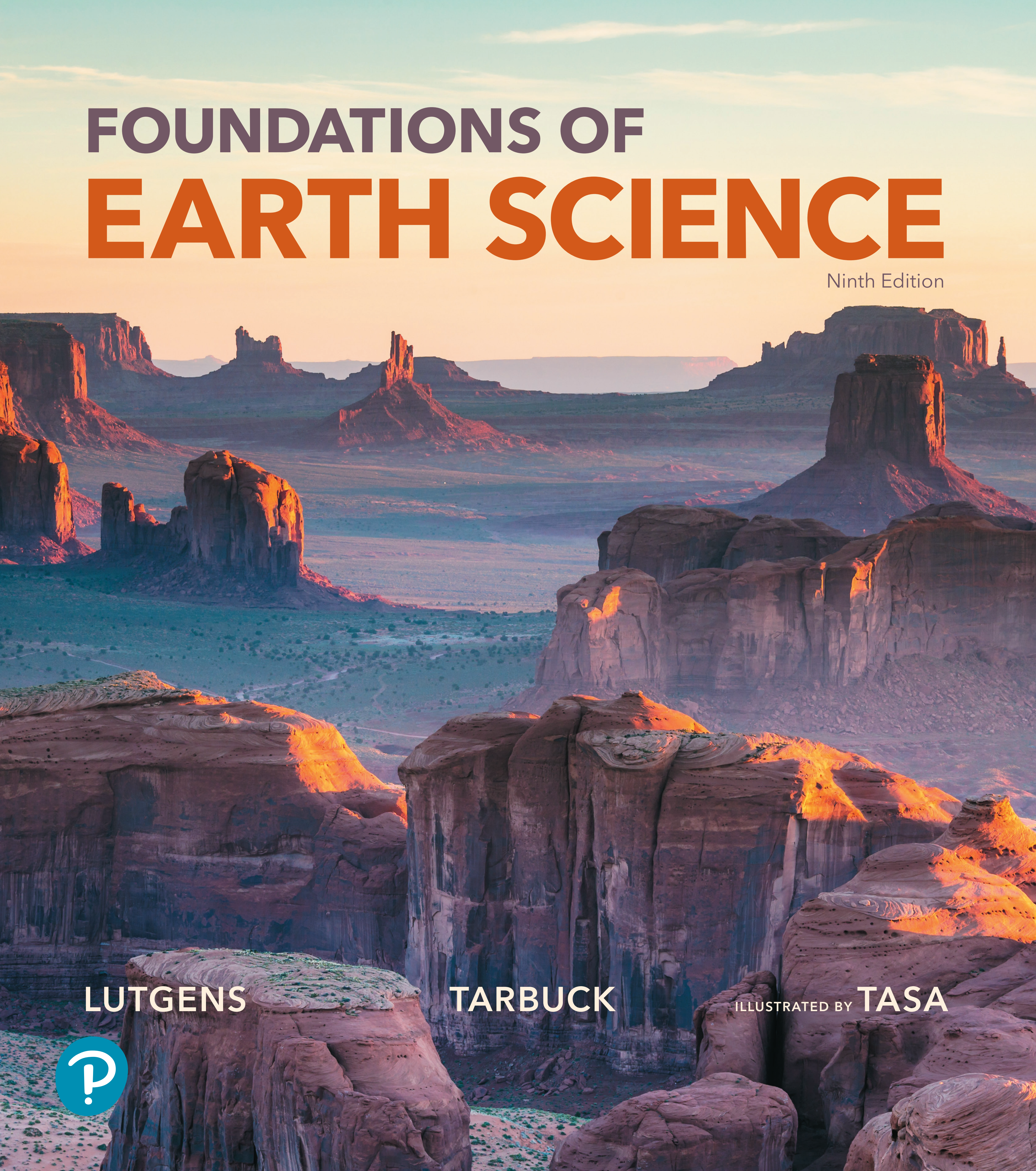
FOUNDATIONS OF EARTH SCIENCE

Ninth Edition



LUTGENS TARBUCK

ILLUSTRATED BY TASA

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NINTH EDITION

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Pearson

To Our Grandchildren

Allison and Lauren

Shannon, Amy, Andy, Ali, and Michael

Each is a bright promise for the future.

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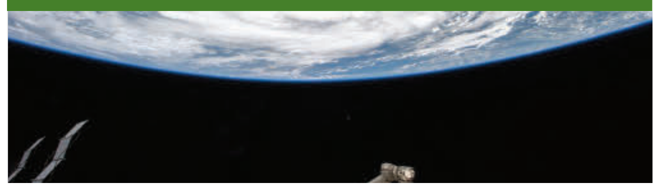

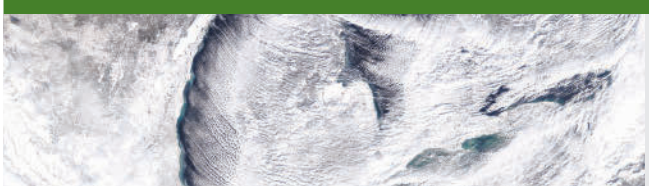

SMARTFIGURES

- **SmartFigure Videos** are short video clips that help illustrate diverse subjects as mineral properties and the structure of ice sheets, and include new media such as quadcopter drone videos of coastal erosion in California. These videos can be accessed through links in the text or through embedded links in the eText, and are assignable in Mastering Geology™.

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Preface

Foundations of Earth Science, 9th edition, is a college-level text designed for an introductory course in Earth Science. It consists of seven units that emphasize broad and up-to-date coverage of basic topics and principles in geology, oceanography, meteorology, and astronomy. The book is intended to be a meaningful, nontechnical survey for undergraduate students who may have a modest science background. Usually these students are taking an Earth Science class to meet a portion of their college's or university's general requirements.

In addition to being informative and up-to-date, *Foundations of Earth Science,* 9th edition, strives to meet the need of beginning students for a readable and user-friendly text and a highly usable "tool" for learning basic Earth Science principles and concepts.

New and Important Features

Extensive revisions and new additions took place in the 9th edition. In addition, integrated textbook and digital resources enhance the learning experience.

- **New: *In the News*** is a chapter-opening current-events story and related two-page photo spread that illustrates real-world connections to the chapter contents. Topics are fun and engaging; for example, students learn about keeping cities safe in earthquake zones, whether Glacier National Park may have to change its name, and the effects of an intense storm called a bomb cyclone.
- **Significant updating and revision of content.** A basic function of a college science textbook is to present material in a clear, understandable way that is accurate, engaging, and up-to-date. In the long history of this textbook, our number-one goal has always been to keep *Foundations of Earth Science* current, relevant, and highly readable for beginning students. To that end, every part of this text has been examined carefully. Many discussions, case studies, examples, and illustrations have been updated and revised.
- **New: Revised organization.** In the geology portion of the text, the unit on *Forces Within* now precedes the unit on *Sculpting Earth's Surface*. This was done in response to many users and reviewers of previous editions who wanted the theory of plate tectonics presented earlier in the text because of the unifying role it plays in our understanding of planet Earth. Of course, each unit is basically independent of the others and can be taught in any order desired by the instructor.
- **SmartFigures that make *Foundations of Earth Science* much more than a traditional textbook.** Through its many editions, an important strength of *Foundations* has always been clear, logically organized, and well-illustrated explanations. Complementing and reinforcing this strength are a series of SmartFigures. SmartFigures allow students to follow unique and innovative avenues that will increase their insight and understanding of important ideas and concepts. SmartFigures are truly art that teaches! The ninth edition of *Foundations of Earth Science* has more than 200 SmartFigures, of five different types, including many new videos and animations:
  1. SmartFigure Tutorials. Each of these 3- to 4-minute features, most prepared and narrated by Professor Callan Bentley, is a mini-lesson that examines and explains the concepts illustrated by the figure.
  2. SmartFigure Mobile Field Trips. Scattered throughout this new edition are 29 video field trips that explore classic sites from Iceland to Hawaii. On each trip you will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to see and learn about landscapes that relate to discussions in the chapter.
  3. SmartFigure Condor Videos. The 10 *Project Condor* videos take you to locations in the American West. By coupling aerial footage acquired by a drone quadcopter aircraft with ground-level views, effective narratives, annotations, and helpful animations, these videos transport you into the field and engage you in real-life case studies.
  4. SmartFigure Animations. These animations and accompanying narrations bring art to life, illustrating and explaining difficult-to-visualize topics and ideas more effectively than static art alone.
  5. SmartFigure Videos. Rather than providing a single image to illustrate an idea, these figures include short video clips that help illustrate such diverse subjects as mineral properties and the structure of ice sheets.
- **Active learning path.** *Foundations of Earth Science,* 9th edition, is designed for learning. Here is how it is accomplished. Each chapter has been designed to be self-contained so that materials may be taught in a different sequence, according to the preference of the instructor or the needs of the laboratory.
  1. Every chapter begins with *Focus on Concepts*. Each numbered learning objective corresponds to a major section in the chapter. The statements identify the knowledge and skills students should master by the end of the chapter and help students prioritize key concepts.
  2. Within the chapter, each major section concludes with *Concept Checks* that allow students to check their understanding and comprehension of important ideas and terms before moving on to the next section.
  3. *Concepts in Review* is an end-of-chapter feature that coordinates with the *Focus on Concepts* at the start of the chapter and with the numbered sections

within the chapter. It is a readable and concise overview of key ideas, with photos, diagrams, and questions that also help students focus on important ideas and test their understanding of basic concepts.

4. The questions and problems in *Give It Some Thought* challenge learners by involving them in activities that require higher-order thinking skills, such as application, analysis, and synthesis of chapter material.

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

Digital and Print Resources

Mastering Geology™ with Pearson eText

Used each year by over 3 million science students, the Mastering platform is the most effective and widely used online tutorial, homework, and assessment system for the sciences. Now available with *Foundations of Earth Science*, 9th edition, **Mastering Geology**™ offers tools for use before, during, and after class:

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

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

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

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

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

For Instructors

Instructor Resource Manual

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

TestGen Computerized Test Bank (Download Only)

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

Instructor Resource Materials (Download Only)

All of your lecture resources are now in one easy-to-reach place:

- All of the line art, tables, and photos from the text in JPEG files.
- PowerPoint Presentations: two PowerPoint files for each chapter. Cut down on your preparation time, no matter what your lecture needs, by taking advantage of these components of the PowerPoint files:
  - **Exclusive art.** All the photos, art, and tables from the text as JPEG files and PowerPoint slides for each chapter.
  - **Lecture outlines.** This set averages 50 slides per chapter and includes customizable lecture outlines with supporting art.
- Word and PDF versions of the *Instructor's Manual*.

For Students

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

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

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

Acknowledgments

Writing a college textbook requires the talents and cooperation of many people. It is truly a team effort, and the authors are fortunate to be part of an extraordinary team at Pearson Education. In addition to being great people to work with, all are committed to producing the best textbooks possible. Special thanks to Christian Botting, Cady Owens, Tom Hoff, Aileen Pogran, Terry Haugen, Chelsea Noack and Maria Reyes. We truly appreciate their enthusiasm, hard work, and quest for excellence. The 9th edition of *Foundations of Earth Science* was certainly improved by the talents of our developmental editor, Erin Strathmann. Our sincere thanks to Erin for her fine work. It was the job of the production team, led by Katie Ostler at SPi Global, to turn our manuscript into a finished product. The team also included photo researcher Kristin Piljay. We think these talented people do great work. All are true professionals, with whom we are very fortunate to be associated.

The authors owe special thanks to four people who were very important contributors to this project.

- Working with Dennis Tasa, who is responsible for all of the text's outstanding illustrations and some excellent animations, is always special for us. He has been part of our team for more than 35 years. We value not only his artistic talents, hard work, patience, and imagination but his friendship as well.
- As you read this text, you will see dozens of extraordinary photographs by Michael Collier. Most are aerial shots taken from his 60-year-old Cessna 180. Michael was also responsible for preparing the 29 remarkable Mobile Field Trips that are scattered through the text. Among his many awards is the American Geosciences Institute Award for Outstanding contribution to the Public Understanding of Geosciences. We think that Michael's photographs and field trips are the next best thing to being there. We were very fortunate to have had Michael's assistance on *Foundations of Earth Science*, 9th edition. Thanks, Michael.
- Callan Bentley is a professor of geology at Northern Virginia Community College in Annandale, where he has been honored many times as an outstanding teacher. He is a frequent contributor to *Earth* magazine and is author of the popular geology blog *Mountain Beltway*. Callan was responsible for preparing the SmartFigure Tutorials that appear throughout the text. As you take advantage of these outstanding learning aids, you will hear his voice explaining the ideas.
- We are pleased that Alvin Coleman has joined the *Foundations of Earth Science* team. Alvin is a professor at North Carolina's Cape Fear Community College where he teaches introductory Earth science and geology. He is responsible for revising, updating, and expanding the learning opportunities available in Mastering Geology™. When students access *Mastering*, they will benefit from Alvin's years of experience, depth of knowledge, and understanding of student needs. Welcome, Alvin.

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:

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Last but certainly not least, we gratefully acknowledge the support and encouragement of our wives, Nancy Lutgens and Joanne Bannon. Preparation of *Foundations of Earth Science* 9th edition would have been far more difficult without their patience and understanding.

Fred Lutgens

Ed Tarbuck

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IN THE NEWS

Why Do Flash Floods and Mudflows Often Follow Wildfires?

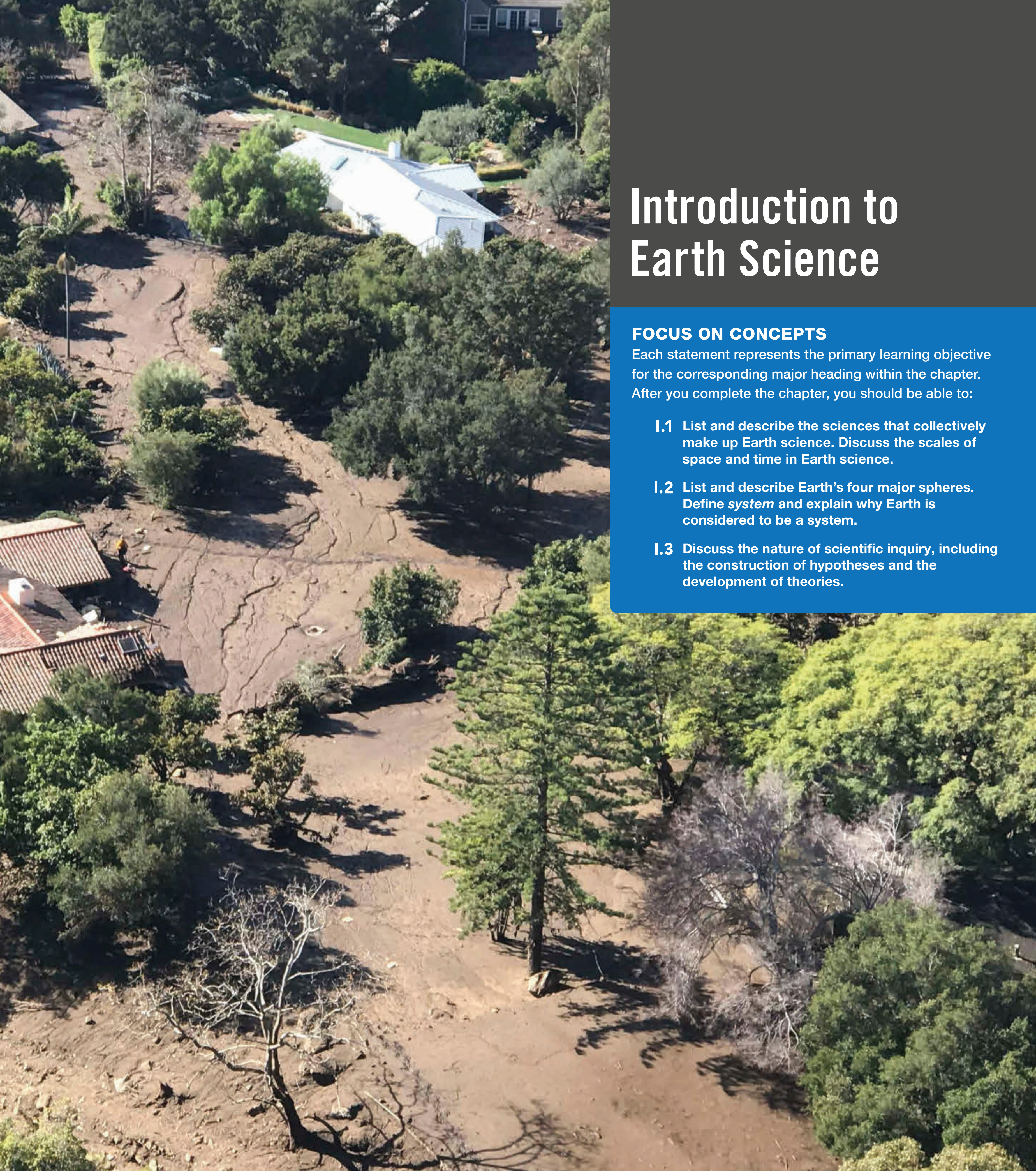
In December 2017, wildfires burned large areas in the rugged hills of southern California. The fires were especially fierce because the weather had been unusually dry and then strong, hot seasonal Santa Ana winds fanned the flames.

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

▲ Raging wildfire in southern California.

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

► **Wildfires swept through the Montecito, California area in December 2018, burning much of the hillside vegetation. Heavy rains a month later resulted in massive mudflows inundating the town.** (DOD Photo/Alamy Stock Photo; insert: George Rose/Getty Images)



Introduction to Earth Science

FOCUS ON CONCEPTS

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

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

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

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

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 questions about our environment. What forces produce mountains? Why is our daily weather so variable? Why is climate 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? It also deals with practical matters, such as whether a successful well can be located at a particular 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.

I.1 What Is Earth Science?

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

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

Earth science is often perceived as science that is performed outdoors—and rightly so. A great deal of an Earth scientist's study is based on observations and experiments conducted in the field. But Earth science is also conducted in the laboratory, where, for example, the study of various Earth materials provides insights into many basic processes and the creation of complex computer models allows for the simulation of our planet's complicated climate system. Frequently, Earth scientists require an understanding 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.

Geology

In this text, 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 processes* create earthquakes, build mountains, and produce volcanic structures (**Figure I.1**). At the surface, *external processes* break rock apart and sculpt a broad array of landforms. The erosional effects of water, wind, and ice result in a great diversity of landscapes. Because rocks and minerals form in response to Earth's internal and external processes, their interpretation is basic to an understanding of our planet.

In contrast to physical geology, the aim of *historical geology* is to understand the origin of Earth and the development of the planet through its 4.6-billion-year history (**Figure I.2**). It strives to establish an orderly chronological arrangement of the multitude of physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of Earth history because we must first understand how Earth works before we attempt to unravel its past.

Oceanography

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

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

Meteorology

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

Astronomy

Unit 7, *Earth's Place in the Universe*, demonstrates that an understanding of Earth requires that we relate our planet to the larger universe. Because Earth is related to all the other objects in space, the science of **astronomy**—the study of the universe—is very useful in probing the origins of our own environment. Because

▲ **Figure I.1**
Volcanic eruption Internal processes are those that occur beneath Earth's surface. Sometimes they lead to the formation of major features at the surface. (Terray Sylvester/Reuters)

▲ **SmartFigure I.2**
Arizona's Grand Canyon The erosional work of the Colorado River along with other external processes created this natural wonder. For someone studying historical geology, hiking down the South Kaibab Trail in Grand Canyon National Park is a trip through time. These rock layers hold clues to millions of years of Earth history. (Michael Collier)

Mobile Field Trip
https://media.pearsoncmg.com/ph/esm/esm_lutgens_foundations_9/media/

DID YOU KNOW?

Most people living in highly industrialized countries do not realize the quantity of resources needed to maintain their modern standard of living. An estimate by the U.S. Geological Survey determined that the annual per capita consumption of nonmetallic and metallic resources for the United States is about 11,000 kilograms (12 tons). About 97 percent of these resources are nonmetallic (sand and gravel, stone, salt, cement, etc.). About 3 percent are metallic (iron, aluminum, copper, etc.). This is each person's prorated share of the materials required by industry to provide the vast array of products modern society demands.

we are so closely acquainted with the planet on which we live, it is easy to forget that Earth is just a tiny object in a vast universe. Indeed, Earth is subject to the same physical laws that govern the many other objects populating the great expanses of space. Thus, to understand explanations of our planet's origin, it is useful to learn something about the other members of our solar system. Moreover, it is helpful to view the solar system as a part of the great assemblage of stars that comprise our galaxy, which is but one of many galaxies.

Earth Science Is Environmental Science

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

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

For most of history, most people lived in rural areas. However, today more people live in cities than in rural areas. This global trend toward urbanization concentrates millions of people into places that are vulnerable to natural hazards. Coastal sites are becoming more vulnerable because development often destroys natural defenses such as wetlands and sand dunes. In addition, there is a growing threat associated with human influences on the Earth system, such as sea level rise that is linked to global warming. Other urban areas are exposed to seismic (earthquake) and volcanic hazards where inappropriate land use and poor construction practices, coupled with rapid population growth, increase vulnerability (**Figure I.3**).

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

Global Climate Change Among the most important environmental issues linked to human activities is global climate change. During Earth's long history, its climate has been naturally variable. However, when recent and future climate changes are considered, natural variability is overshadowed by the influence of human activities, largely associated with burning fossil fuels. Burning coal, oil, and natural gas causes changes in the composition of the atmosphere, which cause global temperatures to rise (**Figure I.4**). Among the many potential impacts of global warming are a rise in sea level, more extreme weather events, and the extinction of many plant and animal species.

People Influence Earth Processes Not only do Earth processes have an impact on people, but we humans can dramatically influence Earth processes as well. Human activities alter the composition of the atmosphere, triggering air pollution episodes and causing global climate change. Landslides and river flooding occur naturally, but the magnitude and frequency of these events can be changed significantly by human activities such as clearing forests, building cities, and constructing roads and dams. Unfortunately, natural systems do not always adjust to artificial

▶ **Figure I.3**
Earthquake in Ecuador On April 16, 2016, a magnitude 7.8 earthquake struck coastal Ecuador. It was the strongest quake in that region in 40 years. There were nearly 700 fatalities and more than 7000 people injured. Natural hazards are *natural processes*. They become hazards only when people try to live where the processes occur. (Bloomberg/Getty Images)

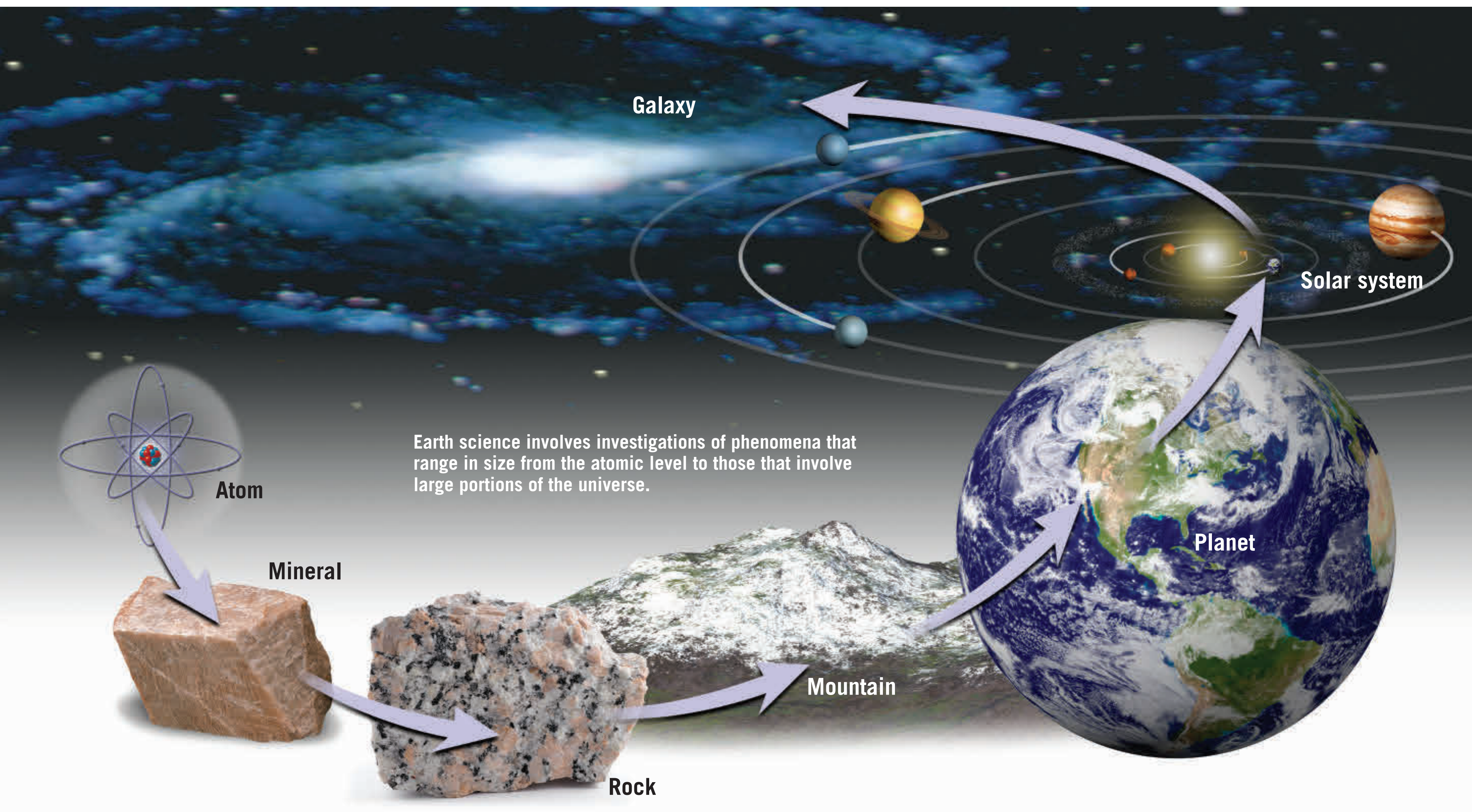
changes in ways that we can anticipate. Thus, an alteration to the environment that was intended to benefit society often has the opposite effect.

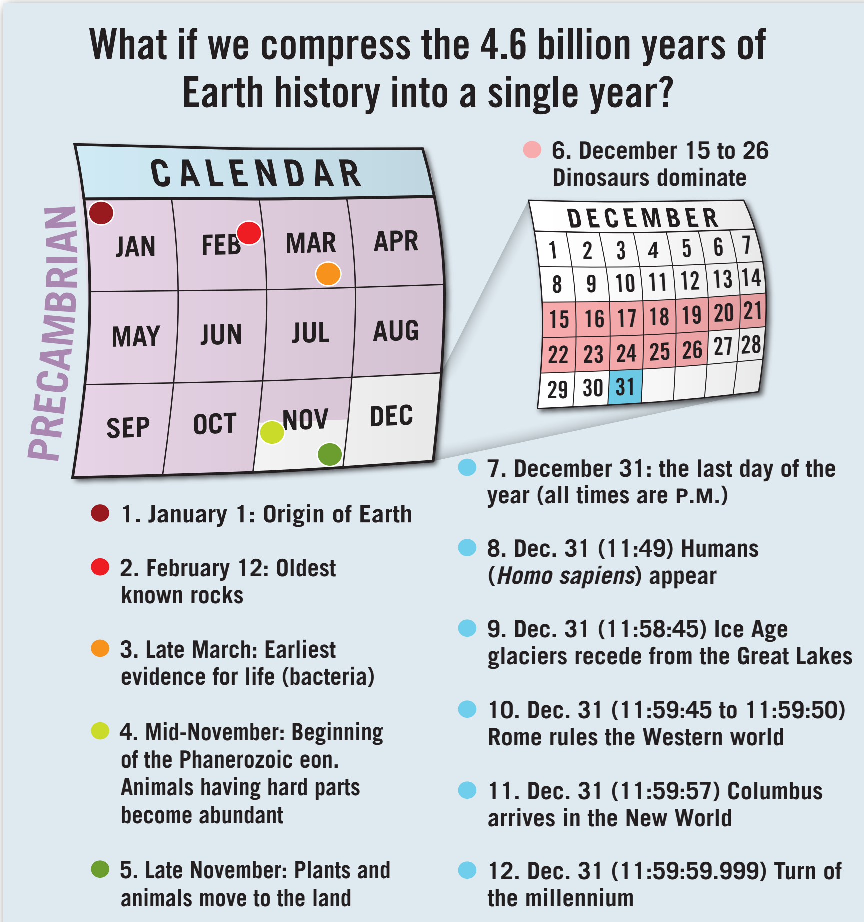
◀ **Figure I.4**
People impact the atmosphere Emissions from motor vehicles, power plants, and other human activities are largely responsible for the global warming experienced over the past 100 years. (Levi Bianco/Getty Images)

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 I.5**). Some phenomena are relatively easy for us to imagine, such as the size and duration of an afternoon thunderstorm or the dimensions of a sand dune. Other phenomena are so vast or so small that they are difficult to imagine. The number of stars and distances in our galaxy (and beyond!) and the internal arrangement of atoms in a mineral crystal are examples of such phenomena.

▼ **Figure I.5**
From atoms to galaxies Earth science involves investigations of phenomena that range in size from atoms to galaxies and beyond.





▶ **SmartFigure I.6**
Magnitude of geologic time

Tutorial
https://media.pearsoncmg.com/ph/esm/esm_lutgens_foundations_9/media/

DID YOU KNOW?

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

DID YOU KNOW?

The Sun contains 99.86 percent of the mass of the solar system, and its circumference is 109 times that of Earth. A jet plane traveling at 1000 km/hr (620 mi/hr) would require nearly 182 days to circle the Sun.

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 about 50 million years ago, and they continue to develop today.

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

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 nearly 4.6-billion-year history, an event that occurred 50 million years ago may be characterized as "recent" by a geologist, and a rock sample that has been dated at 5 million years may be called "young."

An appreciation for the *magnitude of geologic time* is important in the study of 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, 7 days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.6 billion! **Figure I.6** provides another interesting way of viewing the expanse of Earth history. Although helpful in conveying the magnitude of geologic time, this figure and other analogies, no matter how clever, only begin to help us comprehend the vast expanse of Earth history. Nevertheless, they help us shift from thinking a million years is impossibly long ("never in a million years") to thinking that a million years is a "blink of an eye" in the history of Earth.

CONCEPT CHECKS I.1

1. List and briefly describe the sciences that collectively make up Earth science.
2. List at least four different natural hazards. Aside from natural hazards, describe another important connection between people and Earth science.
3. How old is Earth?

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I.2 Earth as a System

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

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

Earth's Spheres

The images in **Figure I.7** are important because they let humanity see Earth differently than ever before. These early views from the NASA Moon missions of the late 1960s and early 1970s profoundly altered our conceptualizations of Earth. Seen from space, Earth is breathtaking in its beauty 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."

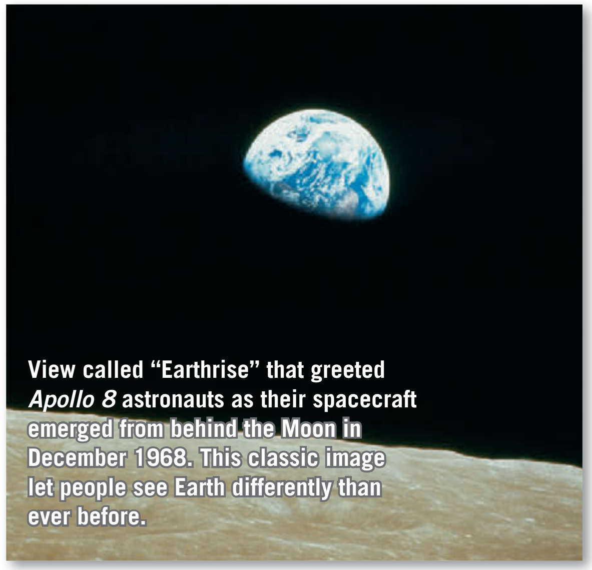
As we look closely at our planet from space, it becomes apparent that Earth is much more than rock and soil. In fact, the most conspicuous features of Earth in **Figure 1.7A** are swirling clouds suspended above the surface of the vast global ocean. These features emphasize the importance of water on our planet.

The closer view of Earth from space shown in **Figure 1.7B** helps us appreciate why the physical environment is traditionally divided into three major parts: the water portion of our planet, the *hydrosphere*; Earth's gaseous envelope, the *atmosphere*; and, of course, the solid Earth, or *geosphere*. It needs to be emphasized that our environment is highly integrated and not dominated by rock, water, or air alone. Rather, it is characterized by continuous interactions as air comes in contact with rock, rock with water, and water with air. Moreover, the *biosphere*, which is the totality of all life on our planet, interacts with each of the three physical realms and is an equally integral part of the planet.

The interactions among Earth's spheres are incalculable. **Figure I.8** provides one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air, and these spheres in turn support life-forms in and near the water. In this scene, ocean waves created by the drag of air moving across the water are breaking against the rocky shore. The force of water, in turn, erodes the shoreline.

Hydrosphere Earth is sometimes called the ***blue*** planet. Water, more than anything else, makes Earth unique. The **hydrosphere** is a dynamic mass of water that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface to an average depth of about 3800 meters (12,500 feet). It accounts for more than 96 percent of Earth's water (**Figure I.9**). However, the hydrosphere also includes the freshwater found underground and in streams, lakes, glaciers, and clouds. Moreover, water is an important component of all living things.

Although freshwater constitutes a small fraction of Earth's hydrosphere, it is much more important than its meager percentage indicates. Freshwater is vital for life on land, clouds play a vital role in many weather and climate processes, and streams, glaciers, and groundwater are responsible for sculpting many of our planet's varied landforms.



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

A.

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

B.

◄ **SmartFigure I.7**
Two classic views of Earth from space The accompanying video commemorates the 45th anniversary of *Apollo 8*'s historic flight by re-creating the moment when the crew first saw and photographed Earth rising from behind the Moon. (Johnson Space Center/NASA)

Video
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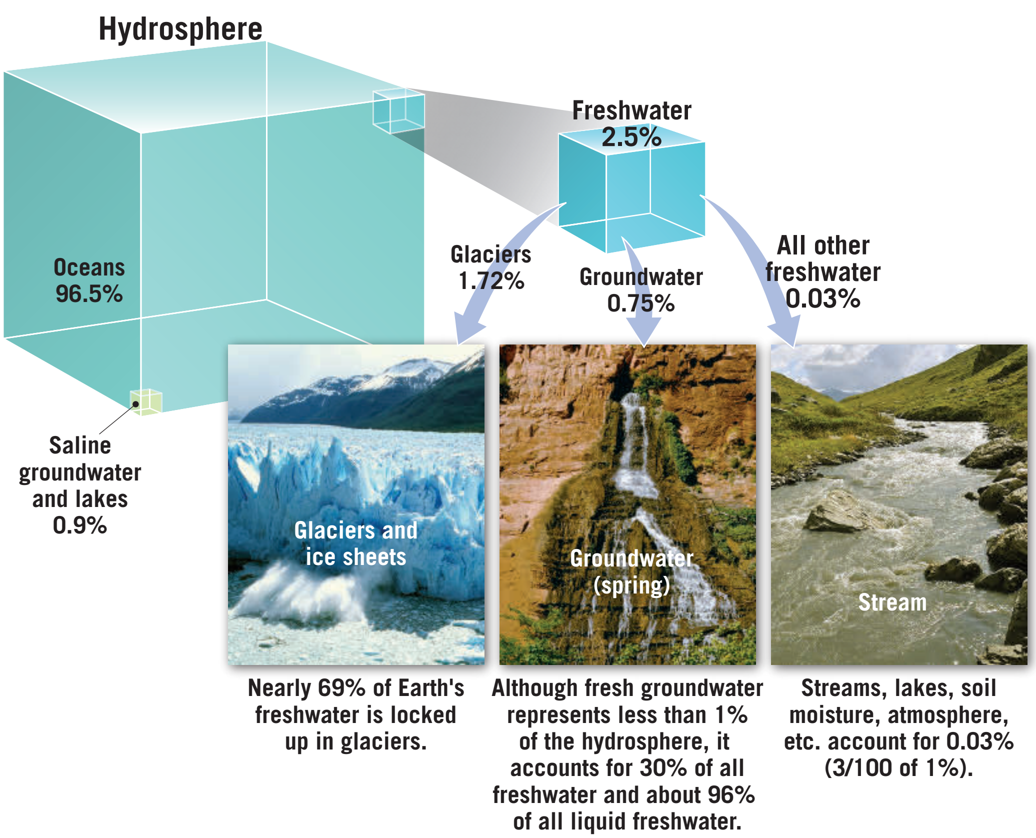
▶ **Figure I.8**
Interactions among Earth's spheres The shoreline is one obvious interface—a common boundary where different parts of a system interact. In this scene, ocean waves (hydrosphere) that were created by the force of moving air (atmosphere) break against a rocky shore (geosphere). The force of the water can be powerful, and the erosional work that is accomplished can be great. (MedioTuerto/Getty Images)



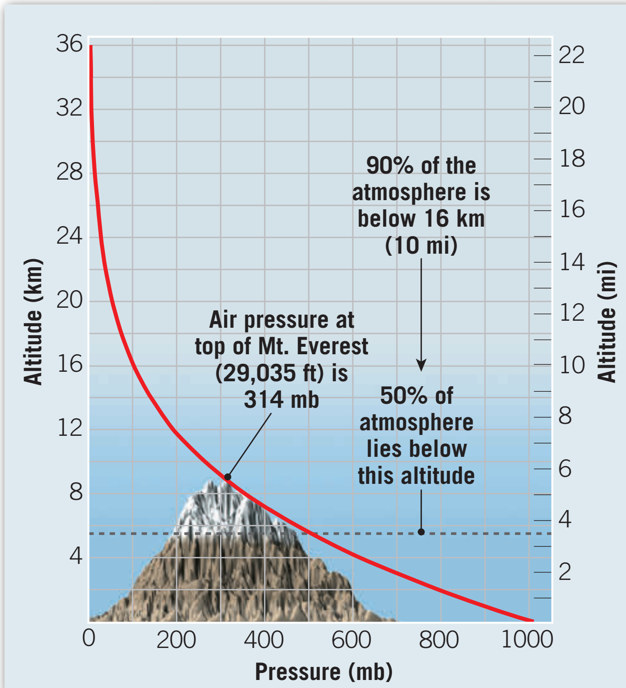
▲ **Figure I.9**
The water planet Distribution of water in the hydrosphere. (left: Image Professionals GmbH/Alamy Stock Photo; center, right: Michael Collier)

Atmosphere Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (Figure I.10). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth (about 6400 kilometers [4000 miles]), the atmosphere is a very shallow layer. Despite its modest dimensions, this thin blanket of air is an integral part of the planet. It not only provides the air we breathe but also protects us from the Sun's intense heat and dangerous ultraviolet radiation. The energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call ***weather*** and ***climate***. Climate has a strong influence on the nature and intensity of Earth's external processes. When climate changes, these processes respond.

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

Biosphere The **biosphere** includes all life on Earth (**Figure I.11**). Ocean life is concentrated in the sunlit upper waters. Most life on land is also concentrated near the surface, with tree roots and burrowing animals reaching a few meters underground and flying insects and birds reaching a kilometer or so into the atmosphere. A surprising variety of life-forms are also adapted to extreme environments. For example, on the ocean floor, where pressures are extreme and no light penetrates, there are places where vents spew hot, mineral-rich fluids that support communities of exotic life-forms, as in Figure 1.11B. On land, some bacteria thrive in rocks as deep as 4 kilometers (2.5 miles) and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth's surface.

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



◄ **Figure I.10**
A shallow layer The atmosphere is an integral part of the planet. Air pressure is simply the force exerted by the weight of the air above. The graph shows that air pressure decreases rapidly near Earth's surface and more gradually at greater heights.

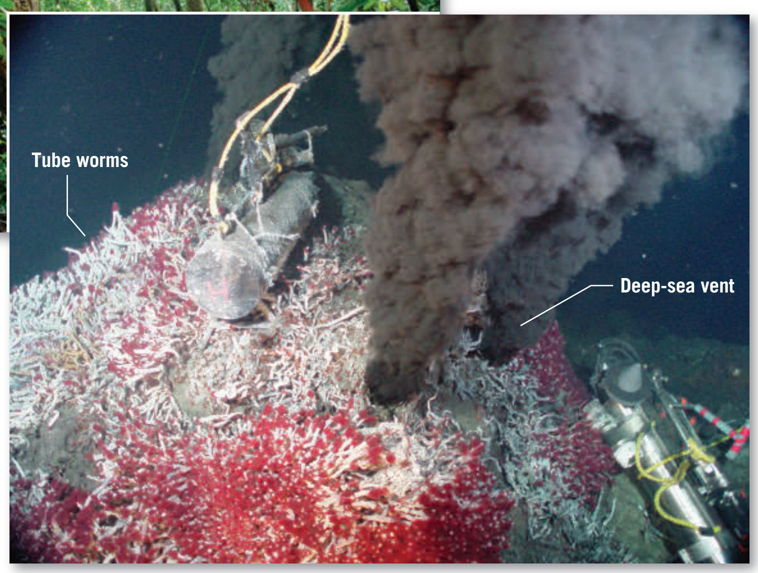
DID YOU KNOW?

The volume of ocean water is so large that if Earth's solid mass were perfectly smooth (level) and spherical, the oceans would cover Earth's entire surface to a uniform depth of more than 2000 m (1.2 mi)!

DID YOU KNOW?

Since the mid-twentieth century, the global average surface temperature has increased by about 1°C (1.8°F). By the end of the twenty-first century, the global average surface temperature may increase by an additional 2° to 4.5°C (3.5° to 8.1°F).

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



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

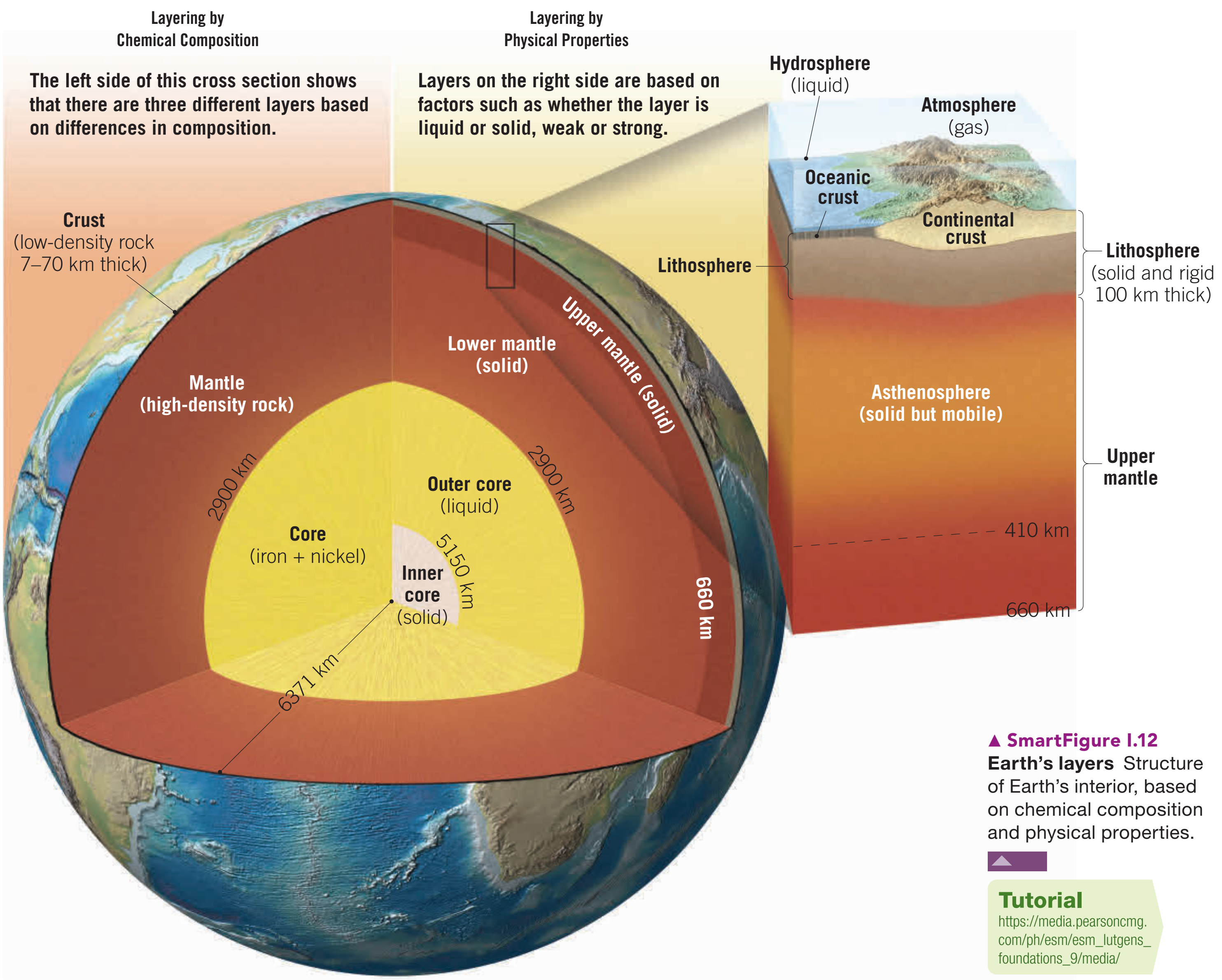
◄ **Figure I.11**
The biosphere The biosphere, one of Earth's four spheres, includes all life. **A.** Tropical rain forests are teeming with life and occur in the vicinity of the equator. **B.** Some life occurs in extreme environments such as the absolute darkness of the deep ocean. (a. age Fotostock/Superstock; b. Image courtesy of NOAA PMEL Vents Program)

Geosphere Lying beneath the atmosphere and the ocean is the solid Earth or **geosphere**. Extending from the surface to the center of the planet, a depth of nearly 6400 kilometers (4000 miles), it is by far the largest of Earth's spheres. Much of our study of the solid Earth focuses on the more accessible surface and near-surface features, but it is worth noting that many of these features are linked to the dynamic behavior of Earth's interior.

Earth's interior is layered (**Figure I.12**) due to differences in ***chemical composition*** and ***physical properties***. On the basis of chemical composition, Earth has three layers: a dense inner sphere called the **core**; the less dense **mantle**; and the **crust**, which is the least dense and very thin outer skin of Earth. The crust is not a layer of uniform thickness. It is thinnest beneath the oceans and thickest where continents exist. Although the crust may seem insignificant when compared with the other layers of the geosphere, which are much thicker, it was created by the same general processes that formed Earth's present structure. Thus, the crust is important in understanding the history and nature of our planet.

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

The two principal divisions of Earth's surface are the continents and the ocean basins. The most obvious difference between these two provinces is their relative vertical levels. The average elevation of the continents



▲ **SmartFigure I.12**
Earth's layers Structure of Earth's interior, based on chemical composition and physical properties.

Tutorial
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above sea level is about 840 meters (2750 feet), whereas the average depth of the oceans is about 3800 meters (12,500 feet). Thus, the continents stand on average 4640 meters (about 4.6 kilometers, or nearly 3 miles) above the level of the ocean floor.

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

Earth System Science

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

A **system** is a group of interacting, or interdependent, parts that form a complex whole. Most of us hear and use the term *system* frequently. We may service our car's cooling *system*, make use of the city's transportation *system*, and be a participant in the political *system*. A weather report might inform us of an approaching storm *system*. Further, we know that Earth is just a small part of a larger system known as the *solar system*, which in turn is a subsystem of an even larger system called the Milky Way Galaxy. The *In the News* feature on the opening page of the chapter and **Figure I.13** provide examples of the interactions among different parts of the Earth system.

The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over. One familiar loop, or subsystem, is the *hydrologic cycle*. It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and geosphere (see Figures 6.6 and 12.1). Water enters the atmosphere through evaporation from Earth's surface and transpiration from plants. Water vapor condenses in the atmosphere to form clouds, which in turn produce precipitation that falls back to Earth's surface. Some of the rain that falls onto the land sinks in and then is taken up by plants or becomes groundwater, and some flows across the surface toward the ocean.

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

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

DID YOU KNOW?

We have never sampled the mantle or core directly. The structure of Earth's interior is determined by analyzing seismic waves from earthquakes. As these waves of energy penetrate Earth's interior, they change speed and are bent and reflected as they move through zones having different properties. Monitoring stations around the world detect and record this energy.

▲ **Figure I.13**
Deadly debris flow This image provides an example of interactions among different parts of the Earth system. Extraordinary rains triggered the debris flow (popularly called a mudslide) that buried this house in Montecito, California in January 2018. (Mike Eliason/SBC Fire Department/ZUMA Press/Newscom)

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 I.14**). The soil that eventually forms will reflect the interactions among many parts of the Earth system—the volcanic parent material, the climate, and the impact of biological activity. Of course, there would also be significant changes in the biosphere. Some organisms and their habitats would be eliminated by the lava and ash, and new settings for life, such as a lake formed by a lava dam, would be created. The potential climate change could also impact sensitive life-forms.

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

Energy for the Earth System The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, in the hydrosphere, and at Earth's surface. Energy from the Sun drives weather and climate, ocean circulation, and erosional processes. Earth's interior is the second

▲ **Figure I.14**
Change is a constant When Mount St. Helens erupted in May 1980, the area shown here was buried by a volcanic mudflow. Now plants are reestablished, and new soil is forming. (left: Terry Donnelly/Alamy Stock Photo; right: USGS)

source of energy. The internal processes that produce volcanoes, earthquakes, and mountains are powered by heat remaining from when our planet formed and heat that is continuously generated by radioactive decay.

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

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

CONCEPT CHECKS I.2

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

I.3 The Nature of Scientific Inquiry

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

Developing an understanding of how science is done and how scientists work is an important theme in this textbook. As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Science is a process of producing knowledge. The process depends both on making careful observations and on creating explanations that make sense of the observations. The types of data collected often help to answer well-defined questions about the natural world. In this textbook you will explore the difficulties in gathering data and some of the ingenious methods that have been developed to overcome these difficulties (**Figure I.15**). You will also see many examples of how hypotheses are formulated and tested, and you will learn about the evolution and development of some major scientific theories.

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

Hypothesis

A scientific **hypothesis** is a proposed explanation for a certain phenomenon that occurs in the natural world. A hypothesis must be *testable*, and it must be possible to make *predictions* based on the hypothesis being considered. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are ultimately discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth until more detailed astronomical observations disproved it.

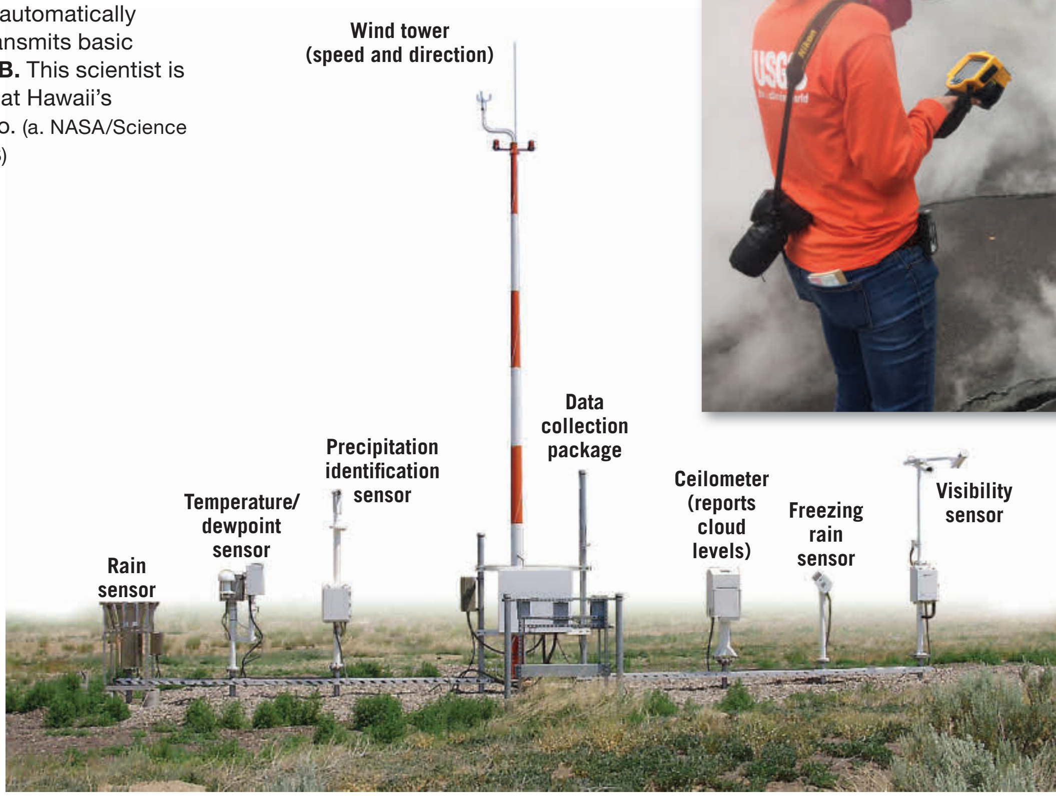
Theory

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. One example is the *nebular theory* discussed in Chapter 15, which explains the

DID YOU KNOW?

A scientific *law* is a basic principle that describes a particular behavior of nature that is generally narrow in scope and can be stated briefly—often as a simple mathematical equation. Because scientific laws have been shown time and time again to be consistent with observations and measurements, they are rarely discarded. Laws may, however, require modifications to fit new findings.

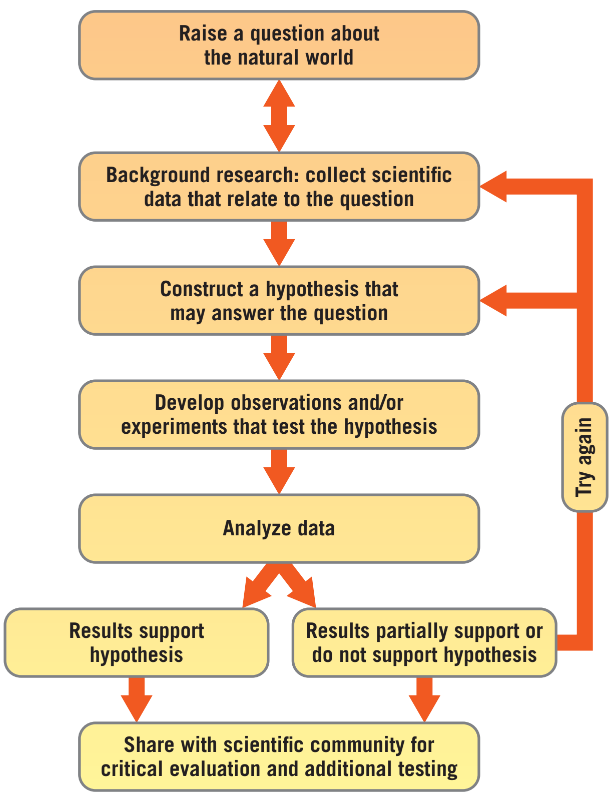
▶ **Figure I.15**
Observation and measurement Gathering data and making careful observations are basic parts of scientific inquiry. **A.** This array of instruments automatically records and transmits basic weather data. **B.** This scientist is gathering data at Hawaii's Kilauea Volcano. (a. NASA/Science Source; b. USGS)



A.

B.

▶ **Figure I.16**
Steps frequently followed in scientific investigations The diagram depicts the steps involved in the process many refer to as the *scientific method*.



formation of our solar system. Another, called the *theory of plate tectonics*, provides the framework for understanding the origin of mountains, earthquakes, and volcanic activity—ideas that are explored in some detail in Chapters 3, 4, and 5.

Scientific Methods

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

There is no fixed path that scientists always follow that leads unerringly to scientific knowledge. However, many scientific investigations involve the steps outlined in **Figure I.16**. In addition, some scientific

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

discoveries result from purely theoretical ideas that stand up to extensive examination. Some researchers use high-speed computers to create models that simulate what is happening in the real world. These models are useful when dealing with natural processes that occur on very long time scales or that take place in extreme or inaccessible locations. Still other scientific advancements are made when a totally unexpected happening occurs during an experiment. These serendipitous discoveries are more than pure luck, for as the nineteenth-century French scientist Louis Pasteur said, "In the field of observation, chance favors only the prepared mind."

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

CONCEPT CHECKS I.3

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

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CONCEPTS IN REVIEW

Introduction to Earth Science

I.1 What Is Earth Science?

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

Key Terms: **Earth science** | **geology** | **oceanography** | **meteorology** | **astronomy** | **geologic time**

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

I.2 Earth as a System

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

Key Terms: **Earth system** | **hydrosphere** | **atmosphere** | **biosphere** | **geosphere** | **core** | **mantle** | **crust** | **lithosphere** | **asthenosphere** | **Earth system science** | **system**

- Earth's physical environment is traditionally divided into three major parts: the solid Earth, called the *geosphere*; the water portion of our planet, called the *hydrosphere*; and Earth's gaseous envelope, called the *atmosphere*.
- A fourth Earth sphere is the *biosphere*, the totality of life on Earth. It is concentrated in a relatively thin zone that extends a few kilometers into the hydrosphere and geosphere and a few kilometers up into the atmosphere.
- Of all the water on Earth, more than 96 percent is in the oceans, which cover nearly 71 percent of the planet's surface.
- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole that is called the *Earth system*.
- *Earth system science* uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our planet and its global environmental problems.
- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmosphere, hydrosphere, and at Earth's surface, and (2) heat from Earth's interior, which powers the internal processes that produce volcanoes, earthquakes, and mountains.

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

(Michael Collier)

I.3 The Nature of Scientific Inquiry

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

Key Terms: hypothesis | theory | scientific method

- Scientists make careful observations, construct tentative explanations for those observations (*hypotheses*), and then test those hypotheses with field investigations, laboratory work, and/or computer modeling.
- In science, a *theory* is a well-tested and widely accepted explanation that the scientific community agrees best fits certain observable facts.
- As we discard flawed hypotheses, scientific knowledge moves closer to a correct understanding, but we can never be fully confident that we know all the answers. Scientists must always be open to new information that forces change in our model of the world.

GIVE IT SOME THOUGHT

1. **The length of recorded history for humankind is about 5000 years. Clearly, most people view this span as being very long. How does it compare to the length of geologic time? Calculate the percentage or fraction of geologic time that is represented by recorded history. To make calculations easier, round the age of Earth to the nearest billion.**
2. **The average distance between Earth and the Sun is 150 million kilometers (93 million miles). About how long would it take a jet plane traveling from Earth at 1000 kilometers (620 miles) per hour to reach the Sun?**
3. **This scene is in British Columbia's Mount Robson Provincial Park. The park is named for the highest peak in the Canadian Rockies. List examples of features associated with each of Earth's four spheres. Which, if any, of these features was created by internal processes? Describe the role of external processes in this scene.**

(Michael Wheatley/age Fotostock)

4. **Humans are part of the Earth system. List at least three examples of how you, in particular, influence one or more of Earth's major spheres.**
5. **Examine Figure I.9 to answer these questions.**
   a. Where is most of Earth's freshwater stored?
   b. Where is most of Earth's liquid freshwater found?
6. **Refer to the graph in Figure I.10 to answer the following questions.**
   a. If you were to climb to the top of Mount Everest, how many breaths of air would you have to take at that altitude to equal one breath at sea level?
   b. If you were flying in a commercial jet at an altitude of 12 kilometers (about 39,000 feet), about what percentage of the atmosphere would be below the plane?
7. **The accompanying photo provides an example of interactions among different parts of the Earth system. It is a view of a mudflow that was triggered by extraordinary rains in March 2014. Describe how each of Earth's four "spheres" was influenced by and/or involved in this natural disaster that buried a 1-square-mile rural neighborhood near Oso, Washington, and caused more than 40 fatalities.**

(Michael Collier)

8. **As you enter a dark room, you turn on a wall switch, but the ceiling light does not come on. Formulate at least three hypotheses that might explain this observation. Once you have formulated your hypotheses, what should be your next step?**

Mastering Geology

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IN THE NEWS

Discovered and Then Resubmerged: The Cave of Crystals

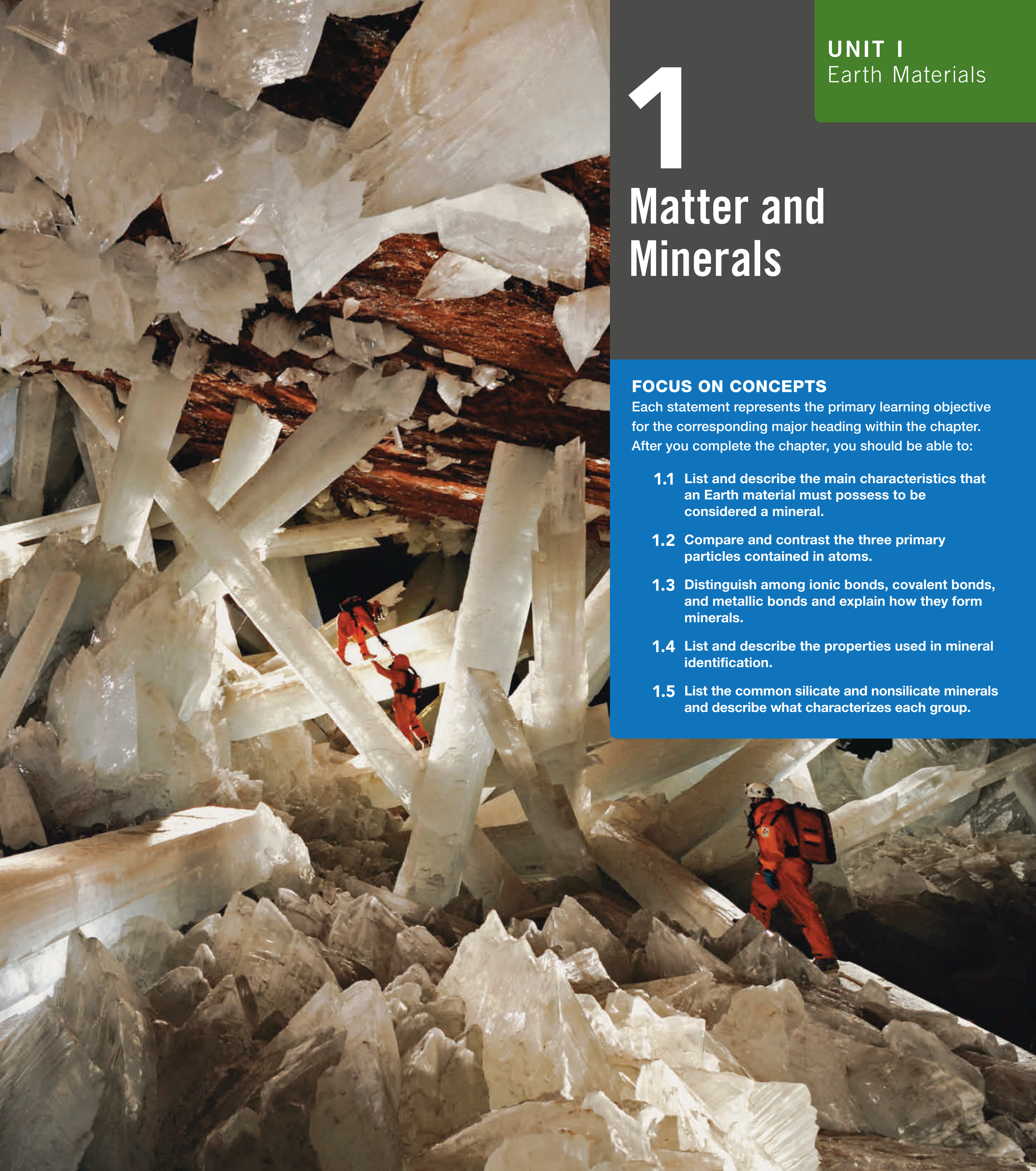
When miners in Naica, Mexico, drilled into a submerged cavern 1000 feet down and pumped the groundwater out, their discovery made the news around the world. They found a cave filled with enormous gypsum crystals, the largest of which was as tall as a three-story building and weighed 55 tons.

Nearly as noteworthy as the crystals were the lengths people had to go to view them. A magma body lying just a few miles below heated the cave's air to 136°F, and the relative humidity exceeded 90 percent. As adventurer and television host George Kourounis put it, "As soon as you walk in, you start to die."

To allow explorers to survive for more than 10 minutes in this extreme environment, a special refrigerated suit and ice-cooled breathing system were developed. After years of study, mining operations in the area ended, and so did the constant pumping out of water. In 2017, the cave reverted to its original, submerged state.

The miners who discovered the Naica Crystal Cave hunted for lead, silver, zinc, and copper. These metals are just a few of the myriad of minerals that exist. Every process that geologists study in some way depends upon the properties of these basic materials of Earth.

► **The Cave of Crystals in Naica, Mexico, contains giant gypsum crystals, some of the largest natural crystals ever found.** (Xinhua/Carsten Peter/National Geographic/Christie's Images/Newscom)



UNIT I
Earth Materials

1 Matter and Minerals

FOCUS ON CONCEPTS

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

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

1.2 **Compare and contrast the three primary particles contained in atoms.**

1.3 **Distinguish among ionic bonds, covalent bonds, and metallic bonds and explain how they form minerals.**

1.4 **List and describe the properties used in mineral identification.**

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

Earth's crust and oceans are home to a wide variety of useful and essential minerals. Most people are familiar with the common uses of many basic metals, including aluminum in beverage cans, copper in electrical wiring, and gold and silver in jewelry. 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 dentists use drill bits impregnated with diamonds to drill through tooth enamel. In fact, practically every manufactured product contains materials obtained from minerals.

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

DID YOU KNOW?

Archaeologists discovered that more than 2000 years ago, the Romans transported water in lead pipes. In fact, Roman smelting of lead and copper ores between 500 B.C.E. and C.E. 300 caused a small rise in atmospheric pollution that was recorded in Greenland ice cores.

1.1 Minerals: Building Blocks of Rocks

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

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

Defining a Mineral

The term mineral is used in several different ways. Those concerned with health and fitness often extol the benefits of vitamins and minerals. The mining industry typically uses the word to refer to anything extracted from Earth, such as coal, iron ore, or sand and gravel. The guessing game Twenty Questions usually begins with the question *Is it animal, vegetable, or mineral?* What criteria do geologists use to determine whether something is a mineral (**Figure 1.1**)?

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

1. **Naturally occurring.** Minerals form by natural geologic processes. Synthetic materials, meaning those produced in a laboratory or by human intervention, are not considered minerals.
2. **Orderly crystalline structure.** Minerals are crystalline substances, made up of atoms (or ions) that are arranged in an orderly, repetitive manner (**Figure 1.2**). This orderly packing of atoms is reflected in regularly shaped objects called *crystals*. Some naturally occurring solids, such as volcanic glass (obsidian), lack a repetitive atomic structure and are not considered minerals.
3. **Solid substance.** Only solid crystalline substances are considered minerals. Ice (frozen water) fits this criterion and is considered a mineral, whereas liquid water and water vapor do not.

▲ **Figure 1.1**
Quartz crystals A collection of well-developed quartz crystals found near Hot Springs, Arkansas. (Jeffrey A. Scovil)

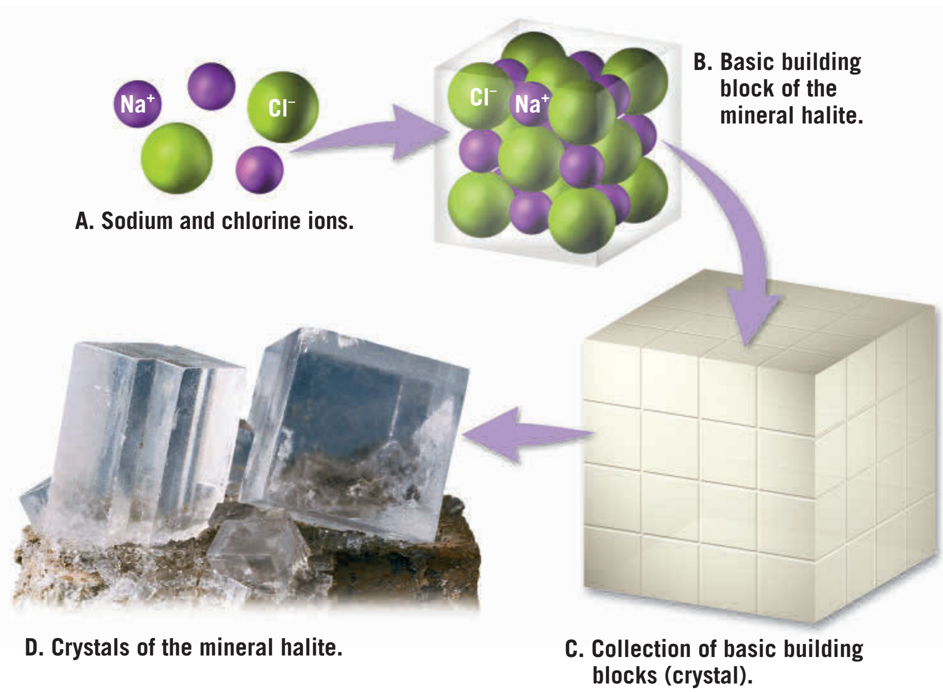
4. **Generally inorganic.** Inorganic crystalline solids, such as ordinary table salt (halite), that are found naturally in the ground are considered minerals. (Organic compounds, on the other hand, are generally not. Sugar, a crystalline solid like salt but extracted from sugarcane or sugar beets, is 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, geologists consider them minerals.
5. **Definite chemical composition that allows for some variation.** Most minerals are chemical compounds having compositions that can be expressed by a chemical formula. For example, the common mineral quartz has the formula SiO_2, which indicates that quartz consists of silicon (Si) and oxygen (O) atoms, in a 1:2 ratio. This proportion of silicon to oxygen is true for any sample of pure quartz, regardless of its origin. However, the compositions of some minerals 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.

What Is a Rock?

Rocks are more loosely defined than minerals. They are any solid mass of mineral, or mineral-like, matter that occurs naturally as part of our planet. Most rocks, like the sample of granite shown in Figure 1.3, are aggregates of several different minerals. The term ***aggregate*** implies that the minerals joined in such a way that their individual properties are retained. Note that the different minerals that make up granite can be easily identified. However, some rocks are composed almost entirely of one mineral. A common example is the sedimentary

DID YOU KNOW?

The purity of gold is expressed by the number of *karats*. Twenty-four karats is pure gold. Gold less than 24 karats is an alloy (mixture) of gold and another metal, usually copper or silver. For example, 14-karat gold contains 14 parts gold (by weight) mixed with 10 parts of other metals.



◄ **Figure 1.2**
Arrangement of sodium and chloride ions in the mineral halite The arrangement of atoms (ions) into basic building blocks that have a cubic shape results in regularly shaped cubic crystals. (Dennis Tasa)

▶ **SmartFigure 1.3**
Most rocks are aggregates of minerals Shown here is a hand sample of the igneous rock granite and three of its major constituent minerals.

Tutorial
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rock ***limestone***, which is an impure mass of the mineral calcite. In addition, some rocks are composed of nonmineral matter. These include the volcanic rocks ***obsidian*** and ***pumice***, which are noncrystalline glassy substances, and ***coal***, which consists of solid organic debris.

Before we discuss rocks and minerals further, it is helpful to review some details on atoms, the building blocks of all matter.

CONCEPT CHECKS 1.1

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

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1.2 Atoms: Building Blocks of Minerals

Compare and contrast the three primary particles contained in atoms.

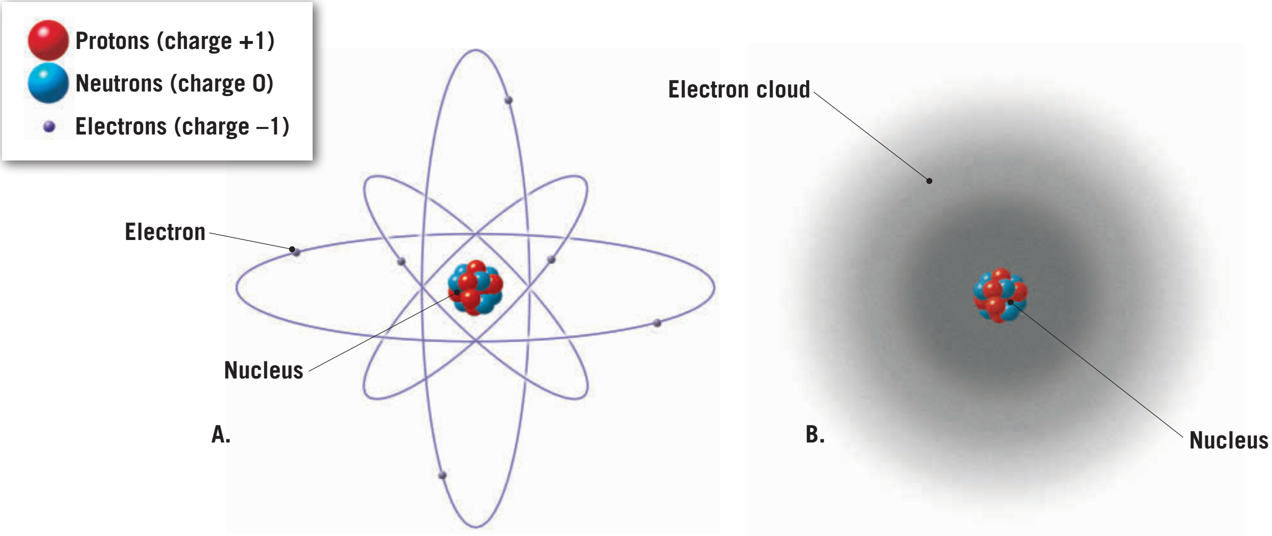
All matter, including minerals, is composed of minute building blocks called **atoms**—the smallest particles that constitute specific elements and cannot be split by chemical means. Atoms, in turn, contain even smaller particles—*protons* and *neutrons* located in a central **nucleus** that is surrounded by *electrons* (**Figure 1.4**).

Properties of Protons, Neutrons, and Electrons

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

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

Illustrations sometimes show electrons orbiting the nucleus in a manner that resembles the planets of



▲ **Figure 1.4**
Two models of an atom A. Simplified view of an atom's central nucleus, composed of protons and neutrons, encircled by high-speed electrons. **B.** An atom model showing spherically shaped electron clouds (shells) surrounding the central nucleus. (Not to scale.)

our solar system orbiting the Sun (see **Figure 1.4A**). However, electrons do not actually behave this way. A more realistic depiction would show electrons as a cloud of negative charges surrounding the nucleus (see **Figure 1.4B**). Studies of the arrangements of electrons show that they move about the nucleus in regions called *principal shells*, each with an associated energy level. Each shell can hold a specific number of electrons, with the outermost shell generally containing **valence electrons**. These outer-shell electrons can be transferred to or shared with other atoms to form chemical bonds.

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

Elements: Defined by Their Number of Protons

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

The **periodic table**, shown in **Figure 1.5**, is used by scientists as a way to organize the known elements. Within this important reference tool, elements with similar properties are aligned in columns, referred to as *groups*. Each element is assigned a one- or two-letter symbol. The atomic number and atomic weight for each element are also included in the periodic table.

Atoms are the basic building blocks of Earth's minerals. Most join to form **chemical compounds**—substances composed of atoms of two or more elements held together by chemical bonds. Examples include the common minerals quartz (SiO_2), halite (NaCl), and calcite $(CaCO_3)$. However, a few minerals, such as diamonds, sulfur, and native gold and copper, are made entirely of atoms of only one element (**Figure 1.6**). (The word *native* is used as a prefix to describe a metal that is found in nature in its pure form.)

CONCEPT CHECKS 1.2

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

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Tendency to lose outermost electrons to uncover full outer shell

Vertical columns contain elements with similar properties.

5 — Atomic number
B — Symbol of element
10.81 — Atomic mass
Boron — Name of element

Tendency to lose electrons

Step-like line divides metals from nonmetals.

Tendency to fill outer shell by sharing electrons

Tendency to gain electrons to make full outer shell

Noble gases are inert because outer shell is full

I A	II A	III B	IV B	V B	VI B	VII B	VIII B	VIII B	VIII B	I B	II B	III A	IV A	V A	VI A	VII A	VIII A
1 H 1.0080 Hydrogen																	2 He 4.003 Helium
3 Li 6.939 Lithium	4 Be 9.012 Beryllium											5 B 10.81 Boron	6 C 12.011 Carbon	7 N 14.007 Nitrogen	8 O 15.9994 Oxygen	9 F 18.998 Fluorine	10 Ne 20.183 Neon
11 Na 22.990 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.974 Phosphorus	16 S 32.064 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon
19 K 39.102 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.90 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.71 Nickel	29 Cu 63.54 Copper	30 Zn 65.37 Zinc	31 Ga 69.72 Gallium	32 Ge 72.59 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.909 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (99) Technetium	44 Ru 101.1 Ruthenium	45 Rh 102.90 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.87 Silver	48 Cd 112.40 Cadmium	49 In 114.82 Indium	50 Sn 118.69 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.30 Xenon
55 Cs 132.91 Cesium	56 Ba 137.34 Barium	#57 TO #71	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.85 Tungsten	75 Re 186.2 Rhenium	76 Os 190.2 Osmium	77 Ir 192.2 Iridium	78 Pt 195.09 Platinum	79 Au 197.0 Gold	80 Hg 200.59 Mercury	81 Tl 204.37 Thallium	82 Pb 207.19 Lead	83 Bi 208.98 Bismuth	84 Po (210) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra 226.05 Radium	#89 TO #103															

57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (147) Promethium	62 Sm 150.35 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.92 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thullium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
89 Ac (227) Actinium	90 Th 232.04 Thorium	91 Pa (231) Protactinium	92 U 238.03 Uranium	93 Np (237) Neptunium	94 Pu (242) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (249) Berkelium	98 Cf (251) Californium	99 Es (254) Einsteinium	100 Fm (253) Fermium	101 Md (256) Mendelevium	102 No (254) Nobelium	103 Lw (257) Lawrencium

Metals
Metalloids
Nonmetals
Lanthanide series
Actinide series

▲ **Figure 1.5**
Periodic table of the elements

▲ **Figure 1.6**
Examples of minerals composed of a single element (Dennis Tasa)

1.3 How Atoms Bond to Form Minerals

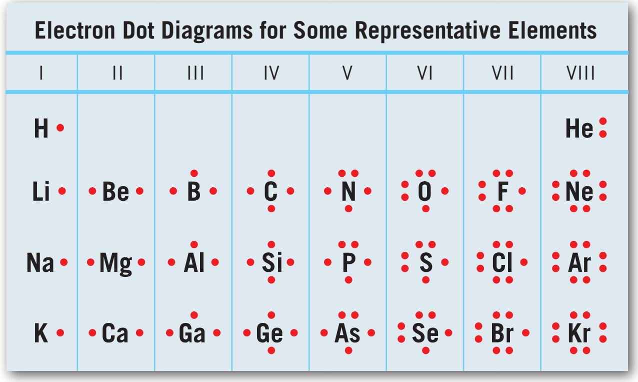
Distinguish among ionic bonds, covalent bonds, and metallic bonds and explain how they form minerals.

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

The Octet Rule and Chemical Bonds

A **chemical bond** is a transfer or sharing of electrons that allows each atom to attain a full valence shell of electrons. As noted earlier, valence (outer-shell) electrons are generally involved in this process. **Figure 1.7** shows a shorthand representation of the number of valence electrons for selected elements. Notice that the elements in Group I have one valence electron each, those in Group II have two valence electrons each, and so on, up to eight valence electrons each in Group VIII.

A chemical guideline known as the **octet rule** states that atoms tend to gain, lose, or share electrons until they are surrounded by eight valence electrons. Although there are exceptions to the octet rule, it is a useful rule of thumb for understanding chemical bonding. When an atom's outer shell does not contain eight electrons, it is likely to chemically bond to other atoms to achieve an octet in its outer shell. The noble gases have very stable electron arrangements with eight valence electrons (except helium, which has two), and this explains their lack of chemical reactivity. There are three primary types of bonds: *ionic, covalent*, and *metallic*.



▲ **Figure 1.7**
Dot diagrams for certain elements Each dot represents a valence electron found in the outermost principal shell.

Ionic Bonds: Electrons Transferred

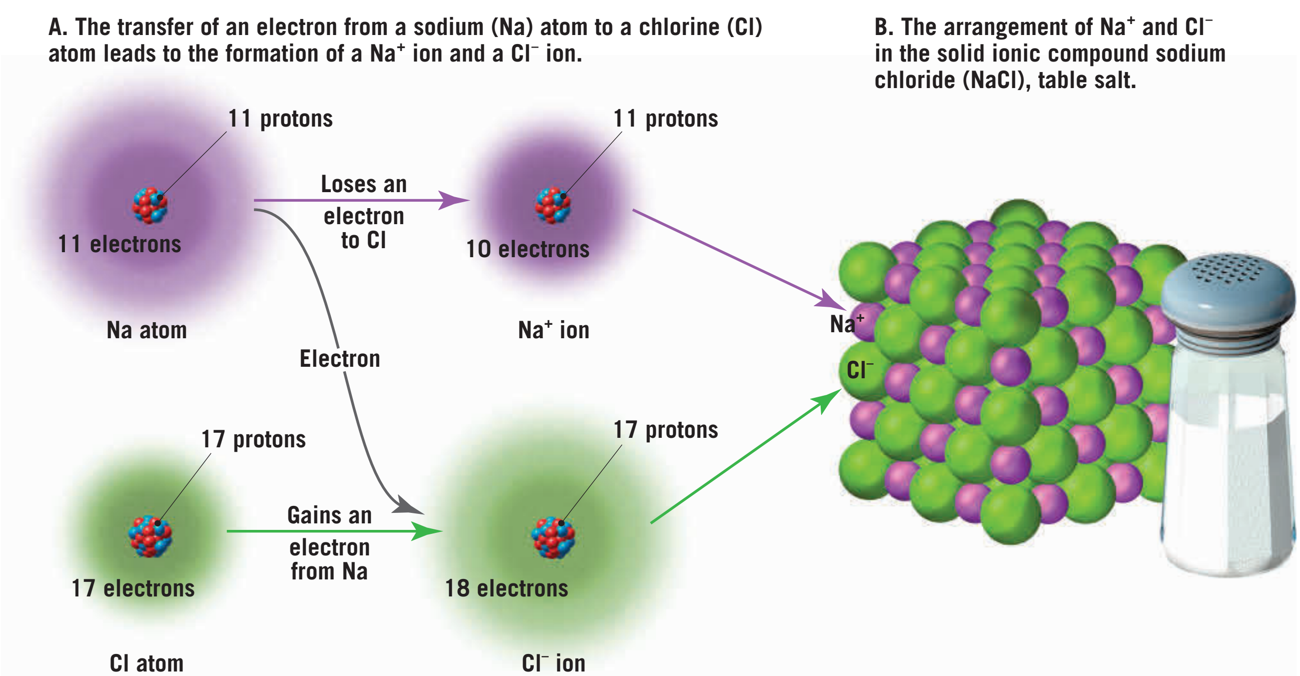
Perhaps the easiest type of bond to visualize is the **ionic bond**, in which one atom gives up one or more valence electrons to another atom to form **ions**—*positively and negatively charged atoms*. The atom that loses electrons becomes a positive ion, and the atom that gains electrons becomes a negative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

Consider the ionic bonding that occurs between sodium (Na) and chlorine (Cl) to produce the solid ionic compound sodium chloride—the mineral halite (common table salt). Notice in **Figure 1.8A** that a sodium atom gives up its single valence electron to chlorine and, as a result, becomes a positively charged sodium ion (Na^+). Chlorine, on the other hand, gains one electron and becomes a negatively charged chloride ion (Cl^-). Because ions with unlike charges attract, an ionic bond is an attraction of oppositely charged ions to produce an electrically neutral ionic compound.

Figure 1.8B illustrates the arrangement of sodium and chlorine ions in ordinary table salt. Notice that salt consists of alternating sodium and chlorine ions, positioned so that each positive ion is attracted to and surrounded on all sides by negative ions and vice versa. This arrangement maximizes the attraction between ions

DID YOU KNOW?

One of the world's heaviest cut and polished gemstones is a 22,892.5-carat golden-yellow topaz. Currently housed in the Smithsonian Institution, this roughly 10-lb gem is about the size of an automobile headlight and could hardly be used as a piece of jewelry, except perhaps by an elephant.



◀ **Figure 1.8**
Formation of the ionic compound sodium chloride

with opposite charges while minimizing the repulsion between ions with identical charges. Thus, ionic compounds consist of an orderly arrangement of oppositely charged ions assembled in a definite ratio that provides overall electrical neutrality.

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

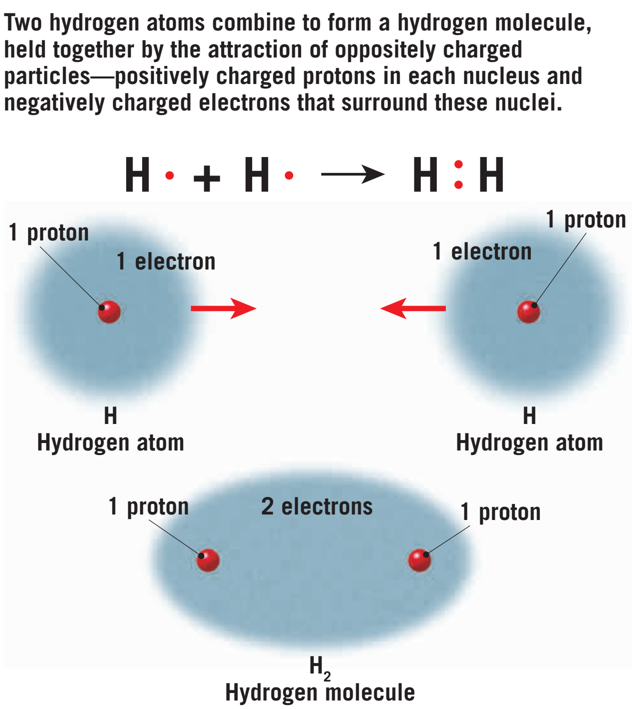
Covalent Bonds: Electron Sharing

With **covalent bonds**, a pair of atoms share one or more valance electrons between them. One example of this is the hydrogen molecule (H_2). Hydrogen is one of the exceptions to the octet rule: Its single shell is full with just two electrons. Imagine two hydrogen atoms (each with one proton and one electron) approaching one another, as shown in **Figure 1.9**. Once they meet, the electron configuration changes so that both electrons primarily occupy the space between the atoms. In other words, the two electrons are shared by both hydrogen atoms and are attracted simultaneously by the positive charge of the proton in the nucleus of each atom. In this situation, the hydrogen atoms do not form ions. Instead, the force that holds these atoms together arises from the attraction of oppositely charged particles—positively charged protons in the nuclei and negatively charged electrons that surround these nuclei.

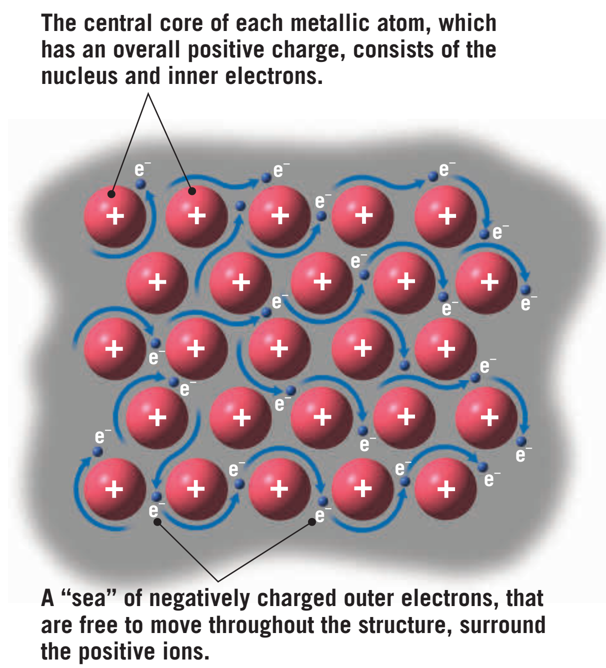
Metallic Bonds: Electrons Free to Move

A few minerals, such as native gold, silver, and copper, are made entirely of metal atoms packed tightly together in an orderly way. The bonding that holds these atoms together results from each atom contributing its valence electrons to a common pool of electrons, which freely move throughout the entire metallic structure. The contribution of one or more valence electrons leaves an array of positive ions immersed in a "sea" of valence electrons, as shown in **Figure 1.10**.

The attraction between this sea of negatively charged electrons and the positive ions produces the **metallic bonds** that give metals unique properties. Metals are good conductors of electricity because the valence electrons are free to move from one atom to



▲ **Figure 1.9**
Formation of a covalent bond When hydrogen atoms bond, the negatively charged electrons are shared by both hydrogen atoms and attracted simultaneously by the positive charge of the proton in the nucleus of each atom.



▲ **Figure 1.10**
Metallic bonding Metallic bonding is the result of each atom contributing its valence electrons to a common pool of electrons that are free to move throughout the entire metallic structure.

another. Metals are also *malleable*, which means they can be hammered into thin sheets, and *ductile*, which means they can be drawn into thin wires. By contrast, ionic and covalent solids tend to be *brittle* and fracture when stress is applied. To visualize the difference between metallic, ionic, and covalent bonds, consider what happens when a metal fork is dropped to the floor compared to a ceramic dinner plate.

CONCEPT CHECKS 1.3

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

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1.4 Properties of Minerals

List and describe the properties used in mineral identification.

Minerals have definite crystalline structures and chemical compositions that give them unique sets of physical and chemical properties shared by all specimens of that mineral, regardless of when or where they formed. For example, two samples of the mineral quartz will be equally hard and equally dense, and they will break in a similar manner. However, the physical properties of individual samples may vary within specific limits due to ionic substitutions, inclusions of foreign elements (impurities), and defects in the crystalline structure. Certain aspects, called **diagnostic properties**, are particularly useful in identifying an unknown mineral. For example, the mineral halite has a salty taste that very few others do, making the taste a diagnostic property of halite. Other properties, particularly color, may vary among different specimens of the same mineral, and are referred to as **ambiguous properties**.

Optical Properties

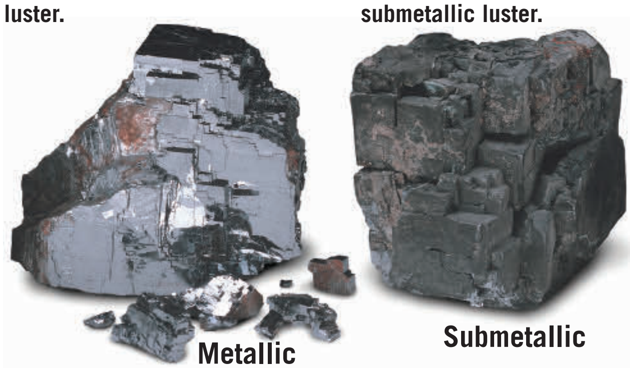
Optical characteristics such as luster, color, streak, and ability to transmit light are frequently used for mineral identification.

Luster The appearance or quality of light reflected from the surface of a mineral is known as **luster**. Minerals that are shiny like a metal, regardless of color, are said to have a *metallic luster* (**Figure 1.11A**). Some metallic minerals, such as native copper and galena, develop a dull coating or tarnish when exposed to the atmosphere. Because they are not as shiny as samples with freshly broken surfaces, these samples are often said to exhibit a *submetallic luster* (**Figure 1.11B**).

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

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

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



▲ **Figure 1.11**
Metallic versus submetallic luster

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 fluorite, for example, give this common mineral a variety of tints, including pink, purple, yellow, white, and green (**Figure 1.12**). Other minerals, such as quartz, also exhibit a variety of hues, with multiple colors sometimes occurring in the same sample. Thus, the use of color as a means of identification is often ambiguous or even misleading.

Streak The color of a mineral in powdered form, called **streak**, is often useful in identification. A mineral's streak is obtained by rubbing it across a *streak plate*