposite ends of the spectrum.
2. How old is Earth?

Students Sometimes Ask...

I’ve heard scientists use the term “light-year” when discussing astronomy. What is a “light-year”?

At first you might think that a light-year is some sort of time measurement. But, actually, the light-year is a unit for measuring distances to the stars. Such distances are so large that familiar units such as kilometers or miles are too cumbersome to use. A light-year is the distance light travels in one Earth year—about 9.5 trillion kilometers (5.8 trillion miles).
According to the **big bang theory**, all of the energy and matter of the universe was compressed into an incomprehensibly hot and dense state. About 13.7 billion years ago, our universe began to expand and cool, causing the first elements that formed (hydrogen and helium) to condense into stars and galaxies. It was in the Milky Way Galaxy 9 billion years later that planet Earth and the rest of our solar system took form.

Earth is one of eight planets that, along with more than 160 moons and numerous smaller bodies, revolve around the Sun. The orderly nature of our solar system leads most researchers to conclude that Earth and the other planets formed at essentially the same time and from the same primordial material as the Sun. The **nebular theory** states that the bodies of our solar system evolved from an enormous rotating cloud called the **solar nebula** (Figure 1.8). Besides the hydrogen and helium atoms generated during the Big Bang, the solar nebula consisted of microscopic dust grains and the ejected matter of long-dead stars. (Nuclear fusion in stars converts hydrogen and helium into the other elements found in the universe.)

Nearly 5 billion years ago this huge cloud of gases and minute grains of heavier elements began to slowly contract due to the gravitational interactions among its particles (Figure 1.8). Some external influence, such as a shock wave traveling from a catastrophic explosion (supernova), may have triggered the collapse. As this slowly spiraling nebula contracted, it rotated faster and faster for the same reason ice skaters do when they draw their arms toward their bodies. Eventually the inward pull of gravity came into balance with the outward force caused by the rotational motion of the nebula (Figure 1.8). By this time the once vast cloud had assumed a flat disk shape with a large concentration of material at its center called the **protosun** (pre-Sun). (Astronomers are fairly confident that the nebular cloud formed a disk because similar structures have been detected around other stars.)

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

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 those sub-
stances with high melting points to condense into tiny par-
ticles 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
(Figure 1.8). Repeated collisions caused these masses to coa-
lesce 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. Not all
of these clumps of matter were incorporated into the planetes-
imals. Those rocky and metallic pieces that remained in orbit
are called asteroids and 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
causd 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
winds.

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 CHECK 1.5**

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.

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**Earth’s Spheres**

The images in Figure 1.9 are considered to be classics because
they let humanity see Earth differently than ever before. Figure 1.9A, known as “Earthrise,” was taken when the Apollo 8
astronauts orbited the Moon for the first time in December 1968.
As the spacecraft rounded the Moon, Earth appeared to rise above
the lunar surface. Figure 1.9B, referred to as “The Blue Marble,” is
perhaps the most widely reproduced image of Earth and was
taken in December 1972 by the crew of Apollo 17 during the last
lunar mission. 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. Bill Anders, the Apollo 8 astronaut who
took the “Earthrise” photo, expressed it this way: “We came all
this way to explore the Moon, and the most important thing is
that we discovered the Earth.”

As we look closely at our planet from space, it becomes appar-
ent that Earth is much more than rock and soil. In fact, the most
conspicuous features in Figure 1.9A are not continents but
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 1.9B
helps us appreciate why the physical environment is tradition-
ally divided into three major spheres: the water portion of our
planet, the hydrosphere; Earth’s gaseous envelope, the atmos-
phere; and, of course, the solid Earth, or geosphere.
It should be emphasized that our environment is highly integrated and is not dominated by rock, water, or air alone. It is instead characterized by continuous interactions as air comes in contact with rock, rock with water, and water with air. Moreover, the biosphere, the totality of life-forms on our planet, extends into each of the three physical realms and is an equally integral part of the planet. Thus, Earth can be thought of as consisting of four major spheres: the hydrosphere, atmosphere, geosphere, and biosphere.

The interactions among the spheres of Earth’s environment are incalculable. **Figure 1.10** provides us with one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air. In this scene, ocean waves that were created by the force of moving air break against the rocky shore. The force of the water can be powerful, and the erosional work that is accomplished can be great. (Photo by Radius Images/photolibrary.com)

**Hydrosphere**

Earth is sometimes called the *blue planet* or, as we saw in Figure 1.9B—“The Blue Marble.” 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 3,800 meters (12,500 feet). It accounts for about 97 percent of Earth’s water (**Figure 1.11**). However, the hydrosphere also includes the fresh water found in streams, lakes, and glaciers, as well as that found underground.

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

**Atmosphere**

Earth is surrounded by a life-giving gaseous envelope called the *atmosphere*. When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. When we consider only the nonocean component, ice sheets and glaciers represent nearly 85 percent of Earth’s freshwater. Groundwater accounts for just over 14 percent. When only liquid freshwater is considered, the significance of groundwater is obvious. (Glacier photo by Bernhard Edmaier/Photo Researchers, Inc.; stream photo by E. J. Tarbuck; and groundwater photo by Michael Collier)

**Figure 1.11** Distribution of Earth’s water. The oceans clearly dominate. When we consider only the nonocean component, ice sheets and glaciers represent nearly 85 percent of Earth’s freshwater. Groundwater accounts for just over 14 percent. When only liquid freshwater is considered, the significance of groundwater is obvious. (Glacier photo by Bernhard Edmaier/Photo Researchers, Inc.; stream photo by E. J. Tarbuck; and groundwater photo by Michael Collier)
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 above Earth. A surprising variety of life-forms are also adapted to extreme environments. For example, on the ocean floor, where pressures are extreme and no light penetrates, there are places where vents spew hot, mineral-rich fluids that support communities of exotic life-forms. On land, some bacteria thrive in rocks as deep as 4 kilometers (2.5 miles) and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth’s surface.

Plants and animals depend on the physical environment for the basics of life. However, organisms do more than just respond to their physical environment. Through countless interactions, life-forms help maintain and alter their physical environment. Without life, the makeup and nature of the geosphere, hydrosphere, and atmosphere would be very different.

**Geosphere**

Beneath the atmosphere and the ocean is the solid Earth or geosphere. The geosphere extends from the surface to the center

FIGURE 1.13 The hydrosphere contains a significant portion of Earth’s biosphere. Modern coral reefs are unique and complex examples and are home to about 25 percent of all marine species. Because of this diversity, they are sometimes referred to as the ocean equivalent of rain forests. (Photo by Darryl Leniuk/age footstock)
of the planet, a depth of 6,400 kilometers, making it by far the largest of Earth’s four spheres. Much of our study of the solid Earth focuses on the more accessible surface features. Fortunately, many of these features represent the outward expressions of the dynamic behavior of Earth’s interior. By examining the most prominent surface features and their global extent, we can obtain clues to the dynamic processes that have shaped our planet. A first look at the structure of Earth’s interior and at the major surface features of the geosphere comes in the next section of this chapter.

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

CONCEPT CHECK 1.6
1. Compare the height of the atmosphere to the thickness of the geosphere.
2. How much of the Earth’s surface do oceans cover?
3. How much of the planet’s total water supply do oceans represent?
4. List and briefly define the four “spheres” that constitute our environment.

A Closer Look at the Geosphere

In this section we make a preliminary examination of the solid Earth. You will become more familiar with the internal and external “anatomy” of our planet and begin to understand that the geosphere is truly dynamic. The diagrams should help a great deal as you begin to develop a mental image of the geosphere’s internal structure and major surface features, so study the figures carefully. We begin with a look at Earth’s interior—its structure and mobility. Then we conduct a brief survey of the surface of the solid Earth. Although portions of the surface, such as mountains and river valleys, are familiar to most of us, those areas that are out of sight on the floor of the ocean are not so familiar.

Earth’s Internal Structure

Early in Earth’s history the sorting of material by compositional (density) differences resulted in the formation of three layers—the crust, mantle, and core (Figure 1.14). In addition to these compositionally distinct layers, Earth is also divided into layers based on physical properties. The physical properties that define these zones include whether the layer is solid or liquid and how weak or strong it is. Knowledge of both types of layers is essential to an understanding of our planet.

Earth’s Crust

The crust, Earth’s relatively thin, rocky outer skin, is of two different types—continental crust and oceanic crust. Both share the word “crust,” but the similarity ends there. The oceanic crust is roughly 7 kilometers (5 miles) thick and composed of the dark igneous rock basalt. By contrast, the continental crust averages about 35 kilometers (22 miles) thick but may exceed 70 kilometers (40 miles) in some mountainous regions such as the Rockies and Himalayas. Unlike the oceanic crust, which has a relatively homogeneous chemical composition, the continental crust consists of many rock types. Although the upper crust has an average composition of a granitic rock called granodiorite, it varies considerably from place to place.

Continental rocks have an average density of about 2.7 g/cm³, and some have been discovered that are 4 billion years old. The rocks of the oceanic crust are younger (180 million years or less) and denser (about 3.0 g/cm³) than continental rocks.³

Earth’s Mantle

More than 82 percent of Earth’s volume is contained in the mantle, a solid, rocky shell that extends to a depth of nearly 2,900 kilometers (1,800 miles). The boundary between the crust and mantle represents a marked change in chemical composition. The dominant rock type in the uppermost mantle is peridotite, which is richer in the metals magnesium and iron than the minerals found in either the continental or oceanic crust.

The upper mantle extends from the crust–mantle boundary to a depth of about 660 kilometers (410 miles). The upper mantle can be divided into two different parts. The top portion of the upper mantle is part of the stiff lithosphere, and beneath that is the weaker asthenosphere.

The lithosphere (sphere of rock) consists of the entire crust and uppermost mantle and forms Earth’s relatively cool, rigid outer shell. Averaging about 100 kilometers in thickness, the lithosphere is more than 250 kilometers thick below the oldest portions of the continents (Figure 1.14). Beneath this stiff layer to a depth of about 350 kilometers lies a soft, comparatively weak layer known as the asthenosphere (“weak sphere”). The top portion of the asthenosphere has a temperature/pressure regime that results in a small amount of melting. Within this very weak zone the lithosphere is mechanically detached from the layer below. The result is that the lithosphere is able to move independently of the asthenosphere, a fact we consider in more detail in Chapter 7.

It is important to emphasize that the strength of various Earth materials is a function of both their composition and of the temperature and pressure of their environment. You should not get the idea that the entire lithosphere behaves like a brittle solid similar to rocks found on the surface. Rather, the rocks of the lithosphere get progressively hotter and weaker (more easily deformed) with increasing depth. At the depth of the uppermost

³Liquid water has a density of 1 g/cm³; therefore, the density of basalt is three times that of water.
FIGURE 1.14 The right side of the globe shows that Earth’s interior is divided into three different layers based on compositional differences—the crust, mantle, and core. The left side of the globe shows the five main layers of Earth’s interior based on physical properties and mechanical strength—the lithosphere, asthenosphere, lower mantle, outer core, and inner core. The block diagram on the left shows an enlarged view of the upper portion of Earth’s interior.

asthenosphere, the rocks are close enough to their melting temperature (some melting may actually occur) that they are very easily deformed. Thus, the uppermost asthenosphere is weak because it is near its melting point, just as hot wax is weaker than cold wax.

From a depth of 660 kilometers to the top of the core, at a depth of 2,900 kilometers (1,800 miles), is the lower mantle. Because of an increase in pressure (caused by the weight of the rock above) the mantle gradually strengthens with depth. Despite their strength, however, the rocks within the lower mantle are very hot and capable of very gradual flow.

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

The core is divided into two regions that exhibit very different mechanical strengths. The outer core is a liquid layer 2,260 kilometers (about 1,400 miles) thick. It is the movement of metallic iron within this zone that generates Earth’s magnetic field. The inner core is a sphere having a radius of 1,216 kilometers (754 miles). Despite its higher temperature, the iron in the inner core is solid due to the immense pressures that exist in the center of the planet.

The Mobile Geosphere Earth is a dynamic planet! If we could go back in time a few hundred million years, we would find the face of our planet dramatically different from what we see today. There would be no Mount St. Helens, Rocky Mountains, or Gulf of Mexico. Moreover, we would find continents having different sizes and shapes and located in different positions than today’s landmasses (Figure 1.15).
Continental Drift and Plate Tectonics  

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

According to the theory of plate tectonics, Earth’s rigid outer shell (lithosphere) is broken into numerous slabs called lithospheric plates, which are in continual motion. More than a dozen plates exist (Figure 1.16). The largest is the Pacific plate, covering much of the Pacific Ocean basin. Notice that several of the large lithospheric plates include an entire continent plus a large area of the seafloor. Note also that none of the plates are defined entirely by the margins of a continent.

Plate Motion  

Driven by the unequal distribution of heat within our planet, lithospheric plates move relative to each other at a very slow but continuous rate that averages about 5 centimeters (2 inches) per year—about as fast as your fingernails grow. Because plates move as coherent units relative to all other plates, they interact along their margins. Where two plates move together, called a convergent boundary, one of the plates plunges beneath the other and descends into the mantle (Figure 1.17). It is only those lithospheric plates that are capped with relatively dense oceanic crust that sink into the mantle.

Any portion of a plate that is capped by continental crust is too buoyant to be carried into the mantle. As a result, when two plates carrying continental crust converge, a collision of the two continental margins occurs. The result is the formation of a major mountain belt, as exemplified by the Himalayas.

Divergent boundaries are located where plates pull apart (Figure 1.17). Here the fractures created as the plates separate are filled with molten rock that wells up from the mantle. This hot material slowly cools to form solid rock, producing new slivers of seafloor. This process occurs along oceanic ridges where, over spans of millions of years, hundreds of thousands of square kilometers of new seafloor have been generated (Figure 1.17). Thus, while new seafloor is constantly being added at the oceanic ridges, equal amounts are returned to the mantle along boundaries where two plates converge.

At other sites, plates do not push together or pull apart. Instead, they slide past one another, so that seafloor is neither created nor destroyed. These zones are called transform fault boundaries.

FIGURE 1.15  Earth as it looked about 200 million years ago, in the late Triassic period. At this time, the modern continents that we are familiar with were joined to form a supercontinent that we call Pangaea (“all land”).

FIGURE 1.16  Illustration showing some of Earth’s lithospheric plates.

FIGURE 1.17  Plate tectonics: Ancestral Pacific Plate, Atlantic Plate, Antarctic Plate, African Plate, South American Plate, North American Plate, European Plate, Indian Plate, Australian-Indian Plate, Nazca Plate, Cocos Plate, Arabian Plate, Caribbean Plate, Scotia Plate, and Scotia Ridge.
The Face of Earth

The two principal divisions of Earth’s surface are the continents and the ocean basins (Figure 1.18). A significant difference between these two areas is their relative levels. 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), continents lie relatively close to sea level, except for limited areas of mountainous terrain. By contrast, 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 elevation difference between the continents and ocean basins is primarily the result of differences in their respective densities and thicknesses. Recall that the continents average about 35 kilometers in thickness and are composed of granitic rocks having a density of about 2.7 g/cm³. The basaltic rocks that comprise the oceanic crust average only 7 kilometers thick and have an average density of about 3.0 g/cm³. Thus, 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 (more dense) one.

Major Features of the Continents

The largest features of the continents can be grouped into two distinct categories: extensive, flat, stable areas that have been eroded nearly to sea level, and uplifted regions of deformed rocks that make up present-day mountain belts. Notice in Figure 1.19 that 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 interior of continents.

Mountain Belts The most prominent topographic features of the continents are linear mountain belts. Although the distribution of mountains appears to be random, this is not the case. When the youngest mountains are considered (those less than 100 million years old), we find that they 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 islands such as the Aleutians, Japan, and the Philippines (Figure 1.18).

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

The Stable Interior Unlike the young mountain belts, which have formed within the last 100 million years, the interiors of the continents have been relatively stable (undisturbed) for the last 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 of deformed crystalline rock. Notice in Figure 1.19 that the Canadian Shield is exposed in much of the northeastern part of North America. Age determinations for various shields have shown that they are truly ancient regions. All contain Precambrian-age rocks that are over 1 billion years old, with some samples approaching 4 billion years in age. These oldest-known rocks exhibit evidence of enormous forces that have folded and faulted them and altered them with great heat and pressure. 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 stable interior 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 (Figure 1.19).

Major Features of the Ocean Basins

If all water were drained from the ocean basins, a great variety of features would be seen, including linear chains of volcanoes, deep canyons, extensive plateaus, and large expanses of monotonously
flat plains. In fact, the scenery would be nearly as diverse as that on the continents (Figure 1.18).

During the past 70 years, oceanographers using modern depth-sounding equipment have gradually mapped significant portions of the ocean floor. From these studies they have defined three major regions: continental margins, deep-ocean basins, and oceanic (mid-ocean) ridges.

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

Although land and sea meet at the shoreline, this is not the boundary between the continents and the ocean basins. Rather, along most coasts a gently sloping platform of material, called the continental shelf, extends seaward from the shore. Because it is underlain by continental crust, it is considered a flooded extension of the continents. A glance at Figure 1.18 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 dropoff that extends from the outer edge of the continental shelf to the floor of the deep ocean (Figure 1.18). 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 accumulation of sediments that moved downslope from the continental shelf to the deep-ocean floor.

**Deep-Ocean Basins** Between the continental margins and oceanic ridges lie the **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 1.18 the Peru-Chile trench off the west coast of South America parallels the Andes Mountains. Other trenches parallel linear island chains called volcanic island arcs.

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

**Oceanic Ridges** The most prominent feature on the ocean floor is the oceanic or mid-ocean ridge. As shown in Figure 1.18, 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 consisting of highly deformed rock, such as 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.

Understanding the topographic features that comprise the face of Earth is critical to our understanding of 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 deep-ocean trenches? What forces crumple rocks to produce majestic mountain ranges? These are questions that are addressed in some of the coming chapters as we investigate the dynamic processes that shaped our planet in the geologic past and will continue to shape it in the future.

**CONCEPT CHECK 1.8**

1. Describe the general distribution of Earth’s youngest mountains.
2. What is the difference between shields and stable platforms?
3. What are the three major regions of the ocean floor and some features associated with each region?
Earth as 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 to produce a complex and continuously interacting whole that we call the Earth system.

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 hills of southern California, triggering destructive landslides. A case study in Chapter 4 (p. 106) explores such an event. 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 1.20 provides another example.

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 looking through the limited lens of only one of the traditional sciences—geology, atmospheric science, chemistry, biology, and so on—Earth system science attempts to integrate the knowledge of several academic fields. Using this interdisciplinary approach, we hope to achieve the level of understanding necessary to comprehend and solve many of our global environmental problems.

Students Sometimes Ask ...

How do we know about the internal structure of Earth?

You might suspect that the internal structure of Earth has been sampled directly. However, humans have never penetrated beneath the crust! The internal structure of Earth is determined by using indirect observations. Every time there is an earthquake, waves of energy (called seismic waves) penetrate Earth’s interior. Seismic waves change their speed and are bent and reflected as they move through zones having different properties. An extensive series of monitoring stations around the world detects and records this energy. The data are analyzed and used to work out the structure of Earth’s interior.

What Is a System? Most of us hear and use the term system frequently. We may service our car’s cooling system, make use of the city’s transportation system, and participate in the political system. A news report might inform us of an approaching weather system. Furthermore, 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 the even larger system called the Milky Way Galaxy.

Loosely defined, a system can be any size group of interacting parts that form a complex whole. Most natural systems are driven by sources of energy that move matter and/or energy from one place to another. A simple analogy is a car’s cooling system, which contains liquid (usually water and antifreeze) that is driven from the engine to the radiator and back again. The role of this system is to transfer heat generated by combustion in the...
engine to the radiator, where moving air removes it from the system; hence the term cooling system.

Systems like a car’s cooling system are self-contained with regard to matter and are called closed systems. Although energy moves freely in and out of a closed system, no matter (liquid in the case of our auto’s cooling system) enters or leaves the system. (This assumes you don’t get a leak in your radiator.) By contrast, most natural systems are open systems and are far more complicated than the foregoing example. In an open system both energy and matter flow into and out of the system. In a weather system such as a hurricane, factors such as the quantity of water vapor available for cloud formation, the amount of heat released by condensing water vapor, and the flow of air into and out of the storm can fluctuate a great deal. At times the storm may strengthen; at other times it may remain stable or weaken.

Feedback Mechanisms Most natural systems have mechanisms that tend to enhance change, as well as other mechanisms that tend to resist change and thus stabilize the system. For example, when we get too hot, we perspire to cool down. This cooling phenomenon works to stabilize our body temperature and is referred to as a negative feedback mechanism. Negative feedback mechanisms work to inhibit change or, in other words, to maintain the status quo. By contrast, mechanisms that enhance or drive change are called positive feedback mechanisms.

Most of Earth’s systems, particularly the climate system, contain a wide variety of negative and positive feedback mechanisms. For example, substantial scientific evidence indicates that Earth has entered a period of global warming. One consequence of global warming is that some of the world’s glaciers and ice caps have begun to melt. Highly reflective snow- and ice-covered surfaces are gradually being replaced by brown soils, green trees, or blue oceans, all of which are darker, so they absorb more sunlight. Therefore, as Earth warms and some snow and ice melt, our planet absorbs more sunlight. The result is a positive feedback that contributes to the warming.

On the other hand, an increase in global temperature also causes greater evaporation of water from Earth’s land-sea surface. One result of having more water vapor in the air is an increase in cloud cover. Because cloud tops are white and highly reflective, more sunlight is reflected back to space, which diminishes the amount of sunshine reaching Earth’s surface and thus reduces global temperatures. Furthermore, warmer temperatures tend to promote the growth of vegetation. Plants in turn remove carbon dioxide ($CO_2$) from the air. Since carbon dioxide is one of the atmosphere’s greenhouse gases, its removal has a negative impact on global warming.4

In addition to natural processes, we must also consider the human element. Extensive cutting and clearing of the tropical rain forests and the burning of fossil fuels (oil, natural gas, and coal) result in an increase in atmospheric $CO_2$. Such activity has been linked to the increase in global temperatures that our planet is experiencing. One of the daunting tasks for Earth system scientists is to predict what the climate will be like in the future by taking into account many variables, including technological changes, population trends, and the overall impact of the numerous competing positive and negative feedback mechanisms.

### The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over again. One example that you will learn about in Chapter 3 traces the movements of carbon among Earth’s four spheres. It shows us, for example, that the carbon dioxide in the air and the carbon in living things and in certain sedimentary rocks is all part of a subsystem described by the carbon cycle.

#### Cycles in the Earth System

A more familiar loop or subsystem is the hydrologic cycle. It represents the unending circulation of Earth’s water among the hydrosphere, atmosphere, biosphere, and geosphere. Water enters the atmosphere by evaporation from Earth’s surface and by 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 to be taken up by plants or become groundwater, and some flows across the surface toward the ocean.

Viewed over long time spans, the rocks of the geosphere are constantly forming, changing, and reforming. 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, such as the hydrologic and rock cycles, are not independent of one another. To the contrary, there are many places where they have an interface. An interface is a common boundary where different parts of a system come in contact and interact. For example, weathering at the surface gradually disintegrates and decomposes solid rock. The work of gravity and running water may eventually move this material to another place and deposit it. Later, groundwater percolating through the debris may leave behind mineral material that cements the grains together into solid rock (a rock that is often very different from the rock we started with). This changing of one rock into another, which is part of the rock cycle, could not have occurred without the movement of water through the hydrologic cycle. There are many places where one cycle or loop in the Earth system has an interface with and is a basic part of another.

#### 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, hydrosphere, and at Earth’s surface. Weather and climate, ocean circulation, and erosional processes such as rivers, glaciers, wind, and waves are driven by energy from the Sun. Earth’s interior is the second source of energy. Heat remaining from when our planet formed, and heat that is continuously generated by decay of radioactive elements, powers the internal processes that produce volcanoes, earthquakes, and mountains.

#### 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 1.21). The soil that eventually forms will reflect the interactions among many parts of the Earth system—the volcanic parent material, the type and rate of weathering, and the impact of biological activity. Of course, there will also be significant changes in the biosphere. Some organisms and their habitats will be eliminated by the lava and ash, whereas new settings for life, such as a lake, will be created. The potential climate change can also impact sensitive life forms.

The Earth system is characterized by processes that vary on spatial scales from fractions of millimeters to thousands of kilometers. Time scales for Earth's processes range from 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.

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 of the other parts. When we burn gasoline and coal, build breakwaters along the shoreline, 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: the hydrologic system, the tectonic (mountain-building) system, and the climate system, to name a few. 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 Earth science. It is a thread that weaves through the chapters and helps tie them together. At the end of each chapter there is a section titled “Examining the Earth System.” The questions and problems found there are intended to help you develop an awareness and appreciation for some of the Earth system's important interrelationships.

CONCEPT CHECK 1.9

1. How is an open system different from a closed system?
2. Contrast positive and negative feedback mechanisms.
3. What are the two sources of energy for the Earth system?

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.

2. Each of the following statements may either be a hypothesis (H), a theory (T), or an observation (O). Use one of these letters to identify each statement. Briefly explain each choice.
   a. A scientist proposes that a recently discovered large ring-shaped structure is the remains of an ancient meteorite crater.
   b. The Redwall Formation in the Grand Canyon is composed primarily of limestone.
   c. The outer part of Earth consists of several large plates that move and interact with each other.
   d. Since 1885, the terminus of Canada's Athabasca Glacier has receded 1.5 kilometers.
   e. The universe originated about 13.7 billion years ago with a period of rapid expansion called the big bang.
3. Consider the possible results of the following scenario and describe one positive and one negative feedback. *Earth is getting warmer, consequently evaporation is increasing.*

4. Making accurate measurements and observations is a basic part of scientific inquiry. The accompanying photo provides one example. Identify at least five additional images in this chapter that illustrate ways in which scientific data are gathered. Suggest advantages that might be associated with each example.

5. Refer to Figure 1.20. Which of the four main components of the Earth system (atmosphere, biosphere, geosphere, hydrosphere) were involved in the natural disaster at Caraballeda, Venezuela? Describe how each of the components you list contributed to the debris flow.

6. Look at the concept map linking the four spheres of the Earth system. Between each sphere are arrows representing processes by which these spheres interact and influence each other. For each arrow, describe at least one process.

**In Review**  Chapter 1 Introduction to 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. Geology is traditionally divided into two broad areas: *physical* and *historical*.

- The relationship between people and the natural environment is an important focus of Earth science. This includes natural hazards, resources, and human influences on Earth processes.

- All science is based on the assumption that the natural world behaves in a consistent and predictable manner. The process by which scientists gather facts through observation and careful measurement and formulate scientific hypotheses and theories is called the *scientific method*. To determine what is occurring in the natural world, scientists often (1) pose questions about the natural world and collect facts that relate to these questions; (2) ask questions and develop hypotheses that may answer these questions, (3) develop observations and experiments to test the hypotheses; (4) accept, modify, or reject hypotheses on the basis of extensive testing; and (5) share results with the broader scientific community. Other discoveries represent purely theoretical ideas that have stood up to extensive examination. Still other scientific advancements have been made when a totally unexpected happening occurred during an experiment.

- One of the challenges for those who study Earth is the great variety of space and time scales. The *geologic time scale* subdivides the 4.6 billion years of Earth history into various units.

- 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 began to rotate and assume a disk shape. Material that was gravitationally pulled toward the center became the *protosun*. Within the rotating disk, small centers, called *planetesimals*, swept up more and more of the cloud’s debris. Because of their high temperatures and weak gravitational fields, the inner planets were unable to accumulate and retain many of the lighter components. Because of the very cold temperatures existing far from the Sun, the large outer planets consist of huge amounts of lighter materials. These gaseous substances account for the comparatively large sizes and low densities of the outer planets.

- Earth’s physical environment is traditionally divided into three major parts: the solid Earth or *geosphere*; the water portion of our planet, the *hydrosphere*; and Earth’s gaseous envelope, the *atmosphere*. In addition, the *biosphere*, the totality of life on Earth, interacts with each of the three physical realms and is an equally integral part of Earth.
Earth’s internal structure is divided into layers based on differences in chemical composition and on the basis of changes in physical properties. Compositionally, Earth is divided into a thin outer crust, a solid rocky mantle, and a dense core. Other layers, based on physical properties, include the lithosphere, asthenosphere, lower mantle, outer core, and inner core.

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

The largest features of the continents can be divided into two categories: mountain belts and the stable interior. The ocean floor is divided into three major topographic units: continental margins, deep-ocean basins, and oceanic (mid-ocean) ridges.

Although each of Earth’s four spheres can be studied separately, they are all related in a complex and continuously interacting whole that we call 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.

A system is a group of interacting parts that form a complex whole. Closed systems are those in which energy moves freely in and out, but matter does not enter or leave the system. In an open system, both energy and matter flow into and out of the system.

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.

### Key Terms

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### Examining the Earth System

1. Examine the chapter-opening photo, Figure 1.1, and Figure 1.2. Make a list of features in each photo and indicate whether the item belongs to the geosphere, hydrosphere, atmosphere, or biosphere. Are there any features that might belong to more than one of the spheres?

2. Examine Figure 1.20 and describe how all four spheres of the Earth system might have been involved and/or influenced by the event depicted here.

3. 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.

### Mastering Geology

Looking for additional review and test prep materials? Visit the Self Study area in [www.masteringgeology.com](http://www.masteringgeology.com) to find practice quizzes, study tools, and multimedia that will aid in your understanding of this chapter’s content. In **MasteringGeology** you will find:

- **GEODe: Earth Science**: An interactive visual walkthrough of key concepts
- **Geoscience Animation Library**: More than 100 animations illuminating many difficult-to-understand Earth science concepts
- **In The News RSS Feeds**: Current Earth science events and news articles are pulled into the site with assessment
- **Pearson eText**
- **Optional Self Study Quizzes**
- **Web Links**
- **Glossary**
- **Flashcards**
Cave of Crystals is a cave connected to Naica Mine in Chihuahua, Mexico. The main chamber contains giant gypsum crystals, some of the largest natural crystals ever found. (Photo by Carsten Peter/Spoleoresearch & Films/National Geographic Stock)
Earth's crust and oceans are the source of 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. But 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 drill bits impregnated with diamonds are employed by dentists to drill through tooth enamel, or that the common mineral quartz is the source of silicon for computer chips. In fact, practically every manufactured product contains materials obtained from minerals.

**FOCUS ON CONCEPTS**

To assist you in learning the important concepts in this chapter, focus on the following questions:

- What are minerals, and how are they different from rocks?
- What are the smallest particles of matter?
- How do atoms bond?
- How do isotopes of the same element vary, and why are some isotopes radioactive?
- What are some of the physical and chemical properties of minerals? How can these properties be used to distinguish one mineral from another?
- What are the eight elements that make up most of Earth's continental crust?
- What is the most abundant mineral group?
- What do all silicate minerals have in common?
- What are renewable and nonrenewable resources?
- When is the term ore used with reference to a mineral?

**Minerals: Building Blocks of Rocks**

Minerals: Building Blocks of Rocks

We begin our discussion of Earth materials with an overview of mineralogy *(mineral = mineral, ology = the study of)* because minerals are the building blocks of rocks. In addition, minerals have been employed by humans for both useful and decorative purposes for thousands of years (*Figure 2.1*). The first minerals mined were flint and chert, which people fashioned into weapons and cutting tools. As early as 3700 B.C., Egyptians began mining gold, silver, and copper; and by 2200 B.C., humans discovered how to combine copper with tin to make bronze, a strong, hard alloy. Later, humans developed a process to extract iron from minerals such as hematite—a discovery that marked the decline of the Bronze Age. By about 800 B.C., iron-working technology had advanced to the point that weapons and many everyday objects were made of iron rather than copper, bronze, or wood.

During the Middle Ages, mining of a variety of minerals was common throughout Europe and the impetus for the formal study of minerals was in place.

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 when referring to anything taken out of the
ground, such as coal, iron ore, or sand and gravel. The guessing game known as “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?

Geologists define **mineral** as *any naturally occurring inorganic solid that possesses an orderly crystalline structure and can be represented by a chemical formula*. 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. **Solid substance.** Only crystalline substances that are solid at temperatures encountered at Earth’s surface are considered minerals. Ice (frozen water) fits this criterion and is considered a mineral, whereas liquid water and water vapor do not. The exception is mercury, which is found in its liquid form in nature.

3. **Orderly crystalline structure.** Minerals are crystalline substances, which means their atoms are arranged in an orderly, repetitive manner (Figure 2.2). This orderly packing of atoms is reflected in the regularly shaped objects called crystals. Some naturally occurring solids, such as volcanic glass (obsidian), lack a repetitive atomic structure and are not considered minerals.

4. **Generally inorganic.** Inorganic crystalline solids, such as ordinary table salt (halite), that are found naturally in the ground are considered minerals. Organic compounds, on the other hand, are generally not. Sugar, a crystalline solid like salt but which comes from sugarcane or sugar beets, is a common example of such 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, they are considered minerals by geologists.

5. **Can be represented by a chemical formula.** 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 ratio of one-to-two. This proportion of silicon to oxygen is true for any sample of pure quartz, regardless of its origin. However, the compositions of some minerals 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. An example is the mineral olivine, in which either the element magnesium (Mg) or iron (Fe) may occupy the same site in the crystal structure. Therefore, olivine’s formula, (Mg, Fe)$_2$SiO$_4$, expresses variability in the relative amounts of magnesium and iron. However, the ratio of magnesium plus iron (Mg + Fe) to silicon (Si) and oxygen (O) remains fixed at 2:1:4.

In contrast to minerals, rocks are more loosely defined. Simply a **rock** is any solid that consists of an aggregate of minerals, pieces of preexisting rocks, or a mass of mineral-like matter such as natural glass. Some rocks are composed almost entirely of one mineral. A common example is the sedimentary rock **limestone**, which consists of impure masses of the mineral calcite. However, most rocks, like the common rock granite shown in Figure 2.3, occur as 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 mineral constituents of granite can be easily identified (Figure 2.3).

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. Then, in Chapter 3, we take a closer look at Earth’s major rock groups.
CONCEPT CHECK 2.1

1. List five characteristics that classify an Earth material as a mineral.
2. Based on the definition of a mineral, which of the following materials are not classified as minerals, and why: gold, water, synthetic diamonds, ice, and wood.
3. Define the term rock. How do rocks differ from minerals?

Atoms: Building Blocks of Minerals

When minerals are carefully examined, even under optical microscopes, the innumerable tiny particles of their internal structures are not discernable. Nevertheless, all matter, including minerals, is composed of minute building blocks called atoms—the smallest particles that cannot be chemically split. 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 1/2000th that of a proton. For comparison, if a proton or a neutron had the mass of a baseball, an electron would have 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 charge of protons and electrons are equal in magnitude but opposite in polarity, so when these two particles are paired, the charges cancel each other. Since matter typically contains equal numbers of positively charged protons and negatively charged electrons, most substances are electrically neutral.

In illustrations, electrons are sometimes shown orbiting the nucleus in a manner that resembles the planets of our solar system orbiting the Sun (Figure 2.4A). However, electrons do not actually behave this way. A more realistic depiction shows electrons as a cloud of negative charges surrounding a nucleus.
Students Sometimes Ask...

Are the minerals you talked about in class the same as those found in dietary supplements?

Not ordinarily. From a geologic perspective, a mineral must be a naturally occurring crystalline solid. Minerals found in dietary supplements are human-made inorganic compounds that contain elements needed to sustain life. These dietary minerals typically contain elements that are metals—calcium, potassium, phosphorus, magnesium, and iron. It should also be noted that vitamins are organic compounds not inorganic compounds, like minerals.

(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 containing valence electrons that interact 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 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, all free atoms (not bonded to other atoms) have a full complement of electrons—one for each proton in the nucleus.

**Elements: Defined by Their Number of Protons**

The simplest atoms have only one 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 its chemical nature. All atoms with the same number of protons have the same chemical and physical properties. Together, a group of the same kind of atoms is called an element. There are about 90 naturally occurring elements and 23 that have been synthesized. You are probably familiar with the names of many elements including carbon, nitrogen, and oxygen. All carbon atoms have six protons, all nitrogen atoms have seven protons, and all oxygen atoms have eight protons.

Elements are organized so that those with similar properties line up in columns. This arrangement, called the periodic table, is shown in Figure 2.5. Each element has been assigned a one- or two-letter symbol. The atomic numbers and masses are also included for each element.

**FIGURE 2.5** Periodic table of the elements.
Atoms of the naturally occurring elements are the basic building blocks of Earth’s minerals. A few minerals, such as native copper, diamonds, and gold, are made entirely of atoms of only one element (Figure 2.6). However, most elements tend to join with atoms of other elements to form chemical compounds. Most minerals are chemical compounds composed of atoms of two or more elements.

Octet Rule

The noble gases (except helium) have very stable electron arrangements with eight valence electrons and, therefore, tend to lack chemical reactivity. Many other atoms gain, lose, or share electrons during chemical reactions to end 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 fill its shell. A chemical bond is the transfer or sharing of electrons that allows each atom to attain a full valence shell of electrons. Some atoms do this by transferring all of 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. In any case, the bonding atoms get stable electron configurations, which usually consist of eight electrons in their outermost shells.

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 of its 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 sodium chloride, the mineral halite—common table salt. Notice in Figure 2.8a that sodium gives up its single valence electron to chlorine. As a result, sodium now has a stable configuration with eight electrons in its outermost shell.
shell. By acquiring the electron that sodium loses, chlorine (which has seven valence electrons) gains the eighth electron needed to complete its outermost shell. Thus, through the transfer of a single electron, both the sodium and chlorine atoms have acquired a stable electron configuration.

After electron transfer takes place, the atoms are no longer electrically neutral. By giving up one electron, a neutral sodium atom becomes positively charged (with 11 protons and 10 electrons). Similarly, by acquiring one electron, a neutral chlorine atom becomes negatively charged (with 17 protons and 18 electrons). We know that ions with like charges repel, and those with unlike charges attract. Thus, an ionic bond is the attraction of oppositely charged ions to one another, producing an electrically neutral compound.

Figure 2.8B illustrates the arrangement (packing) of sodium and chlorine ions in table salt.

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, a harmless flavor enhancer that we call table salt. Thus, when elements combine to form compounds their properties change significantly.

**Covalent Bonds: Electrons Shared**

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 (H₂), 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 a pair of electrons between atoms.

Imagine two hydrogen atoms (each with one proton and one electron) approaching one another so that their electron clouds overlap (Figure 2.9). Once they meet, the electron configuration will change so that both electrons will primarily occupy the space between the atoms. In other words, the two electrons are shared by both hydrogen atoms and attracted simultaneously by the positive charge of the proton in the nucleus of each atom. The attraction between the electrons and both nuclei holds these atoms together. Although ions do not exist in hydrogen molecules, the force that holds these atoms together arises from the attraction of oppositely charged particles—protons in the nuclei and electrons shared by the atoms.

**Metallic Bonds: Electrons Free to Move**

In **metallic bonds**, the valence electrons are free to move from one atom to another so that all atoms share the available valence electrons. This type of bonding is found in metals such as copper, gold, aluminum, and silver, and in alloys such as brass and bronze. Metallic bonding accounts for the high electrical conductivity of metals, the ease with which metals are shaped, and numerous other special properties.

**CONCEPT CHECK 2.3**

1. What is the difference between an atom and an ion?
2. What occurs in an atom to produce a positive ion? A negative ion?
3. Briefly distinguish between ionic and covalent bonding and the role that electrons play in both.
Isotopes and Radioactive Decay

The mass number of an atom is simply the total number of its protons and neutrons. All atoms of a particular element have the same number of protons, but they may have varying numbers of neutrons. Atoms with the same number of protons but different numbers of neutrons are isotopes of that element. Isotopes of the same element are labeled by placing the mass number after the element’s name or symbol. For example, carbon has three well-known isotopes. One has a mass number of 12 (carbon-12), another has a mass number of 13 (carbon-13), and the third, carbon-14, has a mass number of 14. Carbon-12 must also have six neutrons to give it a mass number of 12. Carbon-14, on the other hand, has six protons plus eight neutrons to give it a mass number of 14.

In chemical behavior, all isotopes of the same element are nearly identical. To distinguish among them is like trying to differentiate identical twins, with one weighing slightly more than the other. Because isotopes of the same element exhibit the same chemical behavior, they often become parts of the same mineral. For example, when the mineral calcite (CaCO₃) forms, some of its carbon atoms are carbon-12, and some are carbon-14.

The nuclei of most atoms are stable. However, many elements do have isotopes in which the nuclei are unstable—carbon-14 is one example of an unstable isotope. In this context, unstable means that the nuclei change through a random process called radioactive decay. During radioactive decay, unstable isotopes radiate energy and emit particles. The rates at which unstable isotopes decay are measurable. Therefore, certain radioactive atoms are used to determine the ages of fossils, rocks, and minerals. A discussion of radioactive decay and its applications in dating past geologic events appears in Chapter 11.

CONCEPT CHECK 2.4

1. What is an isotope?
2. Name one isotope of carbon that is unstable.
3. If the number of electrons in a neutral atom is 35 and its mass number is 80, calculate the following:
   a. the number of protons
   b. the atomic number
   c. the number of neutrons

Properties of Minerals

Minerals have definite crystalline structures and chemical compositions that give them unique sets of physical and chemical properties shared by all samples of that mineral. For example, all specimens of halite have the same hardness, the same density, and break in a similar manner. Because a mineral’s internal structure and chemical composition are difficult to determine without the aid of sophisticated tests and equipment, the more easily recognized physical properties are frequently used in identification.

Optical Properties

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

Luster The appearance or quality of light reflected from the surface of a mineral is known as luster. Minerals that have the appearance of metals, regardless of color, are said to have a metallic luster (Figure 2.10). Some metallic minerals, such as...
The color of the 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 2.12**). Although the color of a mineral may vary from sample to sample, its streak is usually consistent in color.

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.

It should be noted that not all minerals produce a streak when rubbed across a streak plate. For example, the mineral quartz is harder than a porcelain streak plate. Therefore, no streak is observed using this method.

### Crystal Shape or Habit

Mineralogists use the term **crystal shape** or **habit** to refer to the common or characteristic shape of a crystal or aggregate of crystals. A few minerals exhibit somewhat regular polygons that are helpful in their 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.

While most minerals have only one common habit, a few have two or more characteristic crystal shapes such as the pyrite sample shown in **Figure 2.13**.

By contrast, some minerals rarely develop perfect geometric forms. Many of these, however, develop other characteristic shapes useful for identification. Some minerals tend to grow equally in all three dimensions, whereas others tend to be elongated in one

### The Ability to Transmit Light

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

### 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 mineral quartz, for example, give it a variety of tints including pink, purple, yellow, white, gray, and even black (**Figure 2.11**). 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.
direction, or flattened if growth in one dimension is suppressed. Commonly used terms to describe these and other crystal habits include equant (equidimensional), bladed, fibrous, tabular, prismatic, platy, blocky, and botryoidal. Some of these habits are pictured in Figure 2.14.

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 tenacity, hardness, cleavage, and fracture to describe mineral strength and how minerals break when stress is applied.

Tenacity  The term tenacity describes a mineral’s toughness, or its resistance to breaking or deforming. Minerals that are ionically bonded, such as fluorite and halite, tend to be brittle and shatter into small pieces when struck. By contrast, minerals with metallic bonds, such as native copper, are malleable, or easily hammered into different shapes. Minerals, including gypsum and talc, that can be cut into thin shavings are described as sectile. Still others, notably the micas, are elastic and will bend and snap back to their original shape after the stress is released.

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 2.15A. It should be noted that the Mohs scale is a relative ranking, and it does not imply that mineral number 2, gypsum, is twice as hard as mineral number 10, diamond.

FIGURE 2.13 Although most minerals exhibit only one common crystal shape, some, such as pyrite, have two or more characteristic habits. (Photos by Dennis Tasa)

FIGURE 2.14 Some common crystal habits. A. Bladed. Elongated crystals that are flattened in one direction. B. Prismatic. Elongated crystals with faces that are parallel to a common direction. C. Banded. Minerals that have stripes or bands of different color or texture. D. Botryoidal. Groups of intergrown crystals resembling a bunch of grapes. (Photos by Dennis Tasa)

FIGURE 2.15 Hardness scales. A. Mohs scale of hardness, with the hardness of some common objects. B. Relationship between Mohs relative hardness scale and an absolute hardness scale.
Students Sometimes Ask...

**Are there any artificial materials harder than diamonds?**

Yes, but you won’t be seeing them anytime soon. A hard form of carbon nitride ($C_3N_4$), described in 1989 and synthesized in a laboratory shortly thereafter, may be harder than diamond but hasn’t been produced in large enough amounts for a proper test. In 1999, researchers discovered that a form of carbon made from fused spheres of 20 and 28 carbon atoms—relatives of the famous “buckyballs”—also could be as hard as a diamond. These materials are expensive to produce, so diamonds continue to be used as abrasives and in certain kinds of cutting tools. Synthetic diamonds, produced since 1955, are now widely used in these industrial applications.

as mineral 1, talc. In fact, gypsum is only slightly harder than talc, as Figure 2.15B indicates.

In the laboratory, other common objects can be used to determine the hardness of a mineral. These 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 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 2.16). 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 2.17).

Each cleavage surface that has a different orientation is counted as a different direction of cleavage. For example, some minerals cleave to form six-sided cubes. Because cubes are defined by three different sets of parallel planes that intersect at 90-degree angles, cleavage 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 will break into pieces that all have the same geometry. By contrast, the smooth-sided quartz crystals shown in Figure 2.1 (p. 00) illustrate crystal shape rather than cleavage.

If broken, they fracture into shapes that do not resemble one another or the original crystals.

**Fracture** Minerals having chemical bonds that are equally, or nearly equally, strong in all directions exhibit a property called fracture. When minerals fracture, most produce uneven surfaces and are described as exhibiting **irregular fracture**. However, some minerals, such as quartz, break into smooth, curved surfaces resembling broken glass. Such breaks are called **conchoidal fractures** (Figure 2.18). Still other minerals exhibit fractures that produce splinters or fibers that are referred to as **splintery** and **fibrous fracture**, respectively.

**Density and Specific Gravity**

**Density**, an important property of matter, is defined as mass per unit of volume and is often expressed in grams per cubic centimeter (g/cm³). 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. The specific gravity of water equals 1.

Most common rock-forming minerals have a specific gravity of 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 as quartz. Galena, an ore of lead, has a specific gravity of roughly 7.5, whereas the specific gravity of 24-karat gold is approximately 20.

With a little practice, you can estimate the specific gravity of a mineral by hefting it in your hand. Ask yourself, does this mineral
feel about as “heavy” as similar-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. Furthermore, the streaks of many sulfur-bearing minerals emit odors like rotten eggs. A few minerals, such as magnetite, have a high iron content and can be picked up with a magnet, while some varieties (lodestone) are natural magnets and will pick up small iron-based objects such as pins and paper clips (see Figure 2.25A, p. 00).

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 2.19).

One very simple chemical test involves placing a drop of dilute hydrochloric acid from a dropper bottle onto a freshly broken

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### Figure 2.17 Common cleavage directions exhibited by minerals. (Photos by E. J. Tarbuck and Dennis Tasa)

<table>
<thead>
<tr>
<th>Number of Cleavage Directions</th>
<th>Shape</th>
<th>Sketch</th>
<th>Directions of Cleavage</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat sheets</td>
<td><img src="image1.png" alt="Sketch" /></td>
<td></td>
<td>Muscovite</td>
</tr>
<tr>
<td>2 at 90˚</td>
<td>Elongated form with rectangle cross section (prism)</td>
<td><img src="image2.png" alt="Sketch" /></td>
<td></td>
<td>Feldspar</td>
</tr>
<tr>
<td>2 not at 90˚</td>
<td>Elongated form with parallelogram cross section (prism)</td>
<td><img src="image3.png" alt="Sketch" /></td>
<td></td>
<td>Hornblende</td>
</tr>
<tr>
<td>3 at 90˚</td>
<td>Cube</td>
<td><img src="image4.png" alt="Sketch" /></td>
<td></td>
<td>Halite</td>
</tr>
<tr>
<td>3 not at 90˚</td>
<td>Rhombohedron</td>
<td><img src="image5.png" alt="Sketch" /></td>
<td></td>
<td>Calcite</td>
</tr>
<tr>
<td>4</td>
<td>Octahedron</td>
<td><img src="image6.png" alt="Sketch" /></td>
<td></td>
<td>Fluorite</td>
</tr>
</tbody>
</table>
mineral surface. Using this technique, certain minerals, called carbonates, will effervesce (fizz) as carbon dioxide gas is released (Figure 2.20). This test is especially useful in identifying the common carbonate mineral calcite.

CONCEPT CHECK 2.5

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 is meant when we refer to a mineral’s tenacity? List three terms that describe tenacity.
4. What differentiates cleavage from fracture?
5. What simple chemical test is useful in the identification of the mineral calcite?

FIGURE 2.18 Conchoidal fracture. The smooth, curved surfaces result when minerals break in a glasslike manner. (Photo courtesy of E. J. Tarbuck)

FIGURE 2.19 Double refraction illustrated by the mineral calcite. (Photo by Chip Clark)

FIGURE 2.20 Calcite reacting with a weak acid. (Photo by Chip Clark)

Mineral Groups

Over 4,000 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, as such, are often referred to as the **rock-forming minerals**.

Although less abundant, many other minerals are used extensively in the manufacture of products and 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 the mineral calcite, which is the primary component of the sedimentary rock limestone and has many uses including being used in the production of cement.

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 2.21). These elements, in order of abundance from most to least, are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg). As shown in Figure 2.21, silicon and oxygen 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 under the heading nonsilicates. Although not as common as silicates, some nonsilicate minerals are very important economically. They provide us with iron and aluminum to build our automobiles, gypsum for plaster and drywall for home construction, and copper wire that carries electricity and connects us to the Internet. Some common nonsilicate mineral groups include the carbonates, sulfates, and halides. In addition to their economic importance, these mineral groups include members that are major constituents in sediments and sedimentary rocks.

We first discuss the most common mineral group, the silicates, and then consider some of the prominent nonsilicate mineral groups.

**Silicate Minerals**

Each of the silicate minerals 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 (tetra = four, hedra = a base). This structure consists of four oxygen atoms surrounding a much smaller silicon atom, as shown in Figure 2.22. In some minerals, the tetrahedra are joined into chains, sheets, or three-dimensional networks by sharing oxygen atoms (Figure 2.23). 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 2.23. The feldspars are by far the most plentiful group, comprising over 50 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 2.23 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 muscovite in Figure 2.16). Quartz, which has equally strong silicon–oxygen bonds in all directions, has no cleavage but fractures instead.

How do silicate minerals form? Most 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 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.

**FIGURE 2.21** Relative abundance of the eight most common elements in the continental crust.

**FIGURE 2.22** Two representations of the silicon–oxygen tetrahedron.
A. The four large spheres represent oxygen ions, and the blue sphere represents a silicon ion. The spheres are drawn in proportion to the radii of the ions.
B. An expanded view of the tetrahedron that has an oxygen ion at each of the four corners.
<table>
<thead>
<tr>
<th>Mineral/Formula</th>
<th>Cleavage</th>
<th>Silicate Structure</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine group</td>
<td>None</td>
<td>Single tetrahedrons</td>
<td>Olivine</td>
</tr>
<tr>
<td>(Mg, Fe)2SiO4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyroxene group</td>
<td>Two planes at 90°</td>
<td>Single chains</td>
<td>Augite</td>
</tr>
<tr>
<td>(Augite)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mg,Fe)SiO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amphibole group</td>
<td>Two planes at 60° and 120°</td>
<td>Double chains</td>
<td>Hornblende</td>
</tr>
<tr>
<td>(Hornblende)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca₅(Fe,Mg)₃Si₈O₂₂(OH)₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micas</td>
<td>One plane</td>
<td>Sheets</td>
<td>Biotite</td>
</tr>
<tr>
<td>Biotite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K(Mg,Fe)₃AlSi₃O₁₀(OH)₂</td>
<td></td>
<td></td>
<td>Muscovite</td>
</tr>
<tr>
<td>Muscovite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAl₂(AlSi₃O₁₀)(OH)₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feldspars</td>
<td>Two planes at 90°</td>
<td>Three-dimensional networks</td>
<td>Potassium feldspar</td>
</tr>
<tr>
<td>Potassium feldspar (Orthoclase)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAlSi₃O₈</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>Two planes at 90°</td>
<td>Three-dimensional networks</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>(Ca,Na)AlSi₃O₈</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>None</td>
<td>None</td>
<td>Quartz</td>
</tr>
<tr>
<td>SiO₂</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 2.23** Common silicate minerals. Note that the complexity of the silicate structure increases from top to bottom. (Photos by Dennis Tasa and E. J. Tarbuck)
Students Sometimes Ask...

Are these silicates the same materials used in silicon computer chips and silicone breast implants?

Not really, but all three contain the element silicon (Si). Furthermore, the source of silicon for numerous products, including computer chips and breast implants, comes from silicate minerals. Pure silicon (without the oxygen that silicates have) is used to make computer chips, giving rise to the term “Silicon Valley” for the high-tech region of San Francisco, California’s south bay area, where many of these devices are designed.

Manufacturers of computer chips engrave silicon wafers with incredibly narrow conductive lines, squeezing millions of circuits into every fingernail-size chip. Silicone—the material used in breast implants—is a silicon–oxygen polymer gel that feels rubbery and is water repellent, chemically inert, and stable at extreme temperatures. Concern about the long-term safety of these implants limited their use after 1992.

Table 2.1

<table>
<thead>
<tr>
<th>Mineral Groups [key ion(s) or element(s)]</th>
<th>Mineral Name</th>
<th>Chemical Formula</th>
<th>Economic Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonates (CO$_3^{2-}$)</td>
<td>Calcite</td>
<td>CaCO$_3$</td>
<td>Portland cement, lime</td>
</tr>
<tr>
<td></td>
<td>Dolomite</td>
<td>CaMg(CO$_3$)$_2$</td>
<td>Portland cement, lime</td>
</tr>
<tr>
<td>Halides (Cl$^-$, F$^-$, Br$^-$)</td>
<td>Halite</td>
<td>NaCl</td>
<td>Common salt</td>
</tr>
<tr>
<td></td>
<td>Fluorite (Fluorspar)</td>
<td>CaF$_2$</td>
<td>Hydrofluoric acid production, steelmaking</td>
</tr>
<tr>
<td></td>
<td>Sylvite</td>
<td>KCl</td>
<td>Fertilizer</td>
</tr>
<tr>
<td>Oxides (O$_2^-$)</td>
<td>Hematite</td>
<td>Fe$_2$O$_3$</td>
<td>Ore of iron, pigment</td>
</tr>
<tr>
<td></td>
<td>Magnetite</td>
<td>Fe$_3$O$_4$</td>
<td>Ore of iron</td>
</tr>
<tr>
<td></td>
<td>Corundum</td>
<td>Al$_2$O$_3$</td>
<td>Gemstone, abrasive</td>
</tr>
<tr>
<td></td>
<td>Ice</td>
<td>H$_2$O</td>
<td>Solid form of water</td>
</tr>
<tr>
<td>Sulfides (S$^2-$)</td>
<td>Galena</td>
<td>PbS</td>
<td>Ore of lead</td>
</tr>
<tr>
<td></td>
<td>Sphalerite</td>
<td>ZnS</td>
<td>Ore of zinc</td>
</tr>
<tr>
<td></td>
<td>Pyrite</td>
<td>FeS$_2$</td>
<td>Sulfuric acid production</td>
</tr>
<tr>
<td></td>
<td>Chalcopyrite</td>
<td>CuFeS$_2$</td>
<td>Ore of copper</td>
</tr>
<tr>
<td></td>
<td>Cinnabar</td>
<td>HgS</td>
<td>Ore of mercury</td>
</tr>
<tr>
<td>Sulfates (SO$_4^{2-}$)</td>
<td>Gypsum</td>
<td>CaSO$_4$·2H$_2$O</td>
<td>Plaster</td>
</tr>
<tr>
<td></td>
<td>Anhydrite</td>
<td>CaSO$_4$</td>
<td>Plaster</td>
</tr>
<tr>
<td></td>
<td>Barite</td>
<td>BaSO$_4$</td>
<td>Drilling mud</td>
</tr>
<tr>
<td>Native elements (single elements)</td>
<td>Gold</td>
<td>Au</td>
<td>Trade, jewelry</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>Cu</td>
<td>Electrical conductor</td>
</tr>
<tr>
<td></td>
<td>Diamond</td>
<td>C</td>
<td>Gemstone, abrasive</td>
</tr>
<tr>
<td></td>
<td>Sulfur</td>
<td>S</td>
<td>Sulfur drugs, chemicals</td>
</tr>
<tr>
<td></td>
<td>Graphite</td>
<td>C</td>
<td>Pencil lead, dry lubricant</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>Ag</td>
<td>Jewelry, photography</td>
</tr>
<tr>
<td></td>
<td>Platinum</td>
<td>Pt</td>
<td>Catalyst</td>
</tr>
</tbody>
</table>
According to the textbook, thick beds of halite and gypsum formed when ancient seas evaporated. Has this happened in the recent past?

Yes. During the past 6 million years, the Mediterranean Sea may have dried up and then refilled several times. When 65 percent of seawater evaporates, the mineral gypsum begins to precipitate, meaning it comes out of solution and settles to the bottom. When 90 percent of the water is gone, halite crystals form, followed by salts of potassium and magnesium. Deep-sea drilling in the Mediterranean has encountered thick deposits of gypsum and salt (mostly halite) sitting one atop the other to a maximum thickness of 2 kilometers (1.2 miles). These deposits are inferred to have resulted from tectonic events that periodically closed and reopened the connection between the Atlantic Ocean and the Mediterranean Sea (the modern-day Straits of Gibraltar) over the past several million years. During periods when the Mediterranean was cut off from the Atlantic, the warm and dry climate in this region caused the Mediterranean to nearly “dry up.” Then, when the connection to the Atlantic was opened, the Mediterranean basin would refill with seawater of normal salinity. This cycle was repeated over and over again, producing the layers of gypsum and salt found on the Mediterranean seafloor.
Box 2.1

UNDERSTANDING EARTH

Gemstones

Precious stones have been prized since antiquity. But misinformation abounds regarding gems and their mineral makeup. This stems partly from the ancient practice of grouping precious stones by color rather than mineral makeup. For example, rubies and red spinels are very similar in color, but they are completely different minerals. Classifying by color led to the more common spinels being passed off to royalty as rubies. Even today, with modern identification techniques, common yellow quartz is sometimes sold as the more valuable gemstone topaz.

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 spinel colors of nearly every color (Figure 2.A). 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, and the gem is called ruby. Furthermore, if a specimen is not suitable as a gem, it simply goes by the mineral name corundum. Because of its hardness, corundum that is not of gem quality is often crushed and sold as an abrasive.

To summarize, when corundum exhibits a red hue, it is called ruby; but if it exhibits any other color, the gem is called sapphire. Whereas corundum is the base mineral for two gems, quartz is the parent of more than a dozen gems. Table 2.A lists some well-known gemstones and their parent minerals.

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 (Figure 2.A). (One of the methods used to shape a gemstone is cleaving, the act of splitting the mineral along one of its planes of weakness, or cleavage.) Only those mineral specimens that are of such quality that they can command a price in excess of the cost of processing are considered gemstones.

Gemstones can be divided into two categories: precious and semiprecious. A precious gem has beauty, durability, and rarity, whereas a semiprecious gem generally has only one or two of these qualities. The gems traditionally held in highest esteem are diamonds, rubies, sapphires, emeralds, and some varieties of opal (Table 2.A). All other gemstones are classified as semiprecious. However, large, high-quality specimens of semiprecious stones often command a very high price.

Today, translucent stones with evenly tinted colors are preferred. The most favored hues are red, blue, green, purple, rose, and yellow. The most prized stones are pigeon-blood rubies, blue sapphires, grass-green emeralds, and canary-yellow diamonds. Colorless gems are generally less than desirable except for diamonds that display “flashes of color” known as brilliance.

The durability of a gem depends on its hardness; that is, its resistance to abrasion by objects normally encountered in everyday living. For good durability, gems should be as hard or harder than quartz as defined by the Mohs scale of hardness. One notable exception is opal, which is comparatively soft (hardness 5–6.5) and brittle. Opal’s esteem comes from its “fire,” which is a display of a variety of brilliant colors, including greens, blues, and reds.

It seems to be human nature to treasure that which is rare. In the case of gemstones, large, high-quality specimens are much rarer than smaller stones. Thus, large rubies, diamonds, and emeralds, which are rare in addition to being beautiful and durable, command the very highest prices.

TABLE 2.A Important Gemstones

<table>
<thead>
<tr>
<th>Gem</th>
<th>Mineral Name</th>
<th>Prized Hues</th>
<th>Gem</th>
<th>Mineral Name</th>
<th>Prized Hues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precious</td>
<td></td>
<td></td>
<td>Semiprecious</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>Diamond</td>
<td>Colorless, yellows</td>
<td>Garnet</td>
<td>Garnet</td>
<td>Reds, greens</td>
</tr>
<tr>
<td>Emerald</td>
<td>Beryl</td>
<td>Greens</td>
<td>Jade</td>
<td>Jadeite or nephrite</td>
<td>Greens</td>
</tr>
<tr>
<td>Opal</td>
<td>Opal</td>
<td>Brilliant hues</td>
<td>Moonstone</td>
<td>Feldspar</td>
<td>Transparent blues</td>
</tr>
<tr>
<td>Ruby</td>
<td>Corundum</td>
<td>Reds</td>
<td>Peridot</td>
<td>Olivine</td>
<td>Olive greens</td>
</tr>
<tr>
<td>Sapphire</td>
<td>Corundum</td>
<td>Blues</td>
<td>Smoky quartz</td>
<td>Quartz</td>
<td>Browns</td>
</tr>
<tr>
<td>Semiprecious</td>
<td></td>
<td></td>
<td>Spinel</td>
<td>Spinel</td>
<td>Reds</td>
</tr>
<tr>
<td>Alexandrite</td>
<td>Chrysoberyl</td>
<td>Variable</td>
<td>Topaz</td>
<td>Topaz</td>
<td>Purples, reds</td>
</tr>
<tr>
<td>Amethyst</td>
<td>Quartz</td>
<td>Purples</td>
<td>Tourmaline</td>
<td>Tourmaline</td>
<td>Reds, blue-greens</td>
</tr>
<tr>
<td>Cat’s-eye</td>
<td>Chrysoberyl</td>
<td>Yellows</td>
<td>Turquoise</td>
<td>Turquoise</td>
<td>Blues</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>Quartz (agate)</td>
<td>Banded</td>
<td>Zircon</td>
<td>Zircon</td>
<td>Reds</td>
</tr>
<tr>
<td>Citrine</td>
<td>Quartz</td>
<td>Yellows</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CONCEPT CHECK 2.6

1. List the eight most common elements in Earth’s crust in order of abundance (most to least).
2. Explain the difference between the terms silicon and silicate.
3. Draw a sketch of the silicon–oxygen tetrahedron.
4. What is the most abundant mineral in Earth’s crust?
5. List six common nonsilicate mineral groups. What key ion(s) or element(s) define each group?
6. What is the most common carbonate mineral?
7. List eight common nonsilicate minerals and their economic uses.

Natural Resources

Earth’s crust and oceans are the source of a wide variety of useful and essential materials that have played a crucial role in the development of civilization. From the first use of clay to make pottery nearly 10,000 years ago, the use of Earth materials has expanded resulting in more complex societies. Today, practically every manufactured product contains materials obtained from minerals. Table 2.1 lists some of the most economically important mineral groups.

Renewable versus Nonrenewable Resources

Resources are commonly divided into two broad categories. Some are classified as renewable, which means that they can be replenished over relatively short time spans. Common examples are plants and animals for food, natural fibers for clothing, and forest products for lumber and paper. Energy from flowing water, wind, and the Sun are also considered renewable (Figure 2.26).

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 important fuels: oil, natural gas, and coal. Although these and other resources continue to form, the processes that create them are so slow that significant deposits take millions of years to accumulate. In essence, Earth contains fixed quantities of these substances. When the present supplies are mined or pumped from the ground, there will be no more. Although some nonrenewable resources, such as aluminum, can be used over and over again, others, such as oil, cannot be recycled.

FIGURE 2.26 Hydroelectric power is one example of a renewable resource. Lake Powell is the reservoir that was created when Glen Canyon Dam was built across the Colorado River. As water in the reservoir is released, it drives turbines and produces electricity. (Photo by Michael Collier)
Mineral Resources

Mineral resources are those occurrences of useful minerals that are formed in such quantities that eventual extraction is reasonably certain. Resources include deposits from which minerals can be presently extracted profitably, as well as known deposits that are not yet economically or technologically recoverable.

An ore or ore deposit is a naturally occurring concentration of one or more metallic minerals that can be extracted economically (see Figure 2.25). In common usage, the term ore is also applied to some nonmetallic minerals such as fluorite and sulfur. However, materials used for such purposes as building stone, road aggregate, abrasives, ceramics, and fertilizers are not usually called ores; rather, they are classified as industrial rocks and minerals.

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 2.21). Indeed, the natural concentrations of many elements are exceedingly small. A deposit containing the average percentage of a valuable 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.

To have economic value, an element must be concentrated above the level of its average crustal abundance. For example, copper makes up about 0.0135 percent of the crust. For a deposit to be considered as copper ore, it must contain a concentration that is about 100 times this amount. Aluminum, on the other hand, represents 8.13 percent of the crust and can be extracted profitably when it is found in concentrations only about four times its average crustal percentage.

It is important to realize that a deposit may become profitable to extract or lose its profitability because of economic changes. If demand for a metal increases and prices rise sufficiently, the status of a previously unprofitable deposit changes, and it becomes an ore. The status of unprofitable deposits may also change if a technological advance allows the ore to be extracted at a lower cost than before.

Conversely, changing economic factors can turn a once profitable ore deposit into an unprofitable deposit that can no longer be called an ore. This situation was illustrated at the copper mining operation located at Bingham Canyon, Utah, one of the largest open-pit mines on Earth (Figure 2.27). Mining was halted there...

**Figure 2.27** Aerial view of Bingham Canyon copper mine near Salt Lake City, Utah. Although the amount of copper in the rock is less than 1 percent, the huge volume of material removed and processed each day (about 200,000 tons) yields enough metal to be profitable. (Photo by Michael Collier)
in 1985 because outmoded equipment had driven the cost of extracting the copper beyond the current selling price. The owners responded by replacing an antiquated 1,000-car railroad with conveyor belts and pipelines for transporting the ore and waste. These devices achieved a cost reduction of nearly 30 percent and returned this mining operation to profitability.

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 CHECK 2.7**

1. List three examples of renewable and three examples of non-renewable resources.

2. Compare and contrast a mineral resource and an ore deposit.

3. What might cause a mineral deposit that previously could not be mined profitably to become reclassified as an ore?

---

**GIVE IT SOME THOUGHT**

1. Using the geologic definition of mineral as your guide, determine which of the items on the list are minerals and which are not. If an item is not a mineral, explain why not.
   - a. gold nugget
   - b. seawater
   - c. quartz
   - d. cubic zirconia
   - e. obsidian
   - f. ruby
   - g. glacial ice
   - h. amber
   
   Refer to the Periodic Table of the Elements (Figure 2.5) to help you answer questions 2, 3, and 4.

2. If the number of protons in a neutral atom is 92 and its mass number is 238:
   - a. What is the name of that element?
   - b. How many electrons does it have?
   - c. How many neutrons does it have?

3. Which element is more likely to form chemical bonds: xenon (Xe) or sodium (Na)? Explain why.

4. The information below refers to three isotopes of the element potassium. Using this information, determine the appropriate number of protons and neutrons for each isotope. Label each isotope in the manner used in the chapter.

<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Mass Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>39</td>
</tr>
<tr>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>19</td>
<td>41</td>
</tr>
</tbody>
</table>

5. Referring to the accompanying photos of five minerals, determine which of these specimens exhibit a metallic luster and which have a nonmetallic luster.

6. Examine the accompanying photo of a mineral that has several smooth, flat surfaces that resulted when the specimen was broken.
   - a. How many flat surfaces are present on this specimen?
   - b. How many different directions of cleavage does this specimen have?
   - c. Do the cleavage directions meet at 90-degree angles?