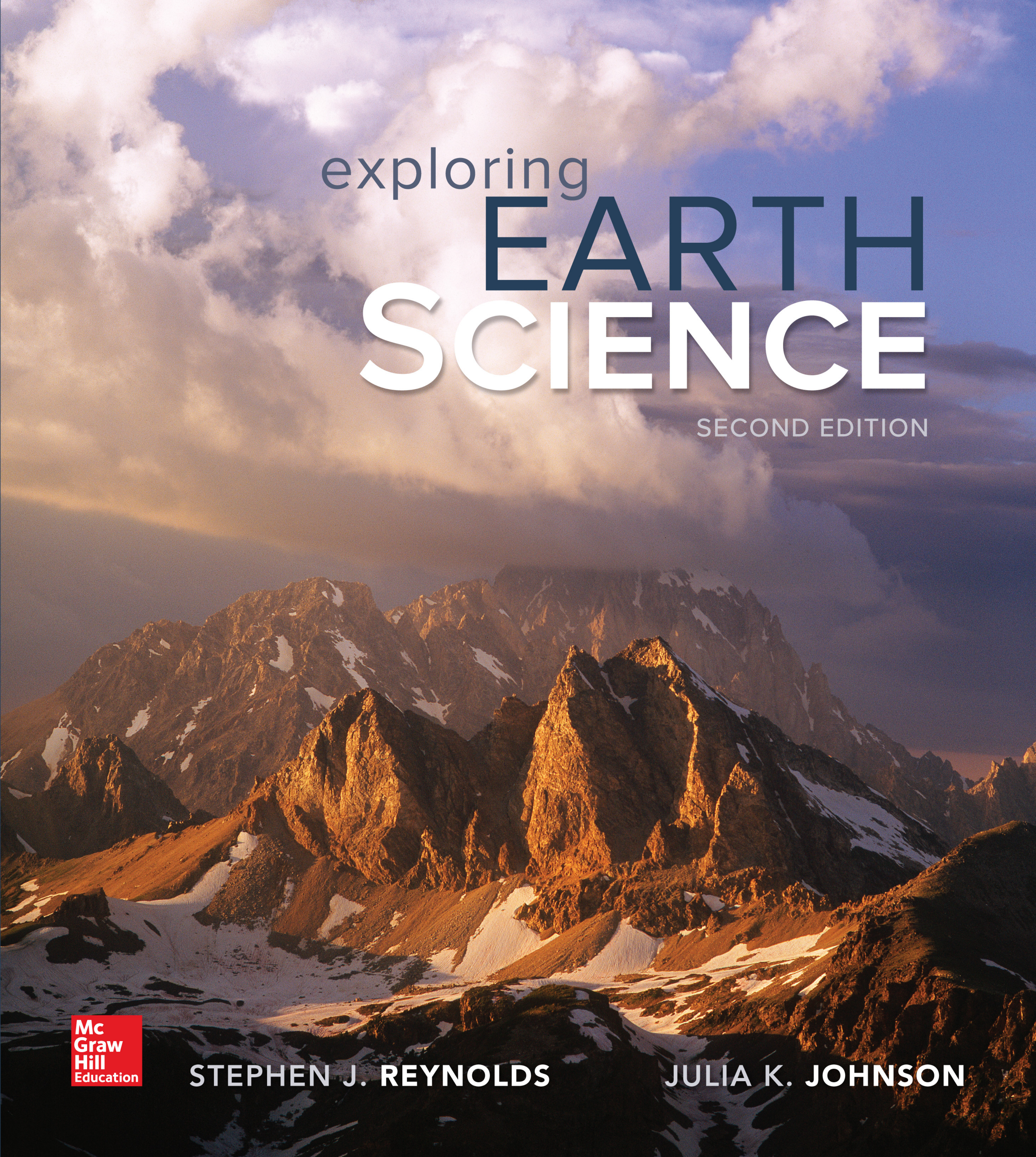
exploring
EARTH SCIENCE

SECOND EDITION



STEPHEN J. REYNOLDS

JULIA K. JOHNSON

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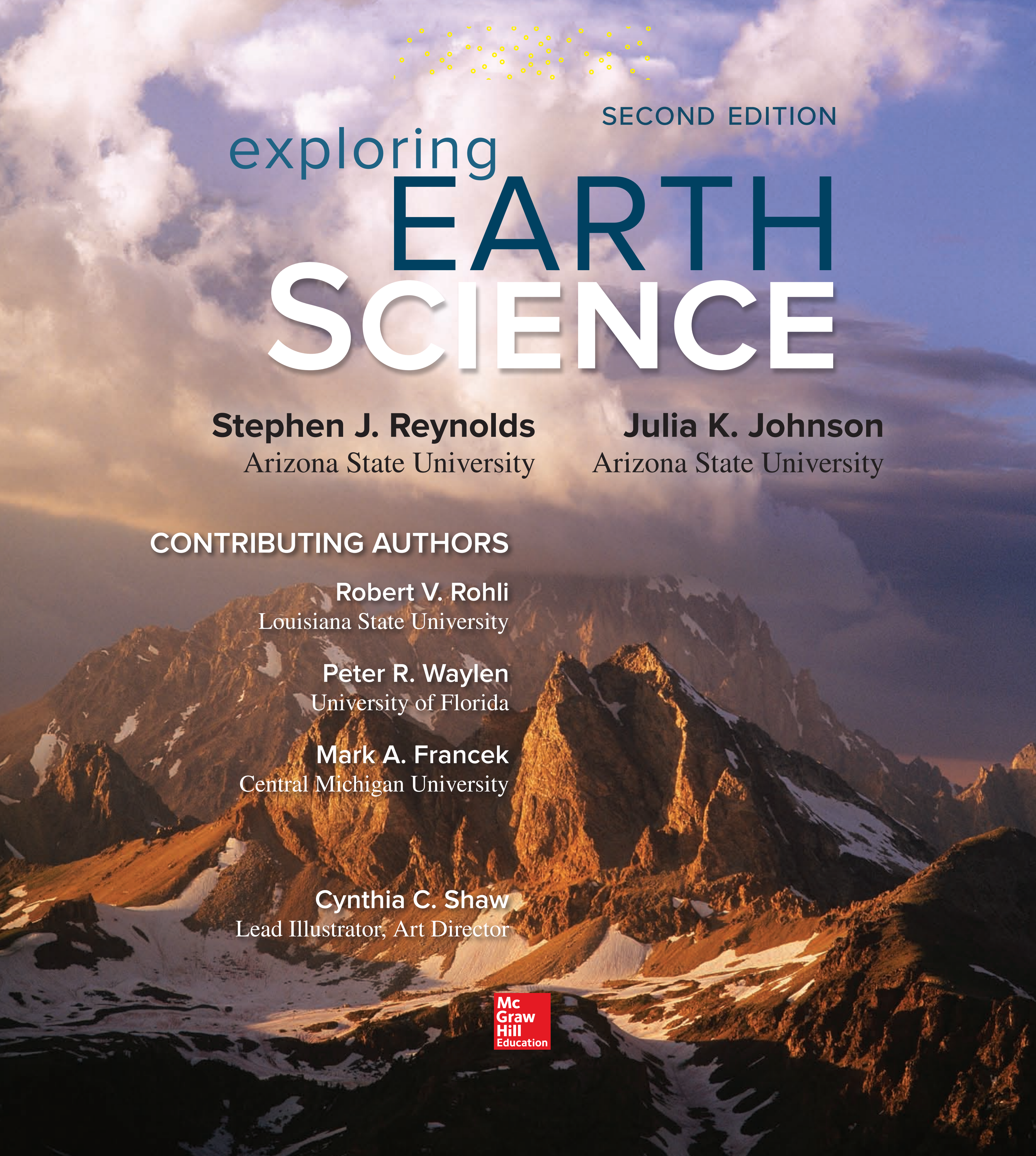
About the Cover

The cover photograph by well-known photographer Michael Collier features the Grand Teton, its top shrouded in clouds. The peaks stand 13,775 feet above sea level, and are within one of the youngest mountain ranges of the extensive Rocky Mountain system. Although the mountain range is very young in geologic terms, it is cored with ancient metamorphic and igneous rocks, some of which formed as much as 2.6 billion years ago, at a time when the North American continent was first forming. The entire Teton Range, looming more than a mile above Jackson Hole, Wyoming, is along the rising edge of a fault-bounded crustal block that has been tilted – up on the east side and down on the west. This tilting and uplift started only five million years ago, and continues today. The Tetons have been thrust up into a windy world of intense weather, where clouds often gather and storms sometimes rage. During the Ice Ages, glaciers left gouges and imparted onto the peaks their overall shapes, and now precipitation pummels the peaks, helping carve the rock into spires and cliffs.

Michael Collier received his BS in geology at Northern Arizona University, MS in structural geology at Stanford, and MD from the University of Arizona. He rowed boats commercially in the Grand Canyon in the 1970s and ’80s, then practiced family medicine in northern Arizona. Collier published books about the geology of Grand Canyon, Death Valley, Denali, and Capitol Reef national parks. He has done books on the Colorado River basin, glaciers of Alaska, climate change in Alaska, and a three-book series on American mountains, rivers, and coastlines. As a special projects writer with the USGS, he produced books about the San Andreas fault, the downstream effects of dams, and climate change. Collier’s photography has been recognized with awards from the USGS, National Park Service, American Geosciences Institute, and National Science Teachers Association.



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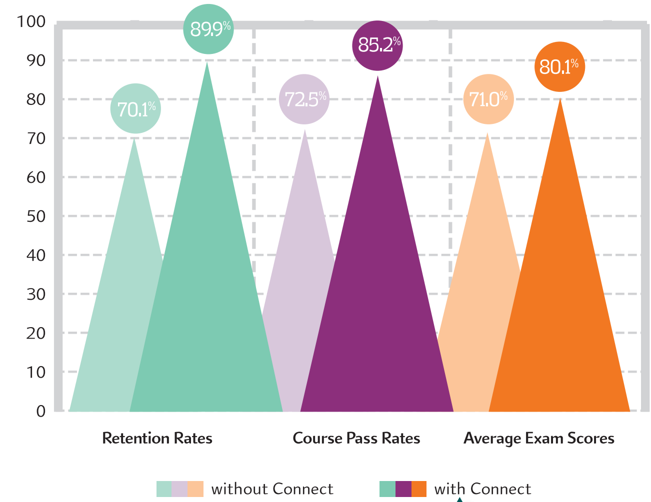

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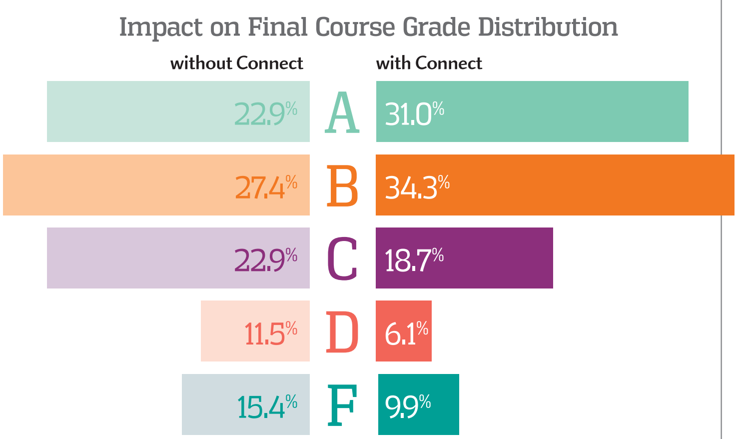

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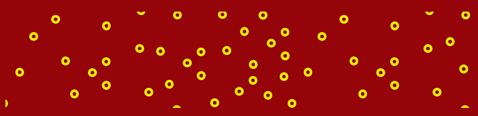

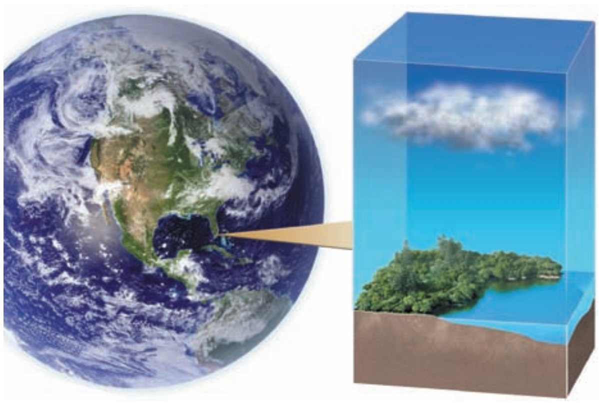

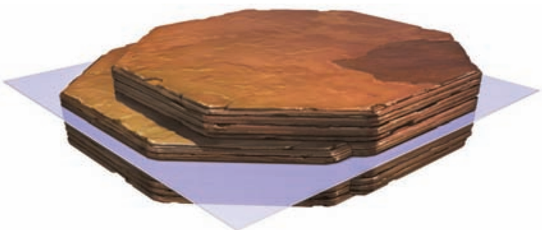

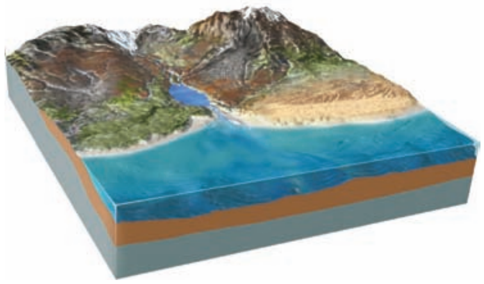

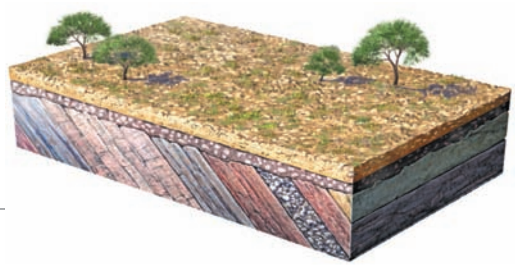

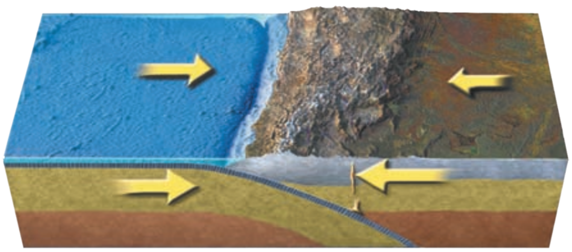

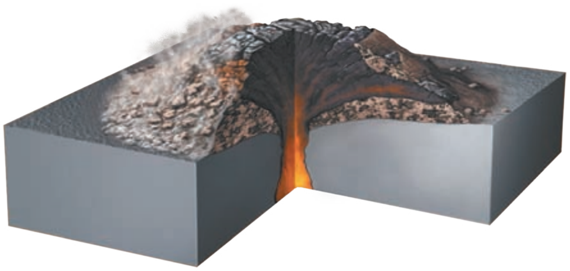

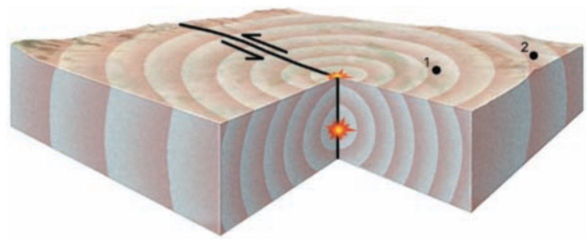
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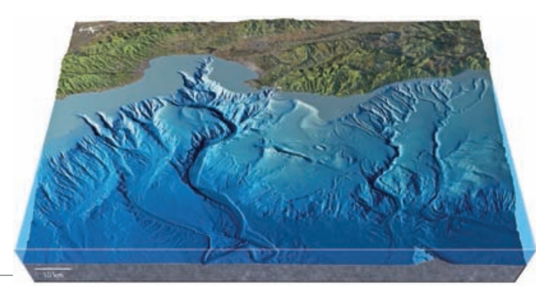

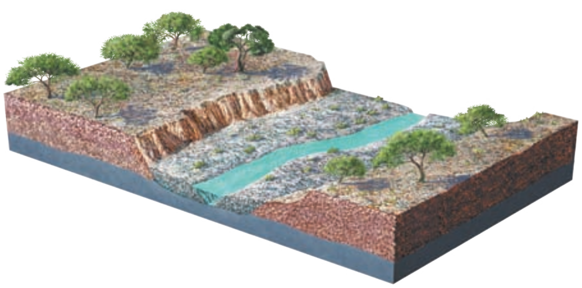

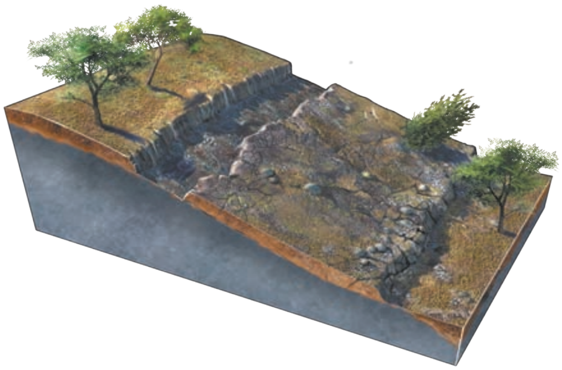

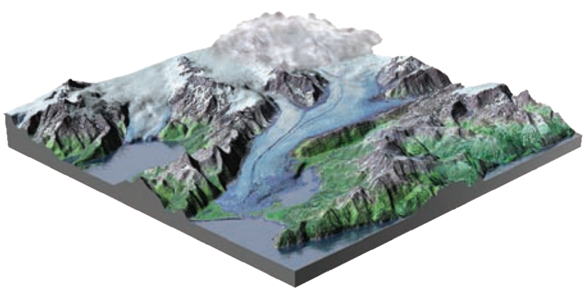

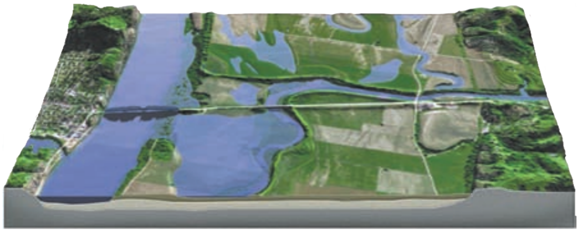

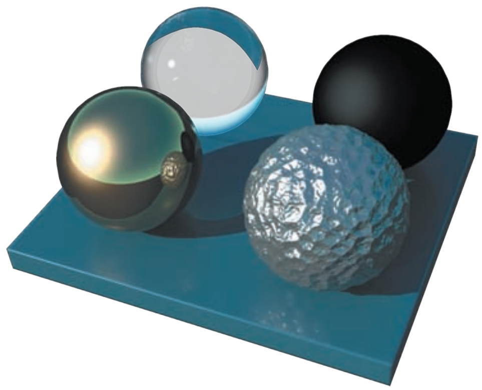

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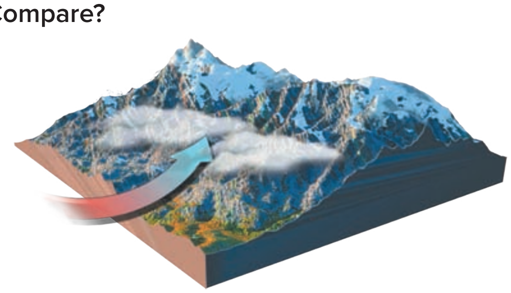

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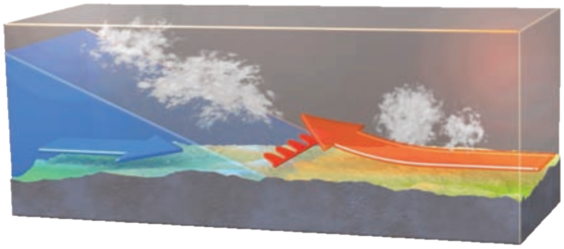

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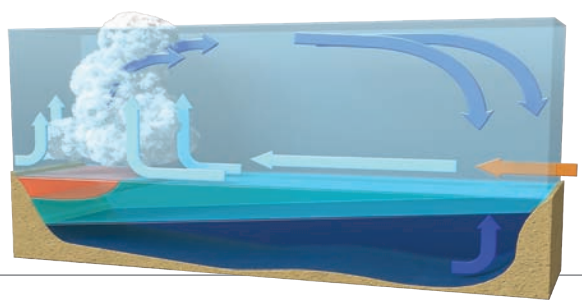

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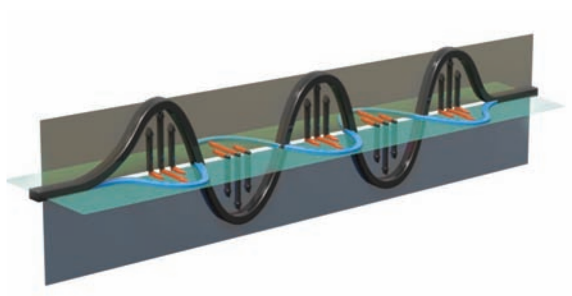


PREFACE

TELLING THE STORY . . .

WE WROTE *EXPLORING EARTH SCIENCE* so that students could learn from the book on their own, freeing up instructors to teach the class in any way they want. I (Steve Reynolds) first identified the need for this type of book while I was a National Association of Geoscience Teachers' (NAGT) distinguished speaker. As part of my NAGT activities, I traveled around the country conducting workshops on how to infuse active learning and scientific inquiry into introductory college science courses, including those with upwards of 200 students. In the first part of the workshop, I asked the faculty participants to list the main goals of an introductory science course, especially for nonmajors. At every school I visited, the main goals were similar to those listed below:

- to engage students in the process of scientific inquiry so that they learn what science is and how it is conducted,
- to teach students how to observe and interpret landscapes and other aspects of their physical environment,
- to enable students to learn and apply important concepts of science,
- to help students understand the relevance of science to their lives, and
- to enable students to use their new knowledge, skills, and ways of thinking to become more informed citizens.

I then asked faculty members to rank these goals and estimate how much time they spent on each goal in class. At this point, many instructors recognized that their activities in class were not consistent with their own goals. Most instructors were spending nearly all of class time teaching content. Although this was one of their main goals, it commonly was not their top goal.

Next, I asked instructors to think about why their activities were not consistent with their goals. Inevitably, the answer was that most instructors spend nearly all of class time covering content because (1) textbooks include so much material that students have difficulty distinguishing what is important from what is not, (2) instructors needed to lecture so that students would know what is important, and (3) many students have difficulty learning independently from the textbook.

In most cases, textbooks drive the curriculum, so my coauthor (Julia Johnson) and I decided that we should write a textbook that (1) contains only important material, (2) indicates clearly to the student what is important and what they need to know, and (3) is designed and written in such a way that students can learn from the book on their own. This type of book would give instructors freedom to teach in a way that is more consistent with their goals, including using local examples to illustrate concepts and their relevance. Instructors would also be able to spend more class time teaching students to observe and interpret landscapes, tectonics, and atmospheric or astronomic phenomena, and to participate in the process of scientific inquiry, which represents the top goal for many instructors.

COGNITIVE AND SCIENCE-EDUCATION RESEARCH

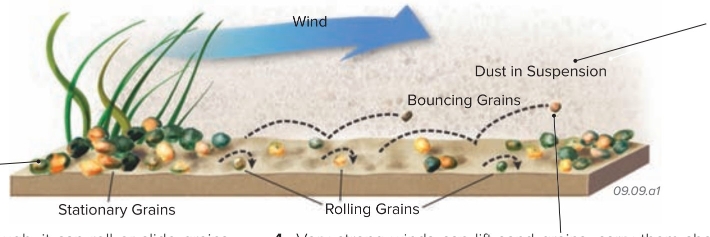
To design a book that supports instructor goals, we delved into cognitive and science-education research, especially research on how our brains process different types of information, what obstacles limit student learning from textbooks, and how students use visuals versus text while studying. We also conducted our own research on how students interact with textbooks, what students see when they observe photographs showing landscape features, and how they interpret different types of scientific illustrations, including maps, cross sections, and block diagrams that illustrate evolution of environments. *Exploring Earth Science* is the result of our literature search and of our own science-education and cognitive research. As you examine *Exploring Earth Science*, you will notice that it is stylistically different from most other textbooks, which will likely elicit a few questions.

A How Does Wind Transport Sediment?

Wind is generated by differences in air pressure and at times is strong enough to transport material, but only relatively small and lightweight fragments, like sand and clay. Transport of these materials by the wind is most efficient in dry climates, where there is limited vegetation to bind materials together and hold them on the ground.

1. Wind is capable of transporting sand and finer sediment, as well as lightweight plant fragments and other materials lying on the surface. It generally moves material in one of three ways and can deposit sediment in various settings, some of which are shown in the photographs below.

2. Most materials on Earth's surface are not moved by the wind because they are too firmly attached to the land (such as rock outcrops), are too large or heavy to be moved, or are both.

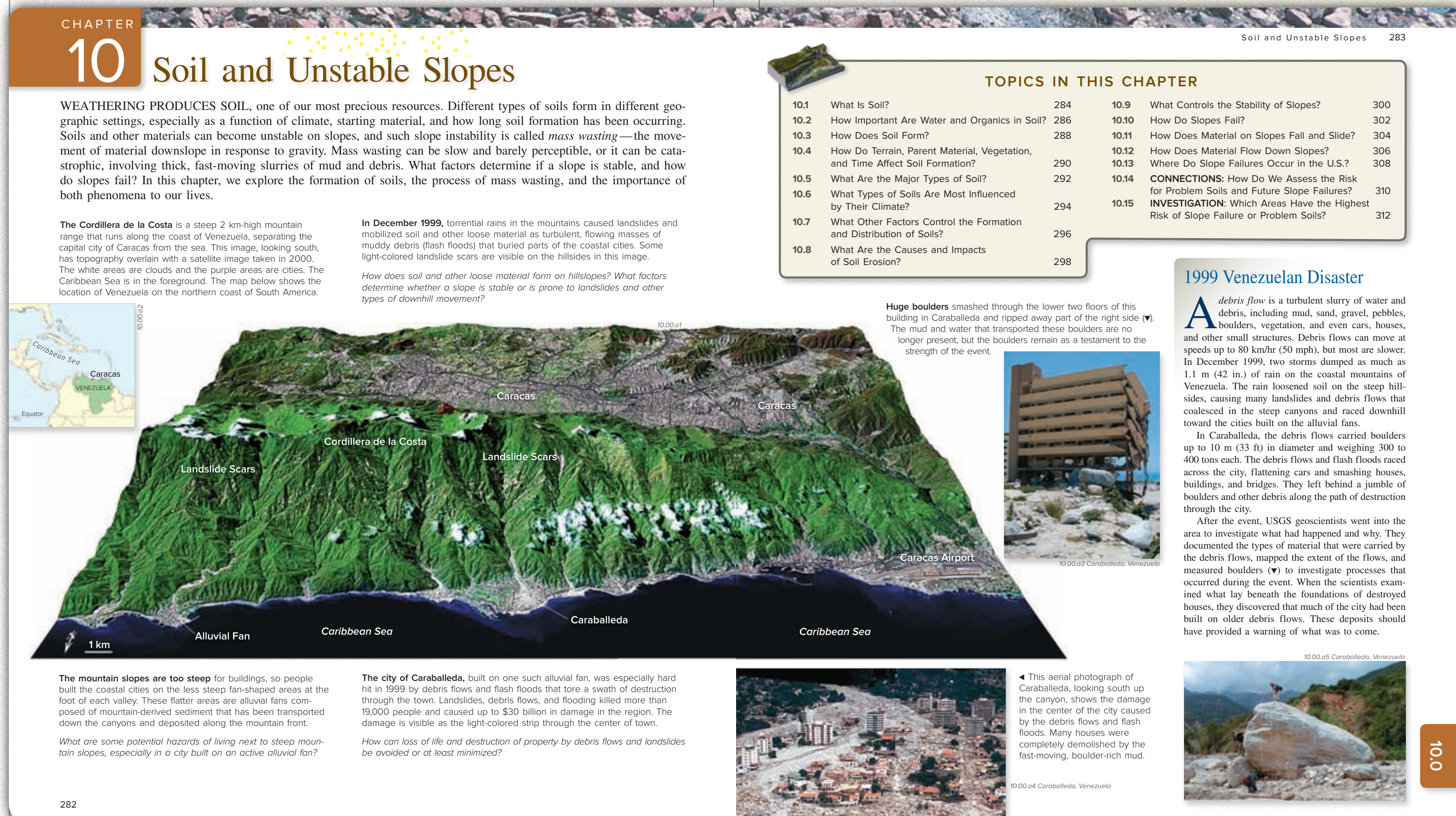


5. Wind can pick up and carry finer material, such as dust, silt, and salt. This mode of transport is called *suspension*, and wind can keep some particles in the air for weeks, transporting them long distances.

3. If wind velocity is great enough, it can roll or slide grains of sand and silt and other loose materials across the ground.

4. Very strong winds can lift sand grains, carry them short distances, and drop them. This process is akin to bouncing a grain along the surface and is called *saltation*.

HOW DOES THIS BOOK SUPPORT STUDENT CURIOSITY AND INQUIRY?



CHAPTER 10

Soil and Unstable Slopes

WEATHERING PRODUCES SOIL, one of our most precious resources. Different types of soils form in different geographic settings, especially as a function of climate, starting material, and how long soil formation has been occurring. Soils and other materials can become unstable on slopes, and such slope instability is called *mass wasting*—the movement of material downslope in response to gravity. Mass wasting can be slow and barely perceptible, or it can be catastrophic, involving thick, fast-moving slurries of mud and debris. What factors determine if a slope is stable, and how do slopes fail? In this chapter, we explore the formation of soils, the process of mass wasting, and the importance of both phenomena to our lives.

The Cordillera de la Costa is a steep 2 km-high mountain range that runs along the coast of Venezuela, separating the capital city of Caracas from the sea. This image, looking south, has topography overlain with a satellite image taken in 2000. The white areas are clouds and the purple areas are cities. The Caribbean Sea is in the foreground. The map below shows the location of Venezuela on the northern coast of South America.

In December 1999, torrential rains in the mountains caused landslides and mobilized soil and other loose material as turbulent, flowing masses of muddy debris (flash floods) that buried parts of the coastal cities. Some light-colored landslide scars are visible on the hillsides in this image.

How does soil and other loose material form on hillslopes? What factors determine whether a slope is stable or is prone to landslides and other types of downhill movement?

The mountain slopes are too steep for buildings, so people built the coastal cities on the less steep fan-shaped areas at the foot of each valley. These flatter areas are alluvial fans composed of mountain-derived sediment that has been transported down the canyons and deposited along the mountain front.

What are some potential hazards of living next to steep mountain slopes, especially in a city built on an active alluvial fan?

The city of Caraballeda, built on one such alluvial fan, was especially hard hit in 1999 by debris flows and flash floods that tore a swath of destruction through the town. Landslides, debris flows, and flooding killed more than 19,000 people and caused up to $30 billion in damage in the region. The damage is visible as the light-colored strip through the center of town.

How can loss of life and destruction of property by debris flows and landslides be avoided or at least minimized?

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TOPICS IN THIS CHAPTER

Huge boulders smashed through the lower two floors of this building in Caraballeda and ripped away part of the right side (▼). The mud and water that transported these boulders are no longer present, but the boulders remain as a testament to the strength of the event.

10.00.a3 Caraballeda, Venezuela

◄ This aerial photograph of Caraballeda, looking south up the canyon, shows the damage in the center of the city caused by the debris flows and flash floods. Many houses were completely demolished by the fast-moving, boulder-rich mud.

10.00.a4 Caraballeda, Venezuela

1999 Venezuelan Disaster

A *debris flow* is a turbulent slurry of water and debris, including mud, sand, gravel, pebbles, boulders, vegetation, and even cars, houses, and other small structures. Debris flows can move at speeds up to 80 km/hr (50 mph), but most are slower. In December 1999, two storms dumped as much as 1.1 m (42 in.) of rain on the coastal mountains of Venezuela. The rain loosened soil on the steep hillsides, causing many landslides and debris flows that coalesced in the steep canyons and raced downhill toward the cities built on the alluvial fans.

In Caraballeda, the debris flows carried boulders up to 10 m (33 ft) in diameter and weighing 300 to 400 tons each. The debris flows and flash floods raced across the city, flattening cars and smashing houses, buildings, and bridges. They left behind a jumble of boulders and other debris along the path of destruction through the city.

After the event, USGS geoscientists went into the area to investigate what had happened and why. They documented the types of material that were carried by the debris flows, mapped the extent of the flows, and measured boulders (▼) to investigate processes that occurred during the event. When the scientists examined what lay beneath the foundations of destroyed houses, they discovered that much of the city had been built on older debris flows. These deposits should have provided a warning of what was to come.

10.00.a5 Caraballeda, Venezuela

10.0

Exploring Earth Science promotes inquiry and science as an active process. It encourages student curiosity and aims to activate existing student knowledge by posing the title of every two-page spread and every subsection as a question. In addition, questions are dispersed throughout the book. Integrated into the book are opportunities for students to observe patterns, features, and examples before the underlying concepts are explained. That is, we employ a *learning-cycle approach* where student exploration precedes the introduction of new terms and the application of knowledge to a new situation. For example, chapter 10 on slope stability begins with a three-dimensional image of northern Venezuela, pictured above, and asks readers to observe where people are living in this area and what natural processes might have formed these sites.

Wherever possible, we introduce terms after students have an opportunity to observe the feature or concept that is being named. This approach is consistent with several educational philosophies, including a learning cycle and just-in-time teaching. Research on learning cycles shows that students are more likely to retain a term if they already have a mental image of the thing being named (Lawson, 2003). For example, this book presents students with maps showing the spatial distribution of earthquakes, volcanoes, and mountain ranges and asks them to observe the patterns and think about what might be causing the patterns. Only then does the textbook introduce the concept of tectonic plates.

Also, the figure-based approach in this book allows terms to be introduced in their context rather than as a definition that is detached from a visual representation of the term. We introduce new terms in italics rather than in boldface, because boldfaced terms on a textbook page cause students to immediately focus mostly on the terms, rather than build an understanding of the concepts. The italics, however, let a student know when they have encountered an important term during their reading. The book includes a glossary for those students who wish to look up the definition of a term to refresh their memory. To expand comprehension of the definition, each entry in the glossary references the pages where the term is defined in the context of a figure.

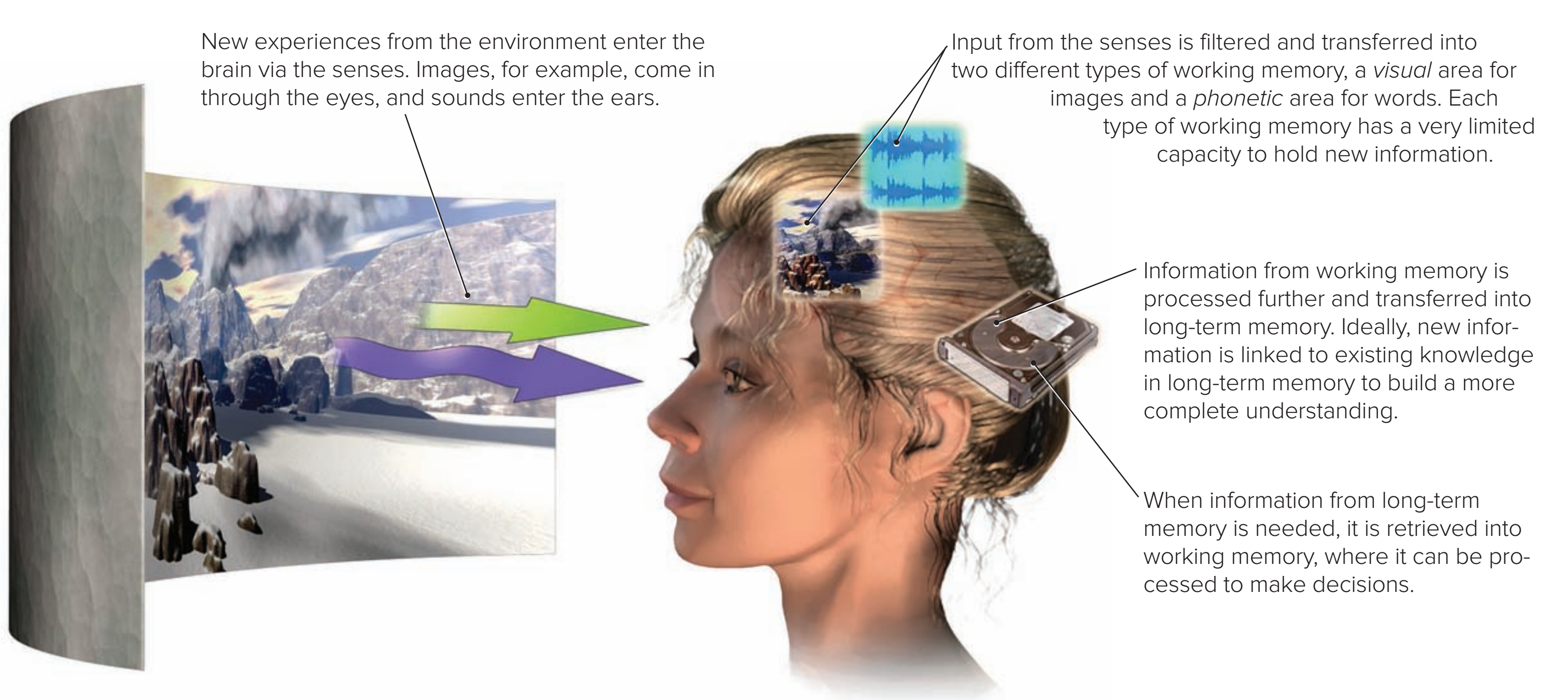
WHY ARE THE PAGES DOMINATED BY ILLUSTRATIONS?

Earth science is a visual science. Earth science textbooks contain a variety of photographs, maps, cross sections, block diagrams, and other types of illustrations. These diagrams help portray the spatial distribution and geometry of features in the landscape, atmosphere, oceans, and universe in ways words cannot. In earth sciences, a picture really is worth a thousand words.

Exploring Earth Science contains a wealth of figures to take advantage of the visual nature of earth science and the efficiency of figures in conveying earth science concepts. This book contains few large blocks of text—most text is in smaller blocks that are specifically linked to illustrations. Examples of our integrated figure-text approach are shown throughout the book. In this approach, each short block of text is one or more complete sentences that succinctly describe a feature, process, or both of these. Most of these text blocks are connected to their illustrations with leader lines so that readers know exactly which feature or part of the diagram is being referenced in the text block. A reader does not have to search for the part of the figure that corresponds to a text passage, as occurs when a student reads a traditional textbook with large blocks of text referencing a figure that may appear on a different page. Most short blocks are numbered to guide students to read the blocks in a specific order.

This approach is especially well suited to covering earth science topics because it allows the text to have a precise linkage to the features and geographic location of the aspect being described. A text block discussing the Intertropical Convergence Zone can have a leader that specifically points to the location of this feature. A cross section of atmospheric circulation, such as those related to El Niño conditions, can be accompanied by short text blocks that describe each part of the system and that are linked by leaders directly to specific locations on the figure. This allows the reader to concentrate on the concepts being presented, not deciding what part of the figure is being discussed.

The approach in *Exploring Earth Science* is consistent with the findings of cognitive scientists, who conclude that our minds have two different processing systems, one for processing pictorial information (images) and one for processing verbal information (speech and written words), as illustrated below. Images enter our consciousness through our eyes, and text can enter either through our eyes, such as when we read, or through our ears, as occurs during a lecture. Research into learning and cognition shows that having text enter via our ears, while our eyes examine an image, is among the best ways to learn. Cognitive scientists also speak about two types of memory: *working memory* holds information and actively processes it, whereas *long-term memory* stores information until we need it (Baddeley, 2007). Both the verbal and pictorial processing systems have a limited amount of working memory, and our minds have to use much of our mental processing space to reconcile the pictorial and verbal types of information in working memory. For information that has both pictorial and verbal components, as most earth-science information does, the amount of knowledge we retain depends on reconciling these two types of information, on transferring information from working memory to long-term memory, and on linking the new information with our existing mental framework. For this reason, this book integrates text and figures, as in the example shown here.

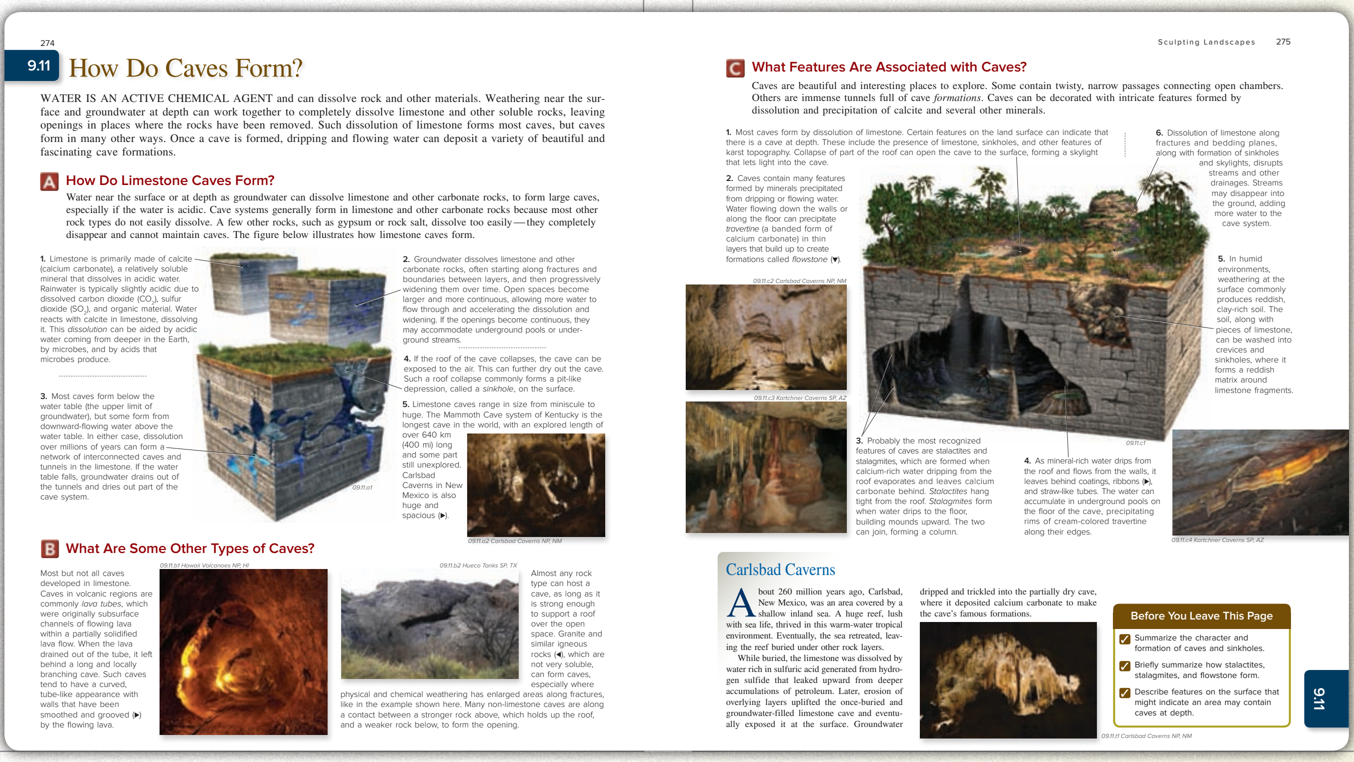


WHY ARE THERE SO MANY FIGURES?

This textbook contains more than 2,500 figures, which is two to three times the number in most earth science textbooks. One reason for this is that the book is designed to provide a concrete example of each process, environment, or feature being illustrated. Research shows that many college students require concrete examples before they can begin to build abstract concepts (Lawson, 1980). Also, many students have limited travel experience, so photographs and other figures allow them to observe places, environments, and processes they have not been able to observe firsthand. The numerous photographs, from geographically diverse places, help bring the sense of place into the student's reading. The inclusion of an illustration for each text block reinforces the notion that the point being discussed is important. In many cases, as in the example below, conceptualized figures are integrated with photographs and text so that students can build a more coherent view of the environment or process.

Exploring Earth Science focuses on the most important earth science concepts and makes a deliberate attempt to eliminate text that is not essential for student learning of these concepts. Inclusion of information that is not essential tends to distract and confuse students rather than illuminate the concept; thus, you will see fewer words. Cognitive and science-education research has identified a redundancy effect, where information that restates and expands upon a more succinct description actually results in a decrease in student learning (Mayer, 2001). Specifically, students learn less if a long figure caption restates information contained elsewhere on the page, such as in a long block of text that is detached from the figure. We avoid the redundancy effect by including only text that is integrated with the figure.

The style of illustrations in *Exploring Earth Science* was designed to be more inviting to today's visually oriented students who are used to photo-realistic, computer-rendered images in movies, videos, and computer games. For this reason, many of the figures were created by world-class scientific illustrators and artists who have worked on award-winning textbooks, on Hollywood movies, on television shows, for *National Geographic,* and in the computer-graphics and gaming industry. In most cases, the figures incorporate real data, such as satellite images, aerial photographs, weather and climatological data, and locations of earthquakes and volcanoes. Our own research shows that many students do not understand cross sections and other subsurface diagrams, so nearly every cross section in this book has a three-dimensional aspect, and many maps are presented in a perspective view that incorporates topography. Research findings by us and other researchers (Roth and Bowen, 1999) indicate that including people and human-related items in photographs and figures attracts undue attention, thereby distracting students from the features being illustrated. As a result, our photographs have nondistracting indicators of scale, like dull coins and plain marking pens. Figures and photographs do not include people or human-related items unless we are trying to (1) illustrate how geoscientists study earth science processes and features (2) reinforce the relevance of the processes on humans, or (3) help students appreciate that geoscience can be done by diverse types of people, potentially including them, as depicted in our photographs.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9.11 How Do Caves Form?

WATER IS AN ACTIVE CHEMICAL AGENT and can dissolve rock and other materials. Weathering near the surface and groundwater at depth can work together to completely dissolve limestone and other soluble rocks, leaving openings in places where the rocks have been removed. Such dissolution of limestone forms most caves, but caves form in many other ways. Once a cave is formed, dripping and flowing water can deposit a variety of beautiful and fascinating cave formations.

A How Do Limestone Caves Form?

Water near the surface or at depth as groundwater can dissolve limestone and other carbonate rocks, to form large caves, especially if the water is acidic. Cave systems generally form in limestone and other carbonate rocks because most other rock types do not easily dissolve. A few other rocks, such as gypsum or rock salt, dissolve too easily—they completely disappear and cannot maintain caves. The figure below illustrates how limestone caves form.

1. Limestone is primarily made of calcite (calcium carbonate), a relatively soluble mineral that dissolves in acidic water. Rainwater is typically slightly acidic due to dissolved carbon dioxide (CO_2), sulfur dioxide (SO_2), and organic material. Water reacts with calcite in limestone, dissolving it. This *dissolution* can be aided by acidic water coming from deeper in the Earth, by microbes, and by acids that microbes produce.

2. Groundwater dissolves limestone and other carbonate rocks, often starting along fractures and boundaries between layers, and then progressively widening them over time. Open spaces become larger and more continuous, allowing more water to flow through and accelerating the dissolution and widening. If the openings become continuous, they may accommodate underground pools or underground streams.

3. Most caves form below the water table (the upper limit of groundwater), but some form from downward-flowing water above the water table. In either case, dissolution over millions of years can form a network of interconnected caves and tunnels in the limestone. If the water table falls, groundwater drains out of the tunnels and dries out part of the cave system.

4. If the roof of the cave collapses, the cave can be exposed to the air. This can further dry out the cave. Such a roof collapse commonly forms a pit-like depression, called a *sinkhole*, on the surface.

5. Limestone caves range in size from miniscule to huge. The Mammoth Cave system of Kentucky is the longest cave in the world, with an explored length of over 640 km (400 mi) long and some part still unexplored. Carlsbad Caverns in New Mexico is also huge and spacious (▶).

09.11.a1

09.11.a2 Carlsbad Caverns NP, NM

B What Are Some Other Types of Caves?

Most but not all caves developed in limestone. Caves in volcanic regions are commonly *lava tubes*, which were originally subsurface channels of flowing lava within a partially solidified lava flow. When the lava drained out of the tube, it left behind a long and locally branching cave. Such caves tend to have a curved, tube-like appearance with walls that have been smoothed and grooved (▶) by the flowing lava.

09.11.b1 Hawaii Volcanoes NP, HI

09.11.b2 Hueco Tanks SP, TX

Almost any rock type can host a cave, as long as it is strong enough to support a roof over the open space. Granite and similar igneous rocks (◀), which are not very soluble, can form caves, especially where physical and chemical weathering has enlarged areas along fractures, like in the example shown here. Many non-limestone caves are along a contact between a stronger rock above, which holds up the roof, and a weaker rock below, to form the opening.

Sculpting Landscapes 275

C What Features Are Associated with Caves?

Caves are beautiful and interesting places to explore. Some contain twisty, narrow passages connecting open chambers. Others are immense tunnels full of cave *formations*. Caves can be decorated with intricate features formed by dissolution and precipitation of calcite and several other minerals.

1. Most caves form by dissolution of limestone. Certain features on the land surface can indicate that there is a cave at depth. These include the presence of limestone, sinkholes, and other features of karst topography. Collapse of part of the roof can open the cave to the surface, forming a skylight that lets light into the cave.

2. Caves contain many features formed by minerals precipitated from dripping or flowing water. Water flowing down the walls or along the floor can precipitate *travertine* (a banded form of calcium carbonate) in thin layers that build up to create formations called *flowstone* (▼).

09.11.c2 Carlsbad Caverns NP, NM

09.11.c3 Kartchner Caverns SP, AZ

3. Probably the most recognized features of caves are stalactites and stalagmites, which are formed when calcium-rich water dripping from the roof evaporates and leaves calcium carbonate behind. *Stalactites* hang tight from the roof. *Stalagmites* form when water drips to the floor, building mounds upward. The two can join, forming a column.

4. As mineral-rich water drips from the roof and flows from the walls, it leaves behind coatings, ribbons (▶), and straw-like tubes. The water can accumulate in underground pools on the floor of the cave, precipitating rims of cream-colored travertine along their edges.

5. In humid environments, weathering at the surface commonly produces reddish, clay-rich soil. The soil, along with pieces of limestone, can be washed into crevices and sinkholes, where it forms a reddish matrix around limestone fragments.

6. Dissolution of limestone along fractures and bedding planes, along with formation of sinkholes and skylights, disrupts streams and other drainages. Streams may disappear into the ground, adding more water to the cave system.

09.11.c1

09.11.c4 Kartchner Caverns SP, AZ

Carlsbad Caverns

About 260 million years ago, Carlsbad, New Mexico, was an area covered by a shallow inland sea. A huge reef, lush with sea life, thrived in this warm-water tropical environment. Eventually, the sea retreated, leaving the reef buried under other rock layers.

While buried, the limestone was dissolved by water rich in sulfuric acid generated from hydrogen sulfide that leaked upward from deeper accumulations of petroleum. Later, erosion of overlying layers uplifted the once-buried and groundwater-filled limestone cave and eventually exposed it at the surface. Groundwater dripped and trickled into the partially dry cave, where it deposited calcium carbonate to make the cave's famous formations.

09.11.t1 Carlsbad Caverns NP, NM

Before You Leave This Page

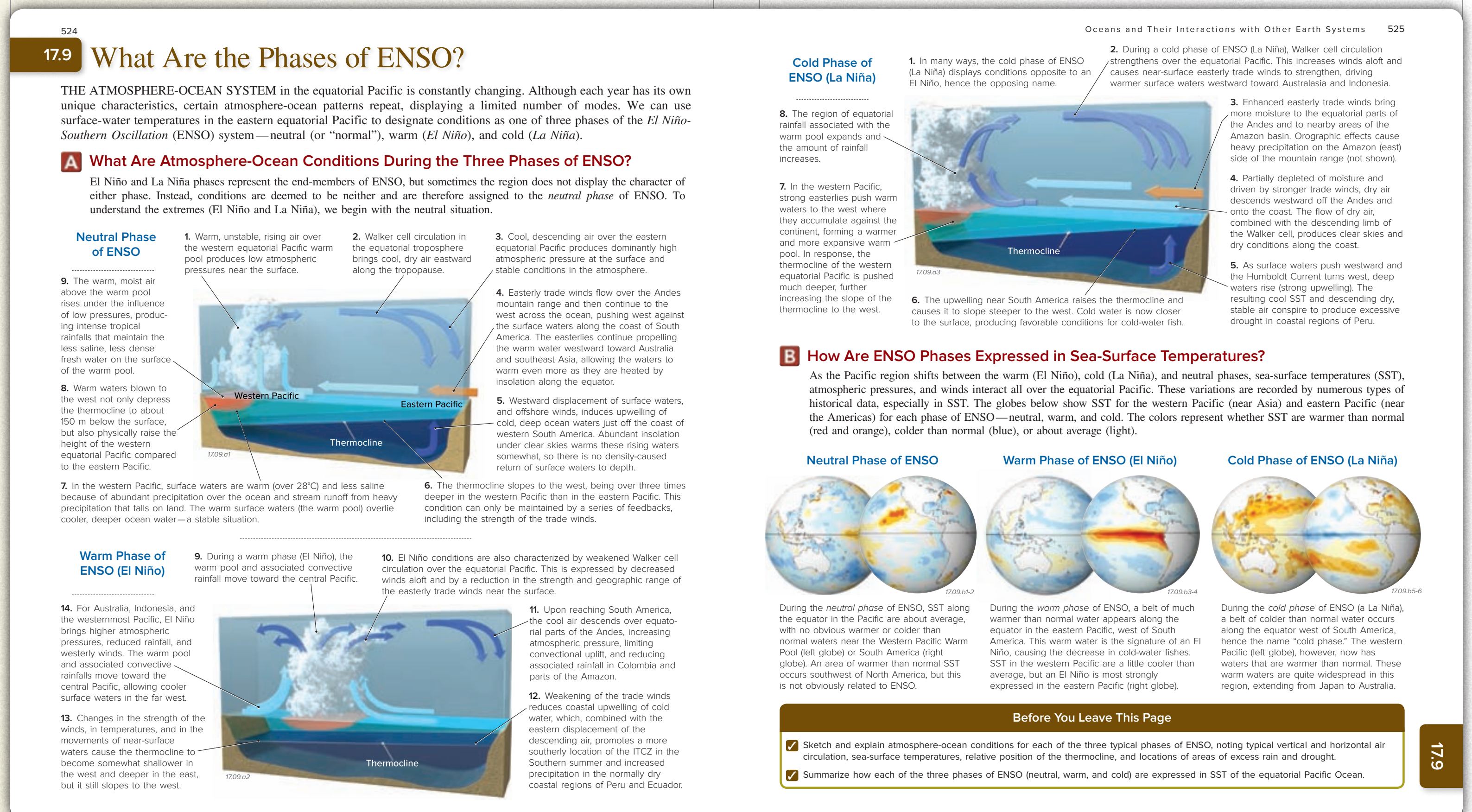
- ✓ Summarize the character and formation of caves and sinkholes.
- ✓ Briefly summarize how stalactites, stalagmites, and flowstone form.
- ✓ Describe features on the surface that might indicate an area may contain caves at depth.

9.11

WHY DOES THE BOOK CONSIST OF TWO-PAGE SPREADS?

This book consists of two-page spreads, most of which are further subdivided into sections. Research has shown that because of our limited amount of working memory, much new information is lost if it is not incorporated into long-term memory. Many students keep reading and highlighting their way through a textbook without stopping to integrate the new information into their mental framework. New information simply displaces existing information in working memory before it is learned and retained. This concept of cognitive load (Sweller, 1994) has profound implications for student learning during lectures and while reading textbooks. Two-page spreads and sections help prevent cognitive overload by providing natural breaks that allow students to stop and consolidate the new information before moving on.

Each spread has a unique number, such as 17.9 for the ninth topical two-page spread in chapter 17. These numbers help instructors and students keep track of where they are and what is being covered. Each two-page spread, except for those that begin and end a chapter, contains a *Before You Leave This Page* checklist that indicates what is important and what is expected of students before they move on. This list contains learning objectives for the spread and provides a clear way for the instructor to indicate to the student what is important. The items on these lists are compiled into a master *What-to-Know List* provided to the instructor, who then deletes or adds entries to suit the instructor's learning goals and distributes the list to students before the students begin reading the book. In this way, the *What-to-Know List* guides the students' studying.



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17.9 What Are the Phases of ENSO?

THE ATMOSPHERE-OCEAN SYSTEM in the equatorial Pacific is constantly changing. Although each year has its own unique characteristics, certain atmosphere-ocean patterns repeat, displaying a limited number of modes. We can use surface-water temperatures in the eastern equatorial Pacific to designate conditions as one of three phases of the *El Niño-Southern Oscillation* (ENSO) system—neutral (or "normal"), warm (*El Niño*), and cold (*La Niña*).

A What Are Atmosphere-Ocean Conditions During the Three Phases of ENSO?

El Niño and La Niña phases represent the end-members of ENSO, but sometimes the region does not display the character of either phase. Instead, conditions are deemed to be neither and are therefore assigned to the *neutral phase* of ENSO. To understand the extremes (El Niño and La Niña), we begin with the neutral situation.

Oceans and Their Interactions with Other Earth Systems 525

B How Are ENSO Phases Expressed in Sea-Surface Temperatures?

As the Pacific region shifts between the warm (El Niño), cold (La Niña), and neutral phases, sea-surface temperatures (SST), atmospheric pressures, and winds interact all over the equatorial Pacific. These variations are recorded by numerous types of historical data, especially in SST. The globes below show SST for the western Pacific (near Asia) and eastern Pacific (near the Americas) for each phase of ENSO—neutral, warm, and cold. The colors represent whether SST are warmer than normal (red and orange), colder than normal (blue), or about average (light).

During the *neutral phase* of ENSO, SST along the equator in the Pacific are about average, with no obvious warmer or colder than normal waters near the Western Pacific Warm Pool (left globe) or South America (right globe). An area of warmer than normal SST occurs southwest of North America, but this is not obviously related to ENSO.

During the *warm phase* of ENSO, a belt of much warmer than normal water appears along the equator in the eastern Pacific, west of South America. This warm water is the signature of an El Niño, causing the decrease in cold-water fishes. SST in the western Pacific are a little cooler than average, but an El Niño is most strongly expressed in the eastern Pacific (right globe).

During the *cold phase* of ENSO (a La Niña), a belt of colder than normal water occurs along the equator west of South America, hence the name "cold phase." The western Pacific (left globe), however, now has waters that are warmer than normal. These warm waters are quite widespread in this region, extending from Japan to Australia.

Before You Leave This Page

- ☑ Sketch and explain atmosphere-ocean conditions for each of the three typical phases of ENSO, noting typical vertical and horizontal air circulation, sea-surface temperatures, relative position of the thermocline, and locations of areas of excess rain and drought.
- ☑ Summarize how each of the three phases of ENSO (neutral, warm, and cold) are expressed in SST of the equatorial Pacific Ocean.

17.9

Two-page spreads and integrated *Before You Leave This Page* lists offer the following advantages to the student:

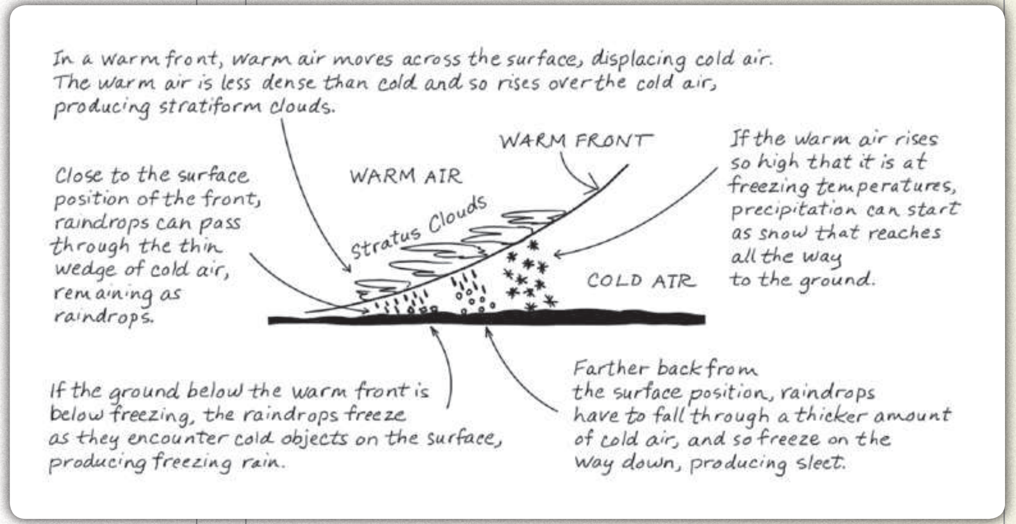
- Information is presented in relatively small and coherent chunks that allow a student to focus on one important aspect or earth system at a time.
- Students know when they are done with this particular topic and can self-assess their understanding with the *Before You Leave This Page* list.
- Two-page spreads allow busy students to read or study a complete topic in a short interval of study time, such as the breaks between classes.
- All test questions and assessment materials are tightly articulated with the *Before You Leave This Page* lists so that exams and quizzes cover precisely the same material that was assigned to students via the *What-to-Know* list.

The two-page spread approach also has huge advantages for the instructor. Before writing this book, the authors wrote most of the items for the *Before You Leave This Page* lists. We then used this list to decide what figures were needed, what topics would be discussed, and in what order. In other words, *the textbook was written from the learning objectives*. The *Before You Leave This Page* lists provide a straightforward way for an instructor to tell students what information is important. Because we provide the instructor with a master *What-to-Know* list, an instructor can selectively assign or eliminate content by providing students with an edited *What-to-Know* list. Alternatively, an instructor can give students a list of assigned two-page spreads or sections within two-page spreads. In this way, the instructor can identify content for which students are responsible, even if the material is not covered in class. Two-page spreads provide the instructor with unparalleled flexibility in deciding what to assign and what not to cover. It allows this book to be easily used for one-semester and two-semester courses.

This textbook, which is purposely designed to allow students to learn on their own, in combination with the components of McGraw-Hill's online learning system (*Connect, SmartBook*, *LearnSmart*), allows an instructor to offload much student learning to out-of-class times. An instructor can rely on the book to teach students content that the instructor does not wish to cover in class, opening up class time for teaching the most important aspects or those with local relevance, for modelling scientific reasoning, or for having students solve earth-science problems. The book and online materials easily provide the necessary components to allow an instructor to use a flipped-class approach, to teach a hybrid class, or for a fully online course. We do all of these.

CONCEPT SKETCHES

Most items on the *Before You Leave This Page* list are by design suitable for student construction of concept sketches. Concept sketches are sketches that are annotated with complete sentences that identify features, describe how the features form, characterize the main processes, and summarize histories (Johnson and Reynolds, 2005). An example of a concept sketch is shown to the right.



Concept sketches are an excellent way to actively engage students in class and to assess their understanding of earth science features, processes, and history. Concept sketches are well suited to the visual nature of earth science, especially cross sections, maps, and block diagrams. Earth scientists are natural sketchers using field notebooks, blackboards, publications, and even napkins, because sketches are an important way to record observations and thoughts, organize knowledge, and try to visualize tectonic processes, the subsurface geometry of rock units, the evolution of landscapes, circulation in the atmosphere and oceans, and motions of astronomical objects. Our research data show that a student who can draw, label, and explain a concept sketch generally has a good understanding of that concept. In our classes, exams are two concept sketches out of a list of 10 to 12 possible questions provided to students ahead of time.

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HOW IS THIS BOOK ORGANIZED?

Two-page spreads are organized into 20 chapters that are arranged into five major parts: (1) introduction to earth systems, earth materials, and geologic time; (2) tectonic processes and features; (3) landscapes; (4) the atmosphere and oceans; and (5) the solar system and universe. The first chapter provides an overview of earth science, how we represent location and geologic features, the scientific approach, and an introduction to *earth systems*—a unifying theme interwoven throughout the rest of the book. Chapter 2 introduces minerals and mineral resources, providing an example of our approach in this book of presenting information about mineral, energy, and water resources in the chapter that is most pertinent to each topic. Chapter 3 follows with an introduction to earth materials and to the processes that form the main families of rocks. Part one of the book ends with Chapter 4, which presents the important concepts about determining sequences of events, ages of rocks, and other aspects of geologic time.

The second part of the book covers various aspects of tectonics. Chapter 5 begins with having students observe large-scale features on land and the seafloor, as well as patterns of earthquakes and volcanoes, as a lead-in to tectonic plates. Integrated into the chapter are two-page spreads on continental drift, paleomagnetism, continental and oceanic hot spots, and evolution of the modern oceans and continents. This is followed by Chapter 6, which explores volcanism, volcanoes, and other igneous processes and features. Chapter 7 begins with general principles of deformation and geologic structures, emphasizing how these are expressed in landscapes. The second half of Chapter 7 takes these principles of deformation and applies them to earthquakes, including their causes, settings, and resulting damage. Chapter 8, the final chapter in the second part of the book, explores explanations for mountains and other regions of high elevations, the formation of continents, and features along continental margins. It also explores the origin of local mountains and basins, a topic unique to this textbook, and provides an introduction to oil and natural gas, including shale gas and oil.

The third part of the book focuses on the broad field of geomorphology—the form and evolution of landscapes. It begins with Chapter 9, a visually oriented introduction to processes that sculpt landscapes and redistribute earth materials. This chapter presents a brief introduction to weathering, erosion, and transport. Wind erosion, transport, deposition, and resulting landforms are integrated into Chapter 9, rather than being a separate, sparse-content chapter that forcibly brings in non-wind topics, as is done in other textbooks. This chapter also illustrates the formation of arches, natural bridges, karst topography, and caves, all of which are topics of interest to many students.

The remaining chapters in the third part of the book cover different aspects of geomorphology. Chapter 10 treats the formation, description, and classification of soils, followed by a figure-based presentation of mass wasting and slope stability. Chapter 11 integrates information about glaciers, coasts, and changing sea level, to highlight the interactions among different earth systems. It introduces glacial movement, landforms, and deposits, along with the causes of glaciation. This chapter then moves to coastal processes, landforms, and hazards, and it ends with the consequences of changing sea level on landforms and humans, emphasizing the role of glaciers in raising and lowering sea level. Chapter 12, the final chapter in this third part, is about various topics involving water, including the hydrologic cycle, water use, streams, stream processes, different types of streams, and flooding. The second half of the chapter explores the relationship between surface water and groundwater, including the important topics of contamination and overpumping of groundwater.

The fourth part of the book is about the atmosphere and oceans. It begins with Chapter 13, an introduction to energy, matter, and the atmosphere, providing a solid background for later chapters. Chapter 14 follows this up with coverage about the processes and manifestations of atmospheric motion. It features separate two-page spreads on circulation in the tropics, high latitudes, and mid-latitudes, allowing students to concentrate on one part of the system at a time, leading to a synthesis of lower-level and upper-level winds. Chapter 14 also covers air pressure, the Coriolis effect, and seasonal and regional winds. These topics lead naturally into Chapter 15, which is an introduction to atmospheric moisture, including clouds and various forms of precipitation. Within the chapter are globes and other maps presenting global, regional, and seasonal patterns of humidity and precipitation. Chapter 16 follows this with a visual, map-oriented discussion of weather and storms, including cyclones, tornadoes, and other severe weather. The next chapter (Chapter 17) is devoted to the oceans and their interactions with the atmosphere and cryosphere. It features sections on ocean currents, sea-surface temperatures, ocean salinity, and a thorough treatment of ENSO. The chapters in this part build into Chapter 18, which presents various aspects of climate, including the controls on climate and climate classification. Chapter 18 features a two-page spread on each of the main climate groups, illustrated with a rich blend of globes, process-oriented figures, climographs, and photographs. These spreads are built around the globes, each of which portray a few related climate types, enabling students to concentrate on the distribution and controls of each climate type. The climate chapter also has a data-oriented presentation on the important topic of climate change, especially the data for climate change, the controlling factors, and predicted consequences. It ends with a two-page spread on alternative (non–fossil fuel) energy sources.

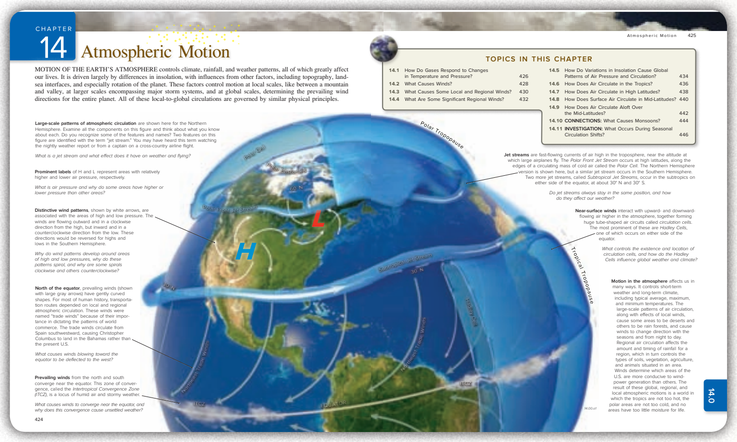
The fifth and final group of chapters focuses on the solar system and the rest of the universe. Chapter 19 presents a highly visual introduction to various objects in the solar system and how we study and investigate them. It is followed by Chapter 20, the final chapter in the book, which explores the rest of the universe. It begins with a treatment of how we observe the universe and our framework for referencing these observations. It introduces forces, motions, and light, presenting the laws of motion of Newton and Kepler. The chapter successively explores stars, stellar evolution, stellar remnants, and galaxies, ending with a discussion of cosmology and the early history of the universe.

TWO-PAGE SPREADS

Most of the book consists of *two-page spreads*, each of which is about one or more closely related topics. Each chapter has four main types of two-page spreads: opening, topical, connections, and investigation.

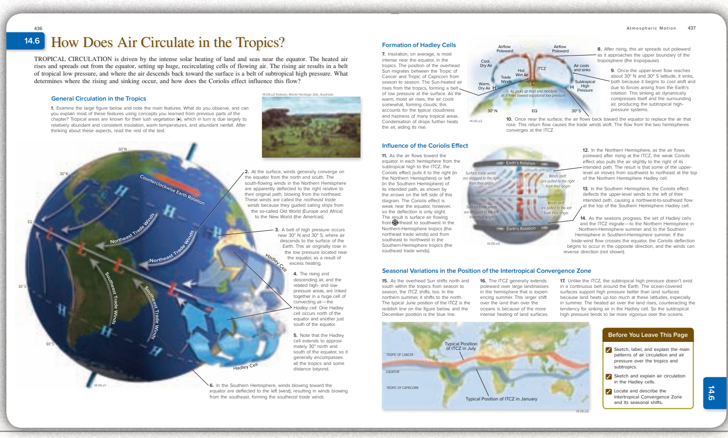
Opening Two-Page Spread

Opening spreads introduce the chapter, engaging the student by highlighting some interesting and relevant aspects and posing questions to activate prior knowledge and curiosity.



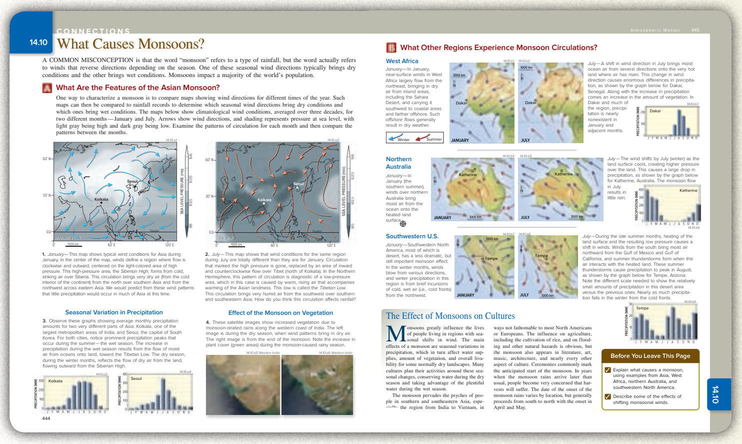
Topical Two-Page Spread

Topical spreads comprise most of the book. They convey the content, help organize knowledge, describe and illustrate processes, and provide a spatial context. The first topical spread in a chapter usually includes some aspects that are familiar to most students, as a bridge or scaffold into the rest of the chapter. Most chapters have at least one two-page spread illustrating how earth science processes impact society and commonly another two-page spread that specifically describes how earth scientists study typical problems.



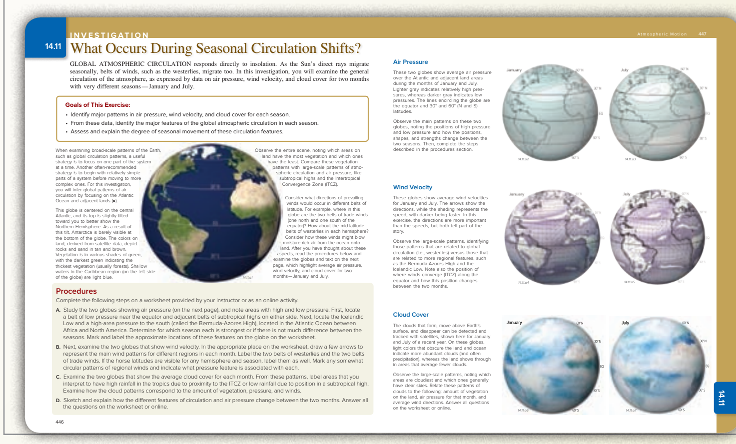
Connections Two-Page Spread

The next-to-last two-page spread in each chapter is a *Connections spread* designed to help students connect and integrate the various concepts from the chapter and to show how these concepts can be applied to an actual location. *Connections* are about real places that illustrate the concepts and features covered in the chapter, often explicitly illustrating how we investigate an earth science problem and how these problems have relevance to society.



Investigation Two-Page Spread

Each chapter ends with an *Investigation* spread that is an exercise in which students apply the knowledge, skills, and approaches learned in the chapter. These exercises mostly involve virtual places that students explore and investigate to make observations and interpretations and to answer a series of relevant questions. Some involve actual global data. Investigations are modeled after the types of problems geoscientists investigate, and they use the same kinds of data and illustrations encountered in the chapter. The Investigation includes a list of goals for the exercises and step-by-step instructions, including calculations and methods for constructing maps, graphs, and other figures. These investigations can be completed by students in class, as part of a laboratory exercise, as worksheet-based homework, or as online activities.



NEW IN THE SECOND EDITION

The second edition of *Exploring Geology* represents a significant revision, with every chapter receiving additions and improvements, including 188 new photographs. Some changes will be obvious, while others are more subtle but nevertheless substantial. The style, approach, and sequence of chapters is unchanged, but every chapter received new photographs, many revised figures, major to minor editing of text blocks, and, in some cases, reorganization. We revised many text blocks to improve clarity and conciseness, or to present recent discoveries and events. Most chapters contain the same number and order of two-page spreads, but one chapter gained two two-page spreads and another had two spreads completely revised. Many sections of two-page spreads were revised in content and layout, such as by the addition of a photograph not in the previous edition. Nearly all changes were made in response to comments by reviewers and students. The most important revisions are listed below:

- This edition features completely different fonts from the previous edition. The new fonts were chosen partly to improve the readability on portable electronic devices, while retaining fidelity to a quality printed book. This font replacement resulted in countless small changes in the layout of individual text blocks on every two-page spread. In addition to replacing all of the fonts within the text, all figure labels were replaced with the new font, a process that required opening, editing, and commonly resizing every illustration that had text, as in the axes of graphs. In addition, all labels were incorporated into the actual artwork, rather than overlaying them on the artwork using the page-layout program, as was done for many figures in the previous edition. This involved adding labels to hundreds of illustrations, but it has the benefit of having every label as an integral part of its associated art file, a useful feature for constructing PowerPoint files.
- This edition contains 188 new photographs, with a deliberate intention to represent a wider geographic diversity and to provide more detail and clarity about various processes and features, whether on land, in the atmosphere, and in the water. Most of these new photographs represent upgrades of existing photographs from the previous edition, but a number are new photographs in the layout. Also, for this edition, we individually reprocessed nearly all photographs that were derived from scanned slides, using technology and techniques that were not available when the original scanned versions were generated and processed. This reprocessing involved opening up the original high-resolution scans or digital photograph and using modern image-processing software to correct brightness, contrast, and color balance, and to remove visual noise. The resulting improvements will be noticeable for many images in the printed book, but they are more conspicuous in the digital e-book and especially in the high-resolution images we provide instructors for use in classrooms.
- This edition contains many new and replaced figures and even more that were lightly revised, such as replacing fonts. Figures from the first edition were replaced with new versions to update information so that it is more recent, to improve student understanding of certain complex topics, and for improved appearance. All fonts were replaced in every figure that has text.
- This edition contains two new two-page spreads on sedimentary environments and a new section on impact craters. We also thoroughly revised the coverage of climate change, more prominently featuring recent climate change at the start of the discussion. This is followed by a new section that discusses the types of climate proxies, using a more geologic, photograph-based approach in place of the previous collection of small graphs of proxies. In the next spread, which covers factors that could cause climate change, the role of CO_2 was moved up front to again start the discussion focussed on factors involved in recent climate change, followed by those that affect climate on geologic time scales.
- Many two-page spreads have been extensively revised with improved layout, illustrations, and text. In addition to the new or revised illustrations, we updated text to reflect new ideas or data. For example, we updated information on Pluto, comets, satellite temperatures, sea-level rise, and many other relatively minor data points.
- Throughout the book, we added numbers to most text boxes to guide students to read the text boxes in a specific order. We also renumbered many figure numbers so that they are in the same order as the newly numbered text boxes. For all chapter-ending Investigations, we replaced numbers with letters in the Procedures lists to avoid confusion with newly numbered text boxes.
- Every box with the learning objectives was changed from "Before You Leave This Page Be Able To" to simply "Before You Leave This Page." This is more concise, and opened up room on nearly every two-page spread.

CHAPTER 1 received a moderate revision, mostly involving nine new photographs (five replacing existing ones) and the reprocessing of most other photographs. The investigation received four additional photographs to depict important features students need to consider in their deliberations. The chapter also has one revised illustration that now incorporates an actual photograph of Pluto.

CHAPTER 2 received a light revision, with eight new photographs, mostly of rocks and mineral resources. Some other photographs were processed from the original scans. Fonts were replaced throughout, resulting in many small changes in wording and layout, as occurred in every chapter.

CHAPTER 3 was heavily revised, featuring 36 new photographs and two new two-page spreads that present an early, visual overview of sedimentary environments on land, near shorelines, and in the ocean. Two new page-spanning illustrations and 14 additional photos accompany this new material. Two of the new photographs are from the Franciscan of California, and are accompanied by a new, brief introduction to melange. Other new photographs are mostly from Florida, Texas, and New Mexico.

CHAPTER 4 contains nine new photographs of rocks, fossils, and environments. It has a new section on impact craters accompanied by three new illustrations. It also now incorporates a new photograph and modified discussion of concretions. Several sections received significant edits.

CHAPTER 5 on plate tectonics is mostly unchanged, but every illustration with text was edited to replace the fonts. Several maps were revised, including the one showing North American transform faults.

CHAPTER 6 has 14 new or replaced photographs representing more diverse locations, including Joshua Tree National Park. It has a new photograph of the Valles Caldera and a number of reprocessed ones. Two photographs of Augustine pyroclastic eruptions were reprocessed and recropped to better convey the vertical extent of the eruptions. In addition to font changes, the chapter has two rebuilt illustrations.

CHAPTER 7 includes eight new photographs of structures and landscape features, including ones in a heavily revised section showing features related to erosion of tilted layers. There is also a new short section on erosion of fault scarps, accompanied by a new photograph. Several illustrations were moderately revised, mostly ones showing seismic waves.

CHAPTER 8 contains eight new photographs illustrating the landscape appearance of different types of rocks. Several sections were reordered and heavily edited around the new photographs. A map of sedimentary basins was revised to better display the geographic features in the area covered by each basin.

CHAPTER 9 on sculpting landscapes was heavily revised, with 24 new photographs of weathered limestone, caves, karst topography, and problem soils. The new photographs are mostly from Florida, Texas, and Carlsbad Caverns National Park. The new photographs of Carlsbad illustrate the size of the cavern better than most textbook images we have seen. The section on trading location for time was vastly improved through changes in layout and a new photograph from Monument Valley that perfectly illustrates the concept.

CHAPTER 10 contains 10 new photographs of soils and slopes, including new photographs specifically retaken of the Slumgullion Landslide and a new computer-generated 3D-perspective showing the 2017 Big Sur landslide.

CHAPTER 11 has 25 new photographs, mostly of coastal regions of Florida and glacial features of the western U.S. and Alaska. The chapter was renamed using coasts instead of shorelines, and text and headings were changed throughout to reflect this change.

CHAPTER 12 on streams, flooding, and groundwater now features 15 new photographs of streams and stream-related features. There are newly inserted photographs of cutbanks, point bars, and entrenched meanders, accompanied by changes in layout and text editing to accomodate the new images. One photograph of a spring was deleted. All the graphs and maps were revised for new fonts and other improvements, such as arrow colors depicting groundwater flow.

CHAPTER 13 is the first of the atmosphere chapters, and received only minor revisions. It contains five new photographs. Each illustration, including each of the many graphs, was edited for the change in fonts and incorporation of labels in the art files.

CHAPTER 14 was for the most part lightly revised, except for font changes in all the illustrations. There are three new versions of figures showing upper-level polar circulation and two new versions of global wind patterns and the Coriolis effect. There is one new photograph, and the investigation has a new layout.

CHAPTER 15 has a number of new versions of illustrations and one new photograph. Globes showing humidity were rebuilt and rerendered, with a clearer legend. There are new versions of figures showing Rossby waves, clouds, freezing rain, and sleet. Global amounts of precipitation are now shown with three globes rather than one flat map. As for all the globes in the book, the authors provide a media file for every globe shown.

CHAPTER 16 had minor revisions on most two-page spreads, but major revisions on some. Major revisions included sections about lightning and upper-level lightning phenomena, where in both cases text was separated from the figures to improve readability and for use in presentation software. The Investigation was heavily revised to include data and discussion of upper-level airflow patterns. The chapter has three new photographs.

CHAPTER 17 features, in additon to all the font changes, several newly redone illustrations, such as on global wind directions and the Southern Oscillation. We revised the labels, layout, and order of globes showing ocean currents. There are two new photographs.

CHAPTER 18 displays major revisions to figures and some two-page spreads. All the climate globes, of which there are many, were rebuilt using new 3D files and rerendered. Likewise, all figures with part of a globe were redrawn using the new renders. We updated a number of figures to show the most current data, such as on sea-level rise, extent of Arctic sea ice, global temperatures, and CO_2. We redid the first two spreads on climate change, aiming to consolidate the discussion of recent climate change at the start of the discussion, followed by climate change over geologic timescales. Graphs of proxies were replaced with photographs to provide a more geologic approach and to better convey the diversity of types of climate proxy data. The role of CO_2 was moved up in the discussion of the possible causes of climate change, with the intent of again leading with recent climate change and then moving to long-term climate changes. A graph of sunspot data was replaced with a photograph.

CHAPTER 19 had moderate revisions, with the addition of four new images depicting more recent images of Pluto, nebulae, and a comet. We added or refined the discussions of Pluto, Ceres, comets, the age of the solar system, and the number of moons of Jupiter, each reflecting current information.

CHAPTER 20 on the Universe had very minor revisions, but fonts on the many text-rich illustrations were replaced, which often involved repositioning and changing layout of the text. Some figures received minor additional revisions.

FRONT AND BACK MATTER, including the *Preface*, *Glossary*, and *Index,* were revised and updated to reflect the revised table of contents and changes in page numbers due to reorganizations.

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This book is a decidedly collaborative effort, incorporating material from our two other textbooks. Our colleagues Chuck Carter, Mike Kelly, and Paul Morin contributed materials to our *Exploring Geology* textbook, and some of this content is included here. Likewise, we have greatly benefitted from our collaboration with geographers Bob Rohli, Peter Waylen, and Mark Francek on our *Exploring Physical Geography* textbook, which provided the starting materials for chapters on the atmosphere and oceans. We gratefully acknowledge the words, figures, organization suggestions, and friendship provided by these colleagues.

This book contains over 2,500 figures, several times more than a typical introductory earth science textbook. This massive art program required great effort and artistic abilities from the illustrators and artists who turned our vision and sketches into what truly are pieces of art. We are especially appreciative of Cindy Shaw, who was lead illustrator, art director, and a steady hand that helped guide the project. For many figures, she extracted data from NOAA and NASA websites and then converted the data into exquisite maps and other illustrations. Cindy also fine-tuned or extensively reworked the authors' layouts, standardized various aspects of the illustrations, and prepared the final figures for printing. This second edition was especially onerous for Cindy, because the two main fonts were replaced throughout the book and in every figure label. Cindy also moved labels from the page-layout program into the art files, partly so that the labels are present in PowerPoint images. Chuck Carter produced many spectacular pieces of art, including virtual places featured in the chapter-ending Investigations. Susie Gillatt contributed many of her wonderful photographs from around the world, photographs that helped us tell the story in a visual way. She also color corrected and retouched most of the photographs in the book, including every image in this edition that was derived from a scanned color slide, and there were many. We also used visually unique artwork by Daniel Miller, David Fierstein, and Susie Gillatt. Suzanne Rohli performed magic with GIS files and helped in many other ways. We were ably assisted in data compilation and other tasks by students and former students Cheryl Replogle, Jenna Donatelli, Emma Harrison, Abeer Hamden, Peng Jia, Javier Vázquez, and Courtney Merjil. Terra Chroma, Inc., of Tucson, Arizona, supported many aspects in the development of this book, including funding parts of the extensive art program and maintaining the *ExploringEarthScience.com* website.

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Steve has authored or edited over 200 geologic maps, articles, and reports, including the 866-page *Geologic Evolution of Arizona*. He also coauthored *Structural Geology of Rocks and Regions*, a structural geology textbook, and *Observing and Interpreting Geology*, a laboratory manual for physical geology. Working with a team of geographers, he authored *Exploring Physical Geography*, which follows the style and approach of his award-winning *Exploring Geology* textbook.

His current geologic research focuses on structure, tectonics, stratigraphic correlations, landscape evolution, and mineral deposits of the Southwest. For several decades, he has conducted science-education research on student learning in college geoscience courses, especially the role of visualization. He was the first geologist with his own eye-tracking laboratory, where he and his students demonstrated that students learn more when using the unique design, layout, and approach of this textbook, compared to how much (or little) they learn from a traditional textbook.

Steve is known for innovative, award-winning teaching methods, and has a widely used website. He was a National Association of Geoscience Teachers (NAGT) distinguished speaker, and he often travels across the country presenting talks and workshops on visualization and on how to infuse active learning and inquiry into large introductory geoscience classes. He is commonly an invited speaker to national workshops and symposia on active learning, visualization, and teaching methods in college geoscience courses. He has been a long-time industry consultant in mineral, energy, and water resources, and has received outstanding alumni awards from UTEP and the University of Arizona.

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Julia K. Johnson is a full-time faculty member in the School of Earth and Space Exploration at Arizona State University. She received an undergraduate degree from Ricks College in eastern Idaho and undergraduate and graduate degrees from Arizona State University. Her graduate research involved structural geology and geoscience education research.

She teaches introductory geoscience to more than 2,000 students per year, both online and in person. She also supervises the associated in-person and online labs, and is the lead author of both the online and in-person versions of *Observing and Interpreting Geology, a Laboratory Manual for Physical Geology*, an innovative laboratory manual in which all learning is built around a virtual world (Painted Canyon). She helps coordinate the introductory geoscience teaching efforts of the School of Earth and Space Exploration (SESE), guiding other instructors as they incorporate active learning, inquiry, and online materials into large lecture classes. She is responsible for the design and deployment of online resources for SESE's introductory physical geology courses, including the lecture and lab components.

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Cindy Shaw, lead illustrator and art director for this book, holds a B.A. in zoology from the University of Hawaii–Manoa as well as a master's in education from Washington State University, where she researched the use of guided illustration as a teaching and learning tool in the science classroom. Now focusing on earth science, mapping, and coral reef ecology, she writes and illustrates for textbooks and museums, and develops ancillary educational materials through her business, Aurelia Press. Her kids' novel, *Grouper Moon*, is used in many U.S. and Caribbean science classrooms, and is making an impact on shaping childrens' attitudes toward fisheries conservation. Currently landlocked in Richland, Washington, Cindy escapes whenever possible to travel, hike, and dive the reefs to field-sketch and do reference photography for her projects. She is also lead illustrator and art director for recent editions of *Exploring Geology* and *Exploring Physical Geography*. In this role, Cindy generates new illustrations, often researching the necessary data for those illustrations, standardizes illustrations contributed by other artists, finalizes page layout, and prepares files for electronic delivery of all materials to the compositors.

PAUL J. MORIN

Paul Morin, coauthor of *Exploring Geology*, is director of the Polar Geospatial Center at the University of Minnesota, which supports National Science Foundation scientific and research operations through remote sensing and other geospatial data. Paul co-founded the GeoWall Consortium, which promoted the use of visualization and stereo projection in the classroom. Over the past five years, Paul has been instrumental in bringing earth science visualization to science museums around the world.

SUSANNE GILLATT

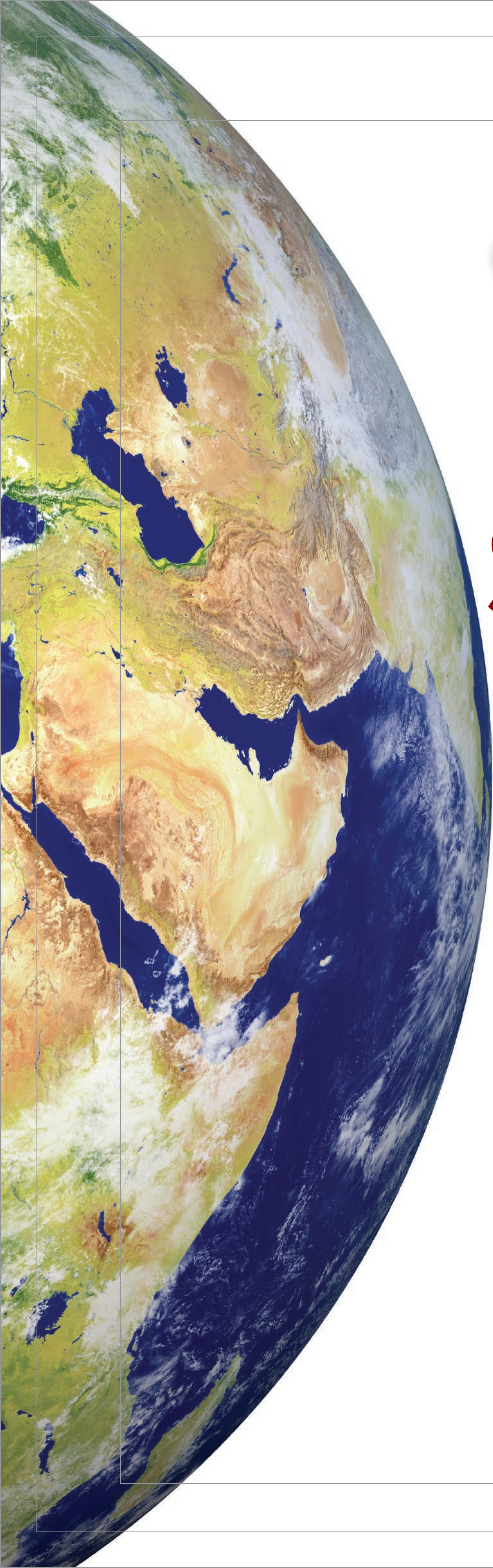
Susie Gillatt received a bachelor of arts degree from the University of Arizona and is president of Terra Chroma, Inc., a multimedia studio. She focuses on scientific illustration and photo preparation for academic books and journals. Many photographs in this book were contributed by Susie from her travels to experience different landscapes, ecosystems, and cultures around the world. Her award-winning art, which combines photographs of nature with digital painting, has been displayed in galleries in Arizona, Colorado, and Texas.

CHUCK CARTER

Chuck Carter has worked in the science and entertainment industries for three decades. He developed the innovative video game, *Myst*, and more than two dozen other video games in a variety of art, animation, and management roles, including computer graphics supervisor and art director. His illustrations and animations have appeared in *National Geographic*, *Scientific American*, *Wired*, the BBC, NASA, and Disney's *Mission to Mars*. Chuck is president of Eagre Games, designing fully immersive adventures, including *ZED*.

DANIEL MILLER

Daniel Miller is a self-taught artist, beginning his career as a silversmith, then goldsmith, painter and sculptor, designer, and art director. Attaining his goal of working in the film industry, he created notable sculptural elements for many major films, including *Stargate* and *Chronicles of Riddick*. He was a concept artist and matte painter for films and video games. He completed large-scale sculptural installments, including *Fountains of the Gods* at Caesars Palace in Las Vegas, where he lives and pursues his passion for oil painting.



exploring

Earth Science

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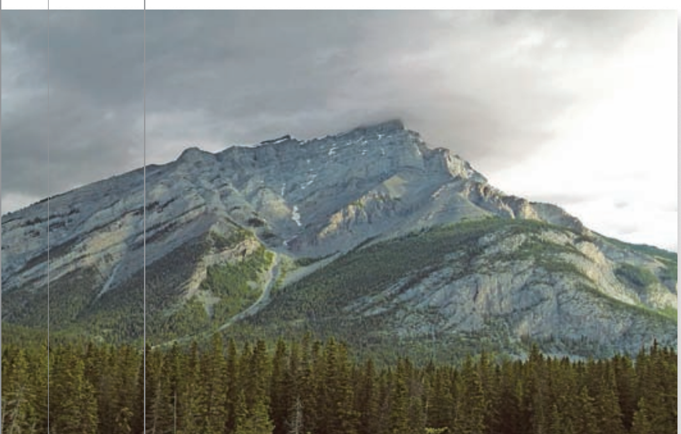
CHAPTER 1

The Nature of Earth Science

EARTH SCIENCE FOCUSES ON THE FOUR COMPONENTS of the earth system — land, water, air, and life — and their interactions. Processes within the solid earth cause volcanoes and earthquakes, form mountains, and rearrange continents. Most of Earth's surface is covered by oceans, but water also forms ecologically important lakes, rivers, and wetlands. Above the surface, the atmosphere contains gases essential to life, as well as clouds, precipitation, wind, and storms. Living things depend upon and interact with the land, water, atmosphere, and energy from space. Together, the various components of our planet control the climate and overall suitability for life, the distribution of natural resources, and the susceptibility for floods, landslides, and other natural disasters. Earth science is the study of the solid earth, oceans, atmosphere, life, and our setting in space.

North America and Central America have a wealth of interesting features. The large image below (▼) is computer-generated and combines different types of data to show features on the land, in the oceans, and in the atmosphere. The shading and colors on land are from space-based satellite images, and whitish colors in the atmosphere are clouds of various types and heights. Can you find the region where you live or visit? What types of landscape features, water bodies, and clouds are there?

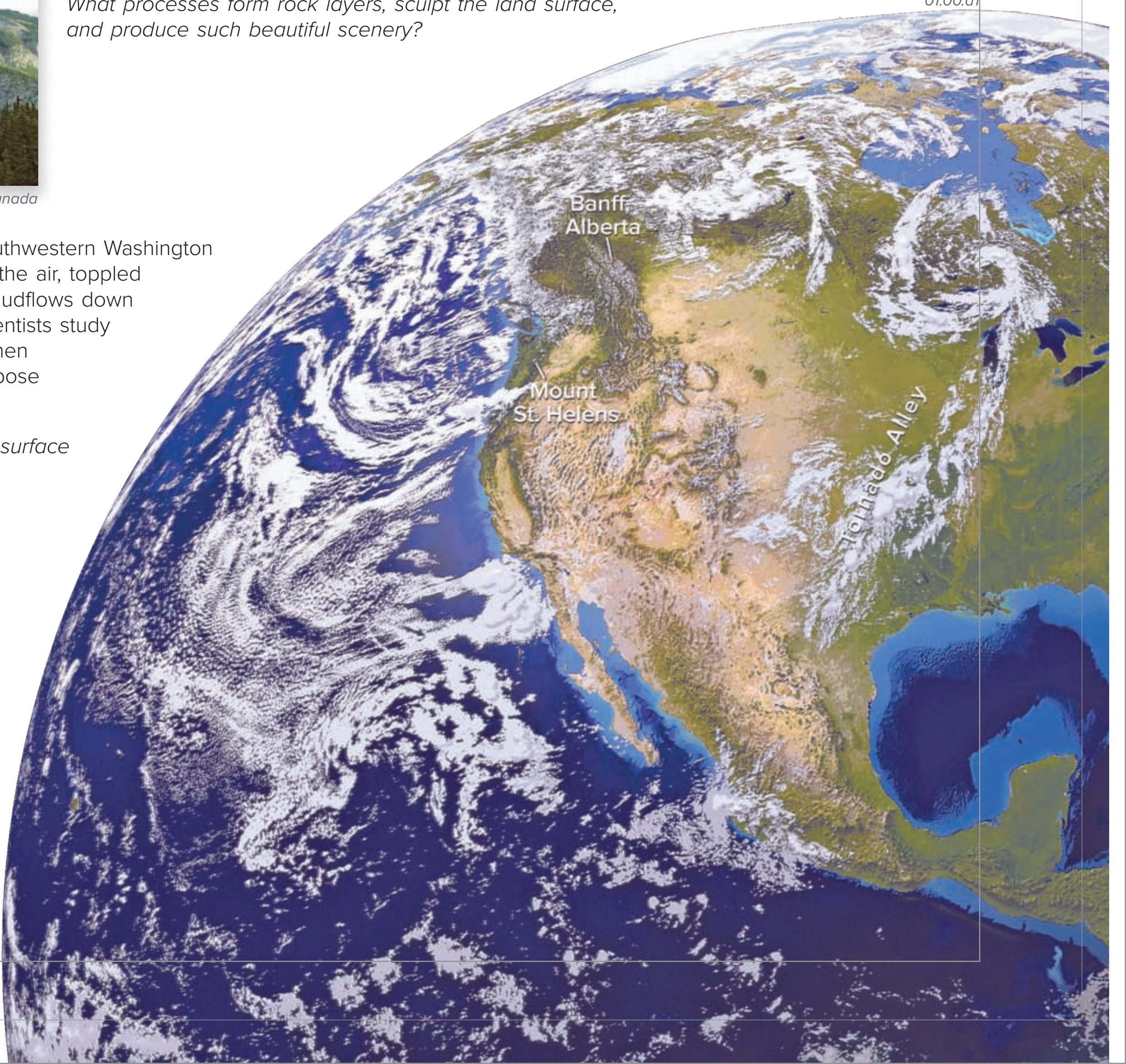


01.00.a2 Banff, Alberta, Canada

◀ **The dramatic scenery of Banff, Alberta**, in the Canadian Rockies, features spectacularly tilted and folded rock layers expressed in various shades of gray. Exposed to sunlight, moisture, plants, animals, and the downward pull of gravity, the rock layers begin to disintegrate, some forming precipitous cliffs and others wearing away into slopes covered by loose pieces. The mountains interact with the atmosphere, causing clouds, rain, and snow to be concentrated over the mountains, influencing the growth of trees and other plants, and affecting the lives of the various creatures, including mammals and birds.

What processes form rock layers, sculpt the land surface, and produce such beautiful scenery?

01.00.a1



The 1980 eruption of Mount St. Helens in southwestern Washington (▼) ejected huge amounts of volcanic ash into the air, toppled millions of trees, unleashed large floods and mudflows down nearby valleys, and killed 57 people. Earth scientists study volcanic phenomena to determine how and when volcanoes erupt and what hazards volcanoes pose to humans and other creatures.

How do studies of the Earth's surface and subsurface help us determine where it is safe to live?

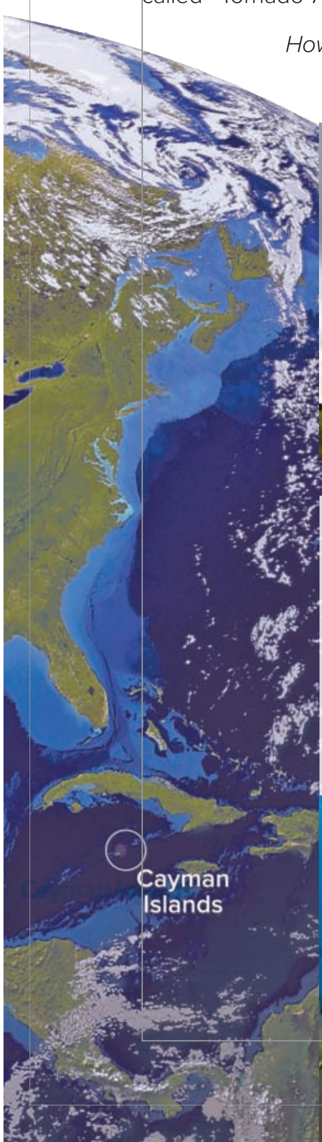
01.00.a3 Mount St. Helens, WA

TOPICS IN THIS CHAPTER

Earth's atmosphere is dynamic, with constantly moving air masses and clouds that produce precipitation (rain, snow, and hail) and locally cause severe storms, like the ominous line of clouds shown below (▼). Heating from the Sun provides the energy for winds, as well as atmospheric moisture for clouds and storms, so Earth's setting in space influences important aspects of our planet, including climate and seasons. Severe weather, including tornadoes, is especially common in the center of the U.S. along a north-south region often called "Tornado Alley."

How do clouds and storms form, and how does the Sun influence winds?

01.00.a4 Tornado Alley, Central U.S.



The oceans, like the atmosphere, are dynamic, with waves and ocean currents that move water and energy from one region to another, and various manifestations of life, such as coral reefs (▼). The major influences on the oceans are the Sun, the rotation of Earth around its axis, and the configuration of the seafloor and continents.

How do the oceans interact with and influence the land, seafloor, atmosphere, and life?

01.00.a5 Cayman Islands

A View of North America

North America is a diverse continent, ranging from the low, tropical rain forests of Central America to the high Rocky Mountains of western Canada. In the large image of North America on the left, the colors on land are from satellite images that show the distribution of rock, soil, plants, and lakes. Green colors represent dense vegetation, including forests shown in darker green, and fields and grassy plains shown in lighter green. Brown colors represent deserts and other regions that have less vegetation, including regions where rock and sand are present. Lakes are shown with a solid blue color. Clouds for a single day are overlain on Earth's surface, but should be viewed as one snapshot of a continuously playing movie—the clouds will have moved by the next day. The image is computer generated from several data sets and is not an actual photograph.

The colors of the ocean reflect the depth to the underlying seafloor, but the actual shape of the seafloor is not shown. Light blue colors represent shallow areas, such as those flanking the continent, whereas dark blue represents places where the seafloor is deep. Observe the larger features on land, at sea, and in the atmosphere. Ask yourself the following questions: What is this feature? Why is it located here? How did it form? In short, what is its story?

Notice that the two sides of North America are very different from each other and from the middle of the continent. The western part of North America has many rugged mountains and deep valleys. The mountains in the eastern United States are more subdued, and the East Coast is surrounded by a broad shelf (shown in a light blue-gray) that continues out beneath the Atlantic Ocean. The center of the continent has no mountains but has broad plains, hills, river valleys, and large lakes. These variations in landscapes greatly affect weather and regional climates.

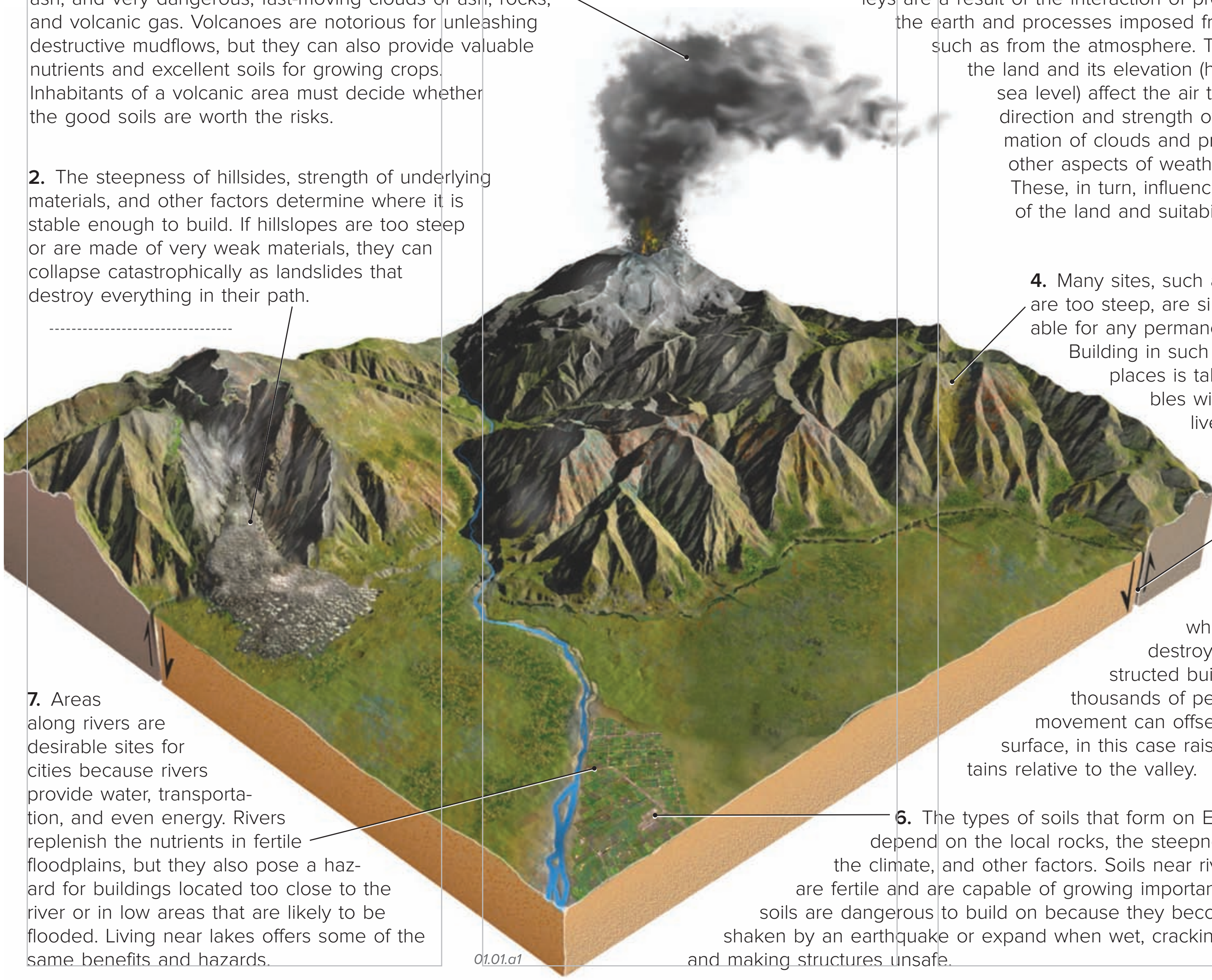
All of the features on this image of Earth are part of earth science. Earth science explains why the mountains on the two sides of the continent are so different and when and how the mountains formed. It explains processes that operate within the waters of the oceans. Earth science addresses climate, weather, water resources, and landscapes, and the impact of these aspects on life. The land, oceans, atmosphere, and life are greatly affected by the Sun, Moon, and certain other features in the universe, so earth science also involves many aspects of *astronomy*. Earth science especially deals with the interactions of these various components, focusing on the Earth as a series of systems, an approach often called *earth-system science*. As shown throughout this book, earth's systems affect many aspects of our society.

1.1 How Do Earth's Features and Processes Influence Where and How We Live?

EARTH PROCESSES INFLUENCE OUR LIVES IN MANY WAYS. A major influence is the shape and character of the land on which we live. This aspect of earth science is part of the discipline of *geology*, the study of the earth. Geologic features and processes constrain where people can live because they determine whether a site is safe from landslides, floods, or other natural hazards. Some areas are suitable building sites, but others are underlain by unstable earth materials that could cause damage to any structure built there. Geologic factors also control the distribution of energy and mineral resources and croplands. The land is imprinted by interactions with the Sun, weather, water, and life, and the entire system is investigated by many types of scientists, including geographers, climatologists, oceanographers, and ecologists. Collectively, we call such scientists *earth scientists* or *geoscientists*.

A Where Is It Safe to Live?

The landscape around us contains many clues about whether a place is relatively safe or whether it is a natural disaster waiting to happen. What important clues should guide our choice of a safe place to live?



B How Do Earth Processes Influence Our Lives?

To explore how earth features and processes affect our lives, observe this photograph, which shows a number of different features, including clouds, snowy mountains, slopes, and a grassy field with horses and cows (the small, dark spots). For each feature you recognize, think about what is there and what processes might be occurring. Then, think about how these features and processes influence the life of the animals and how they would influence your life if this was your home. Think broadly, considering aspects of the land, atmosphere, and any expressions of water or life. Think about this before reading on.

In the distance are snow-covered mountains partially covered with clouds. Snow and clouds both indicate the presence of water, an essential ingredient for life. The mountains have a major influence on water in this scene. As the snow melts, water flows downhill toward the lowlands, to the horses and cows.

The horses and cows roam on a flat, grassy pasture, avoiding slopes that are steep or barren of vegetation. The steepness of slopes reflects the strength of the rocks and soils, and the flat pasture resulted from loose sand and other materials that were laid down during flooding along a desert stream. Where is the likely source of the water needed to grow grass in the pasture?

01.01.b1 Henry Mtns., UT

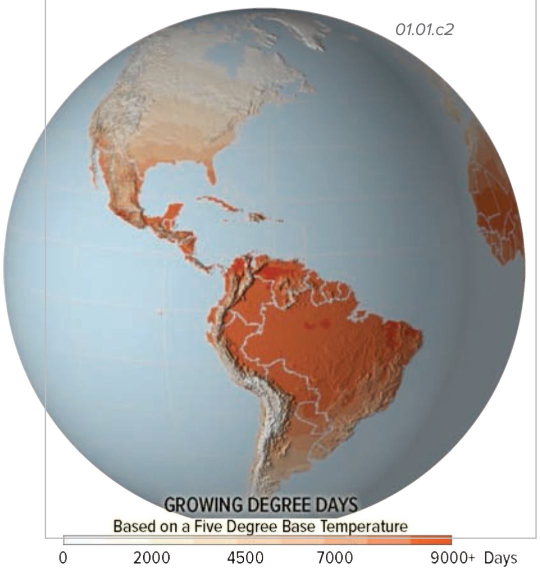
C What Factors Control Where We Can Grow Food?

The suitability of an area for growing crops and raising livestock depends on many factors, especially the overall climate, which incorporates the temperatures, amount and timing of precipitation, and various seasonal effects, such as number of days without freezing temperatures. The climate, steepness of slopes, type of earth materials, types of plants and animals, and other factors in turn control the type and thickness of soil.

The two globes below show important controls on agriculture and ranching. The left globe represents the average amount of precipitation, with darker purple indicating higher amounts of precipitation. The right globe depicts the length of the growing season and how warm it is, using a calculated number called the growing degree days, with darker orange representing conditions with longer, warmer days (generally more favorable for growing plants). What are the conditions where you live, and can you explain some of the patterns?

01.01.c1

01.01.c2



Before You Leave This Page

- ✓ Sketch or list some ways that earth processes control where it is safe to live and the landscape around us.
- ✓ Explain some factors that influence where we can grow food.

1.2 How Does Earth Science Explain Our World?

THE WORLD HAS INTERESTING FEATURES at all scales. Views from space show oceans, continents, mountain belts, and clouds. Traveling through the countryside, we notice smaller things — a beautiful rock formation or soft, green hills. Upon closer inspection, the rocks may include fossils that provide evidence of ancient life and past climates. Here, we give examples of how earth science explains big and small features of our world.

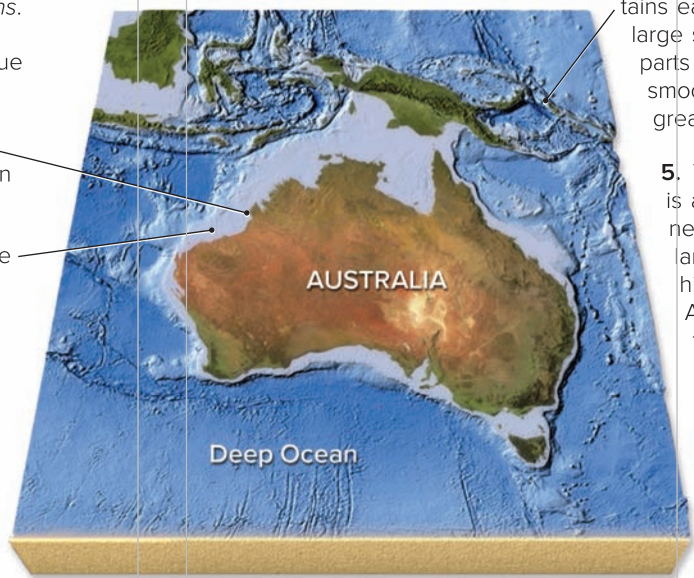
A How Do Continents Differ from Ocean Basins?

Examine the figure below, which is a computer-generated view of the continent of Australia and the surrounding ocean basins. Colors on land show vegetation, rocks, soil, and sand, whereas colors in the oceans indicate depth, with darker blue being the deepest seafloor. Note the main features, especially those on the seafloor.

1. This map illustrates one of the most important distinctions on Earth — our planet is divided into *continents* and *oceans*.

2. The boundary between the blue colors of the oceans and the greens and browns of the land is the coastline, which outlines the familiar shape of Australia as seen on world maps.

3. Surrounding the land is a fringe of seafloor that is not very deep, represented on this map by light blue colors. This fringe of shallow seafloor, called the *continental shelf*, is wider on the north side of the continent than on the other three sides. Earth scientists consider the continent to continue past the coastline and to the outer edge of the continental shelf.



4. The seafloor beneath deep parts of the ocean is locally complex, containing chains of submarine mountains east of Australia and long features that look like large scratch marks south of the continent. The deep parts of the seafloor are much rougher than the smooth-appearing continental shelf. Seafloor depths greatly influence ocean temperatures and currents.

5. The distinction between continents and oceans is a reflection of differences in the types and thicknesses of the rocks and in how each formed. The land varies in elevation and character, such as higher, vegetation-covered mountains in eastern Australia than in the rest of the continent. Within the oceans are major variations in the depth and character of the seafloor from place to place. There is a large variation in the temperature of the ocean in this region, with very warm seawater temperatures to the north and very cold seawater to the south. The landscape, oceans, and other factors affect the weather, climate, abundance and movement of water, and the overall conditions for life.

01.02.a1

B What Stories Do Landscapes Tell?

Observe this photograph of a canyon wall. After you have done this, think of at least two questions about what you notice, before you read the text. Go ahead, try it!

1. The landscape has cliffs and slopes composed of rock units that are shades of tan, brown, and yellow. There are not many plants.

2. In the bottom half of the image, some large, angular blocks of brownish rock are perched near the edge of a lower cliff.

3. Several questions about the landscape come to mind. What types of rocks are exposed here? How did the large, brownish blocks get to their present position? How long will it take for the blocks to fall or slide off the lower cliff? Why are there few plants?

4. The answer to each question helps explain part of the scene. The first and last questions are about the *present*, the second is about the *past*, and the third is about the *future*. The easiest questions to answer are usually about the present, and the hardest ones are about the past or the future.

5. All of the rocks in this view are volcanic rocks, typical of those formed during a very explosive type of volcanic eruption. There are few plants because this region is relatively dry and hot (a desert).

6. The large blocks are composed of the same material as the upper brown cliff and were part of that cliff before falling or sliding downhill.

7. It is difficult to predict when the blocks will fall off the lower cliff. Some blocks near the edge could fall in the next rainstorm, but others will probably be there for hundreds of thousands of years.

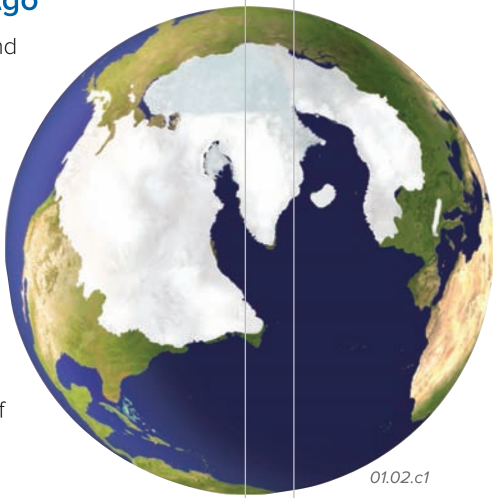
01.02.b1 Superstition Mtns., AZ

C How Has the Global Climate Changed Since the Ice Age?

These computer-generated images show where glaciers and large ice sheets were during the last ice age and where they are today. Note how the extent of these features changed in this relatively short period of time. What caused this change, and what might happen in the future because of global warming or cooling?

28,000 Years Ago

Twenty-eight thousand years ago, Earth's climate was slightly cooler than it is today. Cool climates permitted continental ice sheets to extend across most of Canada and into the upper Midwest of the United States. Ice sheets also covered parts of northern Asia and Europe.



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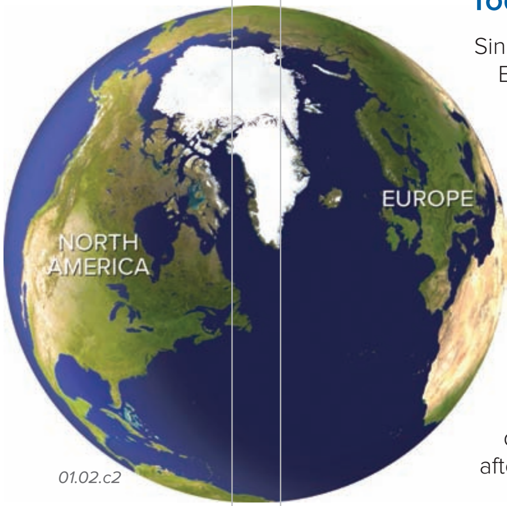


01.02.c2

Today

Since 20,000 years ago, Earth's climate warmed enough to melt back the ice sheets to where they are today. Our knowledge of the past extent of ice sheets comes from earth scientists who examine the landscape for appropriate clues, including glacial features and deposits that remained after the glaciers retreated.

D What Is the Evidence That Life in the Past Was Different from Life Today?

Museums and action movies contain scenes, like the one below, of dinosaurs lumbering or scampering across a land covered by exotic plants. Where does the evidence for these strange creatures come from?

▶ This mural, painted by artist Karen Carr, is two stories tall and shows what types of life are interpreted to have been on Earth during the Jurassic Period, approximately 160 million years ago. Dinosaurs roamed the landscape, while the ancestors of birds began to take flight. Flowering plants were not yet abundant and grasses had not yet appeared, so non-flowering trees, bushes, and ground cover dominated the landscape.

01.02.d1

01.02.d2 Dinosaur NP, UT

◀ Fossil bones of Jurassic dinosaurs are common in Dinosaur National Park, Utah. From such bones and other information, we can infer how long ago these creatures roamed the planet, what the creatures looked like, how big they were, how they lived, and why they died. Studying the rock layers that enclose the bones provides clues to the local and global environments at the time of the dinosaurs. Rocks and fossils are the record of past geologic events, environments, and prehistoric creatures.

Before You Leave This Page

- ✓ Explain the difference in appearance between continents and oceans.
- ✓ Describe some things we can learn about Earth's past by observing its landscapes, rocks, and fossils.

1.2

resize photo

1.3 What Forces and Processes Affect Our Planet?

EARTH IS SUBJECT TO VARIOUS FORCES. Some forces arise within Earth, and others come from the Sun and Moon. Especially important is gravity, the mutual attraction that any two objects exert on one another. The interactions between these forces and Earth's land, water, air, and inhabitants control most natural processes and influence our lives in many ways.

CINDY: ADD COSMIC RAYS AND UPDATE WIND ARROW

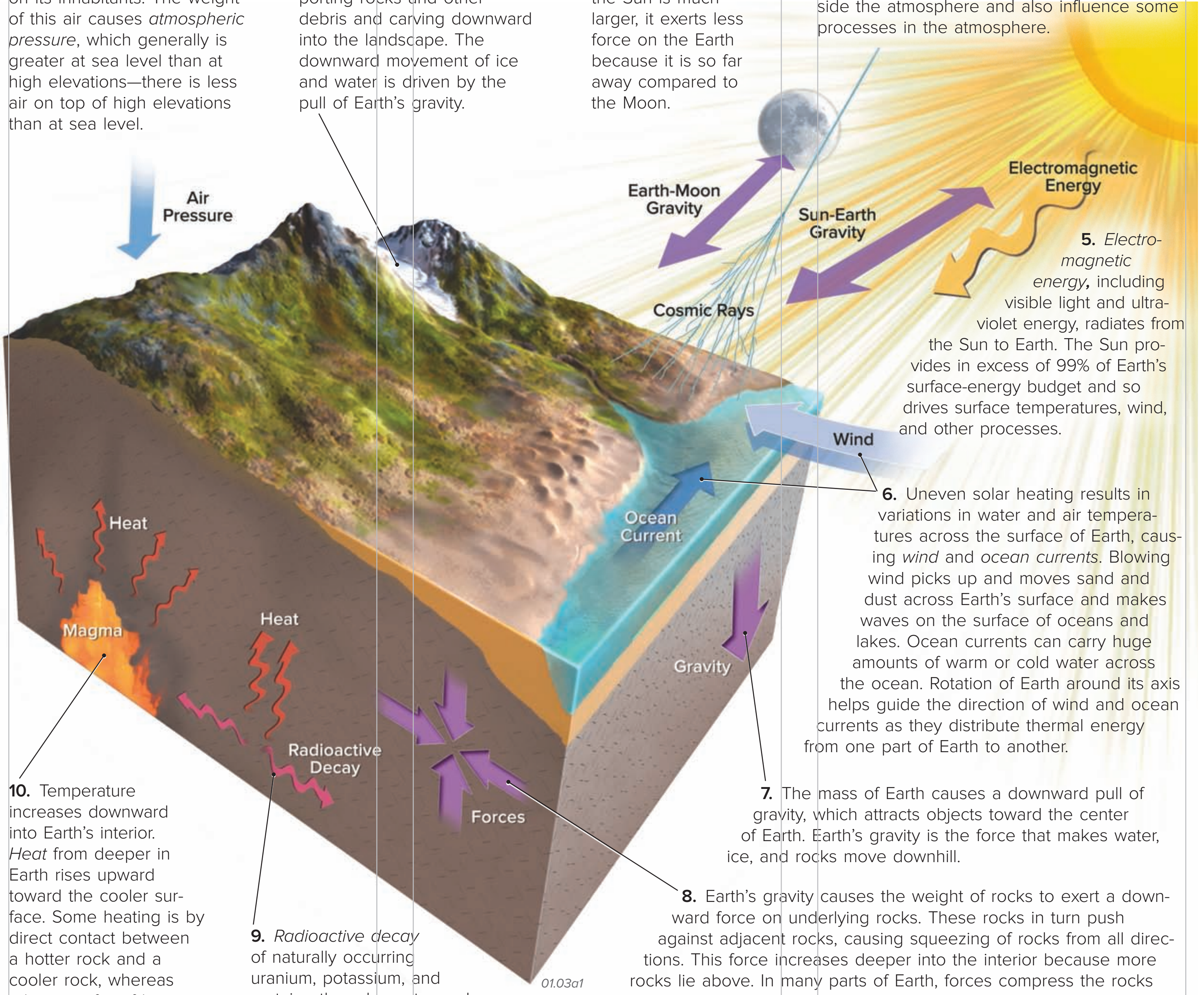
A How Do Forces and Processes Affect Earth?

1. Earth's *gravity* causes air in the atmosphere to press down on Earth's surface and on its inhabitants. The weight of this air causes *atmospheric pressure*, which generally is greater at sea level than at high elevations—there is less air on top of high elevations than at sea level.

2. *Water*, in either liquid or frozen forms, moves downhill in streams and glaciers, transporting rocks and other debris and carving downward into the landscape. The downward movement of ice and water is driven by the pull of Earth's gravity.

3. The Sun and Moon exert a *gravitational pull* on Earth. Although the Sun is much larger, it exerts less force on the Earth because it is so far away compared to the Moon.

4. *Cosmic rays*, high-energy radiation mostly originating deep into the universe, strike the Earth's atmosphere and surface. Cosmic rays pose danger to electronics and people outside the atmosphere and also influence some processes in the atmosphere.



5. *Electromagnetic energy,* including visible light and ultraviolet energy, radiates from the Sun to Earth. The Sun provides in excess of 99% of Earth's surface-energy budget and so drives surface temperatures, wind, and other processes.

6. Uneven solar heating results in variations in water and air temperatures across the surface of Earth, causing *wind* and *ocean currents*. Blowing wind picks up and moves sand and dust across Earth's surface and makes waves on the surface of oceans and lakes. Ocean currents can carry huge amounts of warm or cold water across the ocean. Rotation of Earth around its axis helps guide the direction of wind and ocean currents as they distribute thermal energy from one part of Earth to another.

7. The mass of Earth causes a downward pull of gravity, which attracts objects toward the center of Earth. Earth's gravity is the force that makes water, ice, and rocks move downhill.

8. Earth's gravity causes the weight of rocks to exert a downward force on underlying rocks. These rocks in turn push against adjacent rocks, causing squeezing of rocks from all directions. This force increases deeper into the interior because more rocks lie above. In many parts of Earth, forces compress the rocks equally from all directions, but additional forces arise by other processes deep within Earth, such as from the subsurface movement of rocks and magma. Forces generated in one area can be transferred to an adjacent area, causing sideways pushing, pulling, or shearing on the rocks.

9. *Radioactive decay* of naturally occurring uranium, potassium, and certain other elements produces heat, especially in the crust where these radioactive elements are concentrated.

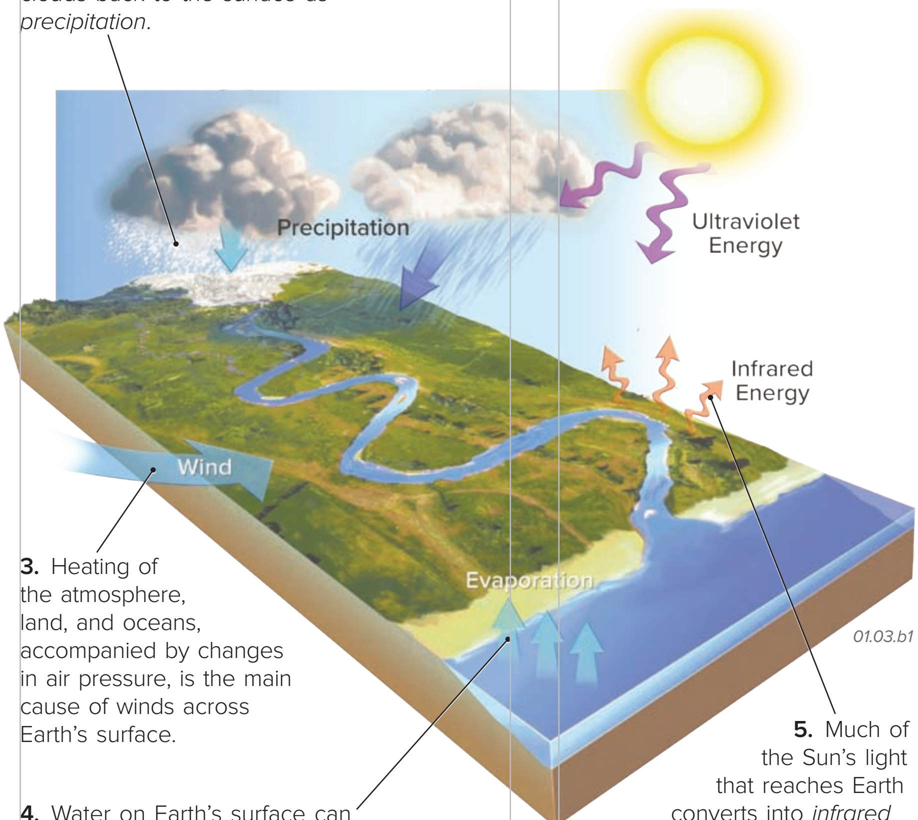
10. Temperature increases downward into Earth's interior. *Heat* from deeper in Earth rises upward toward the cooler surface. Some heating is by direct contact between a hotter rock and a cooler rock, whereas other transfer of heat occurs via a moving material, especially rising molten rock (magma).

B How Do Earth's Surface and Atmosphere Interact with Solar Energy?

Critical interactions occur between radiative energy from the Sun (insolation) and Earth's atmosphere, oceans, and land. These interactions express themselves in wind, clouds, rain, snow, and the climate of an area. Our atmosphere shields Earth from cosmic radiation, transfers water from one place to another, and permits life to exist. Like the oceans, the atmosphere is constantly moving, producing winds, clouds, and storms that impact Earth's surface.

1. The atmosphere is mostly gaseous nitrogen and oxygen, but it includes a low, but important, percentage of water vapor, most of which *evaporated* from Earth's oceans. Under certain conditions, the water vapor condenses to produce clouds, which are made of tiny water droplets or ice crystals. Rain, snow, and hail may fall from clouds back to the surface as *precipitation*.

2. The Sun produces vast amounts of energy, including *ultraviolet radiation* and visible light. In the upper levels of the atmosphere, oxygen absorbs most of the Sun's harmful ultraviolet radiation and prevents it from reaching Earth's surface, where it would have a detrimental effect on many forms of life. Most of the Sun's energy, including light and other forms of radiation, passes through the atmosphere, eventually reaching Earth, warming the planet and providing light for plants and animals.



3. Heating of the atmosphere, land, and oceans, accompanied by changes in air pressure, is the main cause of winds across Earth's surface.

4. Water on Earth's surface can *evaporate***,** becoming water vapor in the atmosphere. Most *water vapor* comes from evaporation in the oceans, but some also comes from evaporation of lakes, rivers, irrigated fields, and other sites of surface water. Some comes from evaporation of water drops in clouds. Plants take moisture from soils, surface waters, or air, and release water vapor into the atmosphere through the process of *evapotranspiration*.

5. Much of the Sun's light that reaches Earth converts into *infrared energy*, a form of energy related to heat. Some of this energy radiates upward and is trapped by the atmosphere, which warms in a process called the *greenhouse effect.* This process regulates global temperatures, which are moderate enough to allow water to exist as liquid water, gaseous water vapor, and solid ice. Water is a key requirement for life.

Energy and Forces

Earth's energy supply originates from internal and external sources. *Internal energy* comes from within Earth and includes heat energy trapped when the planet formed and heat that is produced by radioactive decay. This heat drives many internally generated processes, including mountain building and the melting of rocks at depth to produce magma and volcanoes.

The most significant source of *external energy* is the Sun, which bathes Earth in light, thermal energy, and other electromagnetic energy. Thermal energy and light from the Sun are more intense in equatorial areas of Earth than in polar areas, causing temperature differences in the atmosphere, oceans, and on land. The resulting temperature differences help drive wind and ocean currents. Sunlight is also the primary energy source for plants, through the process of *photosynthesis*.

Early in Earth's history, meteoroids and other objects left over from the formation of the solar system bombarded the planet. During the impacts, *kinetic energy* (energy due to movement of an object) changed into thermal energy, adding a tremendous amount of heat, some of which remains stored in Earth's hot interior.

Internal forces also affect Earth. All objects that have mass exert a gravitational attraction on other masses. If a mass is large and close, the pull of gravity is relatively strong. Earth's gravity acts to pull objects toward the center of the planet. Gravity is probably the most important agent on Earth for moving material from one place to another. It causes loose rocks, flowing glaciers, and running water to move downhill from higher elevations to lower ones, and it drives ocean currents and wind. Moving water, ice, air, and rocks can etch down into Earth's surface, shaping landscapes.

Objects on Earth also feel an *external* pull of gravity from the Sun and Moon. Gravity between the Sun and Earth maintains our planet's orbit around the Sun. The Moon's pull of gravity on Earth is stronger than that of the Sun and causes more observable effects, especially the rise and fall of ocean tides. Many earth scientists and astronomers conclude that long-term changes in Earth's orbit around the Sun and in the tilt of Earth's rotation axis result in large climatic changes, helping start and stop episodes of glaciation.

Before You Leave This Page

- ✓ Describe the different kinds of energy that impact Earth from the outside, and what effects they have on our planet.
- ✓ List the different kinds of energy that arise within Earth's interior and explain their origins.
- ✓ Sketch and explain how Earth's surface and atmosphere interact with solar energy.

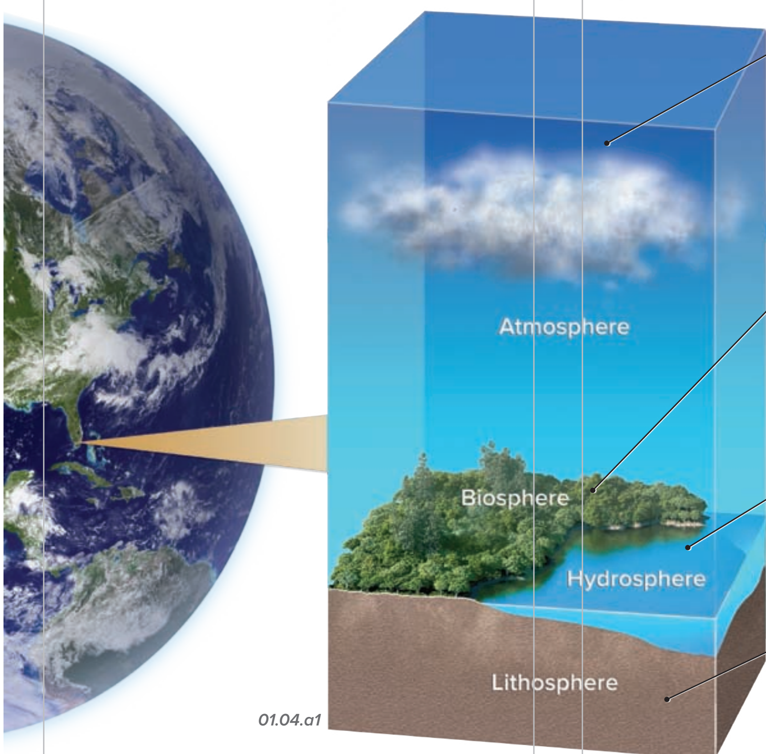
1.3

1.4 How Do Natural Systems Operate?

EARTH HAS A NUMBER OF SYSTEMS in which matter and energy are moved or transformed. These involve processes of the solid Earth, water in all its forms, the structure and motion of the atmosphere, and how these three domains (Earth, water, and air) influence life. Such systems are *dynamic*, responding to any changes in conditions, whether those changes arise internally *within* the system or are imposed externally, from *outside* the system.

A What Are the Four Spheres of Earth?

Earth consists of four overlapping spheres—the atmosphere, biosphere, hydrosphere, and lithosphere—each of which interacts with the other three spheres. The atmosphere is mostly gas, but includes liquids (e.g., water drops) and solids (e.g., ice and dust). The hydrosphere represents Earth's water, and the lithosphere is the solid Earth. The biosphere includes all the places where there is life—in the atmosphere, on and beneath the land, and on and within the oceans.



01.04.a1

1. The *atmosphere* is a mix of mostly nitrogen and oxygen gas that surrounds Earth's surface, gradually diminishing in concentration out to a distance of approximately 100 km, the approximate edge of outer space. In addition to gas, the atmosphere includes clouds, precipitation, and particles such as dust and volcanic ash. The atmosphere is approximately 78% nitrogen, 21% oxygen, less than 1% argon, and smaller amounts of carbon dioxide and other gases. It has a variable amount of water vapor, averaging about 1%, mostly in the lower atmosphere.

2. The *biosphere* includes all types of life (including humans) and all of the places it can exist on, above, and below Earth's surface. In addition to the abundant life on Earth's surface, the biosphere extends about 10 km up into the atmosphere, to the bottom of the deepest oceans, and downward into the cracks and tiny spaces in the subsurface. In addition to visible plants and animals, Earth has a large population of diverse microorganisms.

3. The *hydrosphere* is water in oceans, glaciers, lakes, streams, wetlands, groundwater, moisture in soil, and clouds. Over 96% of water on Earth is salt water in the oceans, and most fresh water is in ice caps, glaciers, and groundwater, not in lakes and rivers.

4. The *lithosphere* refers generally to the solid upper part of the earth, including Earth's crust and uppermost mantle. Water, air, and life extend down into the lithosphere, so the boundary between the solid earth and other spheres is not distinct, and the four spheres overlap.

B What Are Open and Closed Systems?

Many aspects of Earth can be thought of as a system—a collection of matter, energy, and processes that are somehow related and interconnected. For example, an air-conditioning system consists of some mechanical apparatus to cool the air, ducts to carry the cool air from one place to another, a fan to move the air, and a power source. There are two main types of systems: *open systems* and *closed systems*.

01.04.b1 Noxubee NWR, MS

An *open system* allows matter and energy to move into and out of the system. A tree (◀), is an open system, taking in water and nutrients from the soil, extracting carbon dioxide from the air to make the carbon-rich wood and leaves, sometimes shedding those leaves during the winter as shown here, and expelling oxygen as a by-product of photosynthesis, fueled by externally derived energy from the Sun.

A *closed system* does not exchange matter, or perhaps even energy, with its surroundings. The Earth as a whole (▶) is fundamentally a closed system with regard to matter, except for the escape of some light gases into space, the arrival of occasional meteorites, and the exit and return of spacecraft and astronauts. Earth is an open system with regard to energy, which continuously enters and exits the planet.

01.04.b2

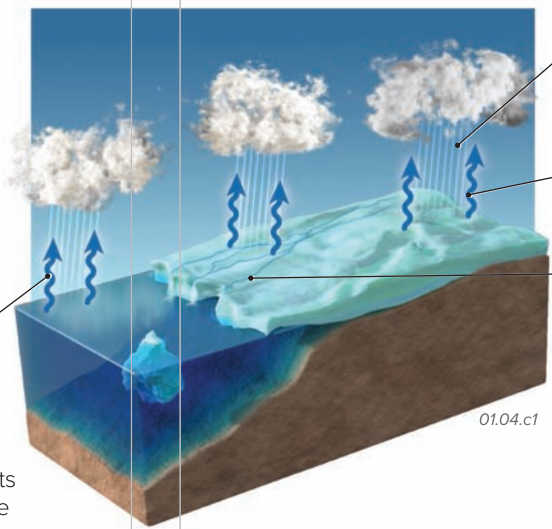
C How Do Earth Systems Operate?

Systems consist of matter and energy, and they respond to internally or externally caused changes in matter and energy, as a tree responds to a decrease in rain (matter) or colder temperatures during the winter (energy). Systems can respond to such changes in various ways, either reinforcing the change or counteracting the change.

System Inputs and Responses

1. One of Earth's critical systems involves the interactions between ice, surface water, and atmospheric water. This complex system, greatly simplified here (▸), remains one of the main challenges for computer models attempting to analyze the causes and possible consequences of climate change.

2. Liquid water on the surface evaporates (represented by the upward-directed blue arrows), becoming water vapor in the atmosphere. If there is enough water vapor, small airborne droplets of water accumulate, forming these low-level clouds.


01.04.c1

3. Under the right conditions, the water freezes, becoming snowflakes or hail, which can fall to the ground. Over the centuries, if snow accumulates faster than it melts, the snow becomes thick and compressed into ice, as in glaciers.

4. The water molecules in snow and ice can return directly to the atmosphere via several processes.

5. If temperatures are warm enough, snow and ice can melt, releasing liquid water that can accumulate in streams and flow into the ocean or other bodies of surface water. Alternatively, the meltwater can evaporate back into the atmosphere. Melting also occurs when icebergs break off from the glacier.

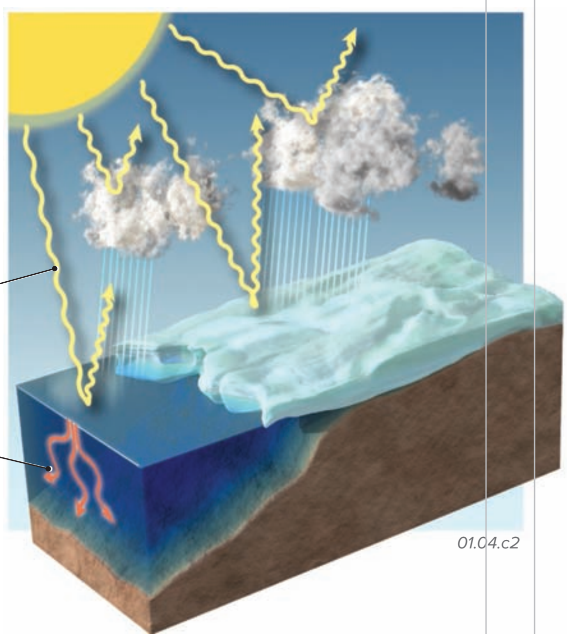
6. The movement of matter and energy carried in the various forms of water is an example of a *dynamic system*—a system in which matter, energy, or both are constantly changing their position, amounts, or form.

Feedbacks

7. The system can respond to changes in various ways, which either can reinforce the effect, causing the overall changes to be more severe, or can partially or completely counteract the effect, causing changes to be less severe. Such reinforcements or inhibitors are called *feedbacks*.

8. In our example, sunlight shines on the ice and water. The ice is relatively smooth and light-colored, reflecting much of the Sun's energy upward, into the atmosphere or into space. In contrast, the water is darker and absorbs more of the Sun's energy, which warms the water.

9. If the amount of solar energy reaching the surface or trapped near the surface increases for whatever reason, this may cause more melting of the ice. As the front of the ice melts back, it exposes more dark water, which absorbs more heat and causes even more warming of the region. In this way, an initial change (warming) triggers a response that causes even more of that change (more warming). Such a reinforcing result is called a *positive feedback*.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10. The warming of the water results in more evaporation, moving water from the surface to the atmosphere. The increase in water vapor may result in more clouds. Low-level clouds are highly reflective, so an increase in cloud cover intercepts more sunlight, leading to less warming. This type of response does not reinforce the change but instead dampens it and diminishes its overall effect. This dampening and resultant counteraction is called a *negative feedback*.

11. As this overly simplified example illustrates, a change in a system can be reinforced by positive feedbacks or stifled by negative ones. Both types of feedbacks are likely and often occur at the same time, each nudging the system toward opposite behaviors (e.g., overall warming or overall cooling). Feedbacks can leave the system largely unchanged, or the combined impact of positive and negative feedbacks can lead to a stable but gradually changing state, a condition called *dynamic equilibrium.*

Before You Leave This Page

- ✓ Describe Earth's four spheres.
- ✓ Explain what is meant by open and closed systems.
- ✓ Sketch and explain examples of positive and negative feedbacks.

1.5 What Are Some Important Earth Cycles?

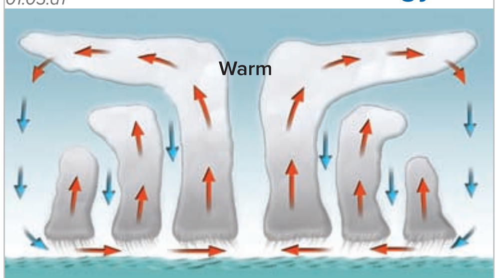
MATTER AND ENERGY MOVE within and between each of the four spheres. A fundamental principle of all natural sciences is that energy and matter can be neither created nor destroyed, but only transferred from one form to another. Also, energy and matter tend to become dispersed into a more uniform spatial distribution. As a result, matter and energy are stored, moved, dispersed, and concentrated as part of dynamic earth systems, where material and energy move back and forth among various sites within the four spheres.

A How Are Energy and Matter Moved in the Atmosphere?

Atmospheric processes involve the redistribution of *energy* and *matter* from one part of the atmosphere to another. The processes by which this occurs cause various types of weather and other phenomena described elsewhere in this book.

Energy

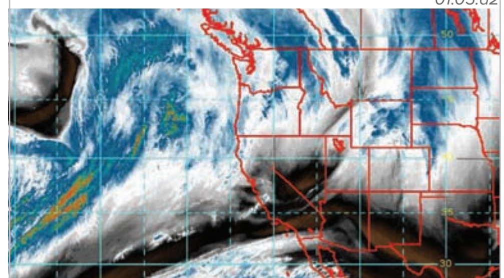
01.05.a1



Storage and transfer of energy are the drivers of Earth's climate and weather. Energy can be moved from one part of the atmosphere to another, such as by air currents associated with storms (◀). Also, energy is released or extracted from the local environment when water changes from one state of matter to another, such as from a liquid to a gas during evaporation.

Matter

01.05.a2



Water in all of its forms, along with other matter, moves globally and tends to disperse, but other factors prevent an even spatial distribution. As a result, some regions, like here in the western U.S., are more humid and cloudy than others, as shown in this satellite image of water vapor (blue is more, brown is less). Water can also cycle between vapor, liquid, and solid states.

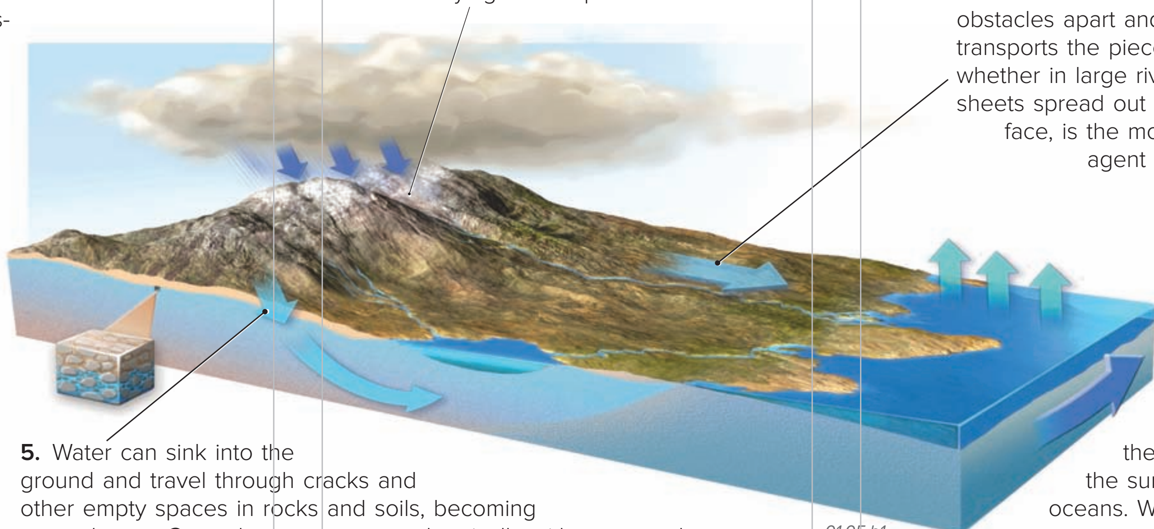
B How Are Matter and Energy Moved in the Hydrosphere?

Many processes in the Earth occur as part of a cycle, a term that describes the movement of matter and energy between different sites in Earth's surface, subsurface, and atmosphere. The most important of these is the *hydrologic cycle*, which involves local- to global-scale storage and circulation of water and associated energy near Earth's surface.

1. Water vapor in the atmosphere can condense to form drops, which can remain suspended in the air as clouds or can fall to the ground as *precipitation*. Once on the surface, water can coat rocks and soils, and it causes the solid earth materials to dissolve, decompose, and erode.

2. When winter snows don't melt completely, as is common at higher elevations and at polar latitudes, ice accumulates in glaciers, which are huge, flowing fields of ice. Glaciers transport sediment and carve the underlying landscape.

3. Moving water on the surface can flow downhill in *streams*, encountering obstacles like solid rock and loose debris. The flowing water and the material it carries breaks these obstacles apart and picks up and transports the pieces. Flowing water, whether in large rivers or in thin sheets spread out across the surface, is the most important agent for sculpting Earth.



01.05.b1

4. The uppermost part of oceans is constantly in motion, partly due to friction between winds in the atmosphere and the surface of the oceans. Winds in the oceans cause waves that erode and shape shorelines, especially during powerful storms.

5. Water can sink into the ground and travel through cracks and other empty spaces in rocks and soils, becoming *groundwater*. Groundwater can react chemically with some rocks through which it flows, dissolving or depositing material. It typically flows toward lower areas, where it may emerge back on Earth's surface as springs.

6. Water evaporates from the oceans, surface waters on land, and from soils and plants, returning to the atmosphere and completing the hydrologic cycle. Phase changes between a solid, liquid, and gas also involve the exchange of energy.

CINDY: I resized and stretched this vertically, like the geology version

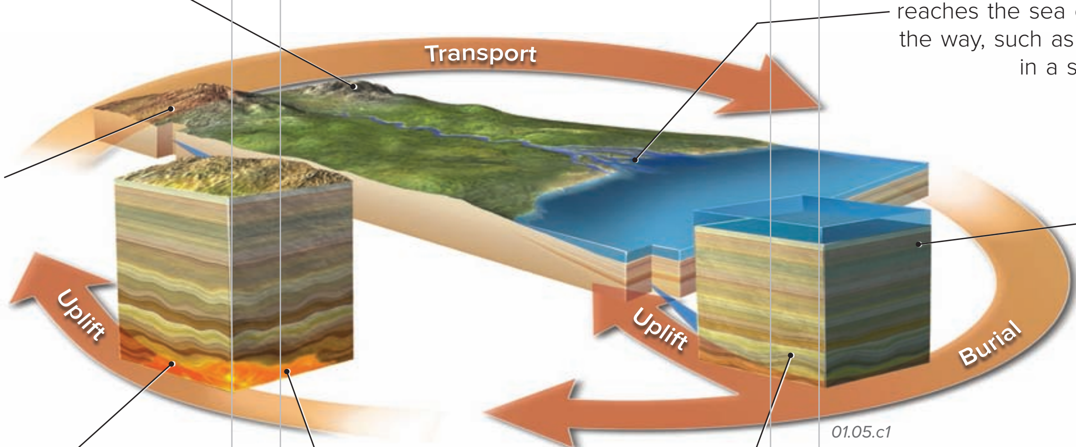
C How Does the Rock Cycle Affect Materials of the Lithosphere?

Rocks and other solid materials are moved on Earth's surface and subsurface. The *rock cycle*, summarized below and discussed in more detail later, describes the movement of earth materials on and below Earth's surface at timescales from seconds to billions of years, involving such processes as erosion, burial, melting, and uplift of mountains.

1. *Weathering:* Rock is broken apart into pieces or can be altered by chemical reactions when exposed to sunlight, rain, wind, plants, and animals at or near the surface. This weathering creates loose pieces of rock called *sediment*.

2. *Erosion and Transport:* Sediment is then stripped away by *erosion,* and *transported* (moved) by gravity, glaciers, flowing water, or wind.

3. *Deposition:* After transport, the sediment is laid down, or *deposited* when it reaches the sea or at any point along the way, such as beside the stream or in a sand dune.



01.05.c1

4. *Burial and Formation of Rock:* Sediment is eventually buried, compacted by the weight of overlying sediment, and perhaps cemented together by chemicals in the water to form a hard *sedimentary rock*.

5. *Deformation and Related Processes:* Rock can be subjected to strong forces that squeeze, bend, and break the rock, causing it to *deform*. The rock might also be heated and deformed so much that it is changed (*metamorphosed*) into a new kind of rock, called a *metamorphic rock*.

6. *Melting:* A rock exposed to high temperatures may melt and become molten, forming a mass of magma, which can remain in place or rise toward the surface.

7. *Solidification:* As magma cools, either at depth or after being erupted onto the surface, it begins to crystallize and solidify into rock. A rock formed by solidification of magma is an *igneous rock*.

8. *Uplift:* Rock may be uplifted back to the surface where it is again exposed to weathering.

D What Cycles and Processes Are Important in the Biosphere?

The biosphere includes life and all of the places it exists. It overlaps the atmosphere, hydrosphere, and lithosphere, extending from more than 10 km above the surface to more than 10 km beneath sea level, both on the seafloor and within Earth's subsurface. Life interacts with the other three spheres, forming a number of important cycles.

1. *Atmosphere*: Plants exchange gases with the atmosphere. They extract carbon dioxide (CO_2) from the atmosphere and use the carbon for their leaves, stems, roots, spines, and other leafy or woody parts. Plants also release oxygen, a key ingredient in life. Life on Earth is currently the main source of the oxygen and CO_2 in the atmosphere.

2. *Hydrosphere*: Life interacts with the hydrologic cycle. Plants take in water from the rocks and soil, which may have arrived from lakes and other bodies of surface water, or directly from the atmosphere, as during precipitation. Plants then release some water back into the environment. The Sun is the ultimate source of energy for photosynthesis, as well as for movement of matter and energy in the atmosphere and for most movement of material on Earth's surface.

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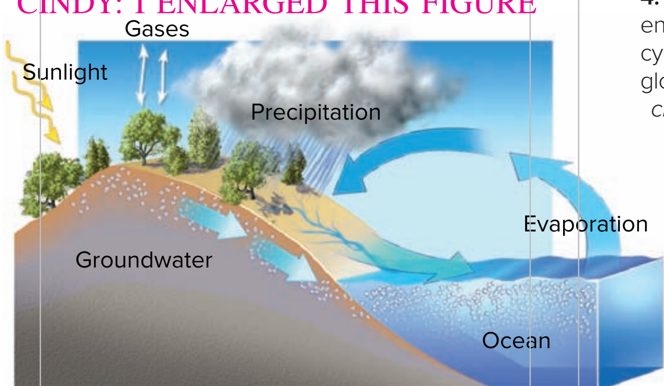


01.05.d1

3. *Lithosphere*: Life also interacts with aspects of the rock cycle. Plants help break down materials on Earth's surface, such as when a plant's roots push open fractures in rocks and soil. Plants help stabilize soils, inhibiting erosion by slowing down the flow of water. The slowed water remains in contact with rocks and soil longer, increasing the rate at which weathering breaks down materials. Organisms can also add material to the lithosphere, such as when corals, sponges, and other organisms build a coral reef.

4. *Biogeochemical Cycles*: Water, nutrients, and other materials are stored and cycled through the biosphere, at local to global scales. We use the term *biogeochemical cycle* to indicate that plants, animals, and bacteria, in addition to chemical and physical processes, are involved in the cycling of a chemical substance through different parts of the environment. For example, the movement of carbon between the biosphere, atmosphere, hydrosphere, and lithosphere is known as the *carbon cycle*.

Before You Leave This Page

- ✓ Describe some examples of transfer of energy and matter in the atmosphere.
- ✓ Sketch and describe the hydrologic cycle, rock cycle, and how the biosphere exchanges matter with the other spheres.

1.5

1.6 How Do Earth's Four Spheres Interact?

EARTH'S DYNAMIC SYSTEMS move energy and matter between the land, water, atmosphere, and biosphere—between the four spheres. There are various expressions of these interactions, many of which we can observe in our daily lives. In addition to natural interactions, human activities, such as the clearing of rain forests, can affect interactions between the spheres. Changes in one component of one sphere can cause impacts that affect components of other spheres.

A What Are Some Examples of Energy and Matter Exchanges Between Two Spheres?

The four spheres interact in complex and sometimes unanticipated ways. As you read each example below, think of other interactions—observable in your typical outdoor activities—that occur between each pair of spheres.

Atmosphere-Hydrosphere

01.06.a1 Indonesia

The Sun's energy evaporates water from the ocean and other parts of the hydrosphere, moving the water molecules into the atmosphere. The water vapor can remain in the atmosphere or can condense into tiny drops that form most clouds. Under the right conditions, the water returns to the surface as precipitation, usually rain or snow.

Atmosphere-Lithosphere

01.06.a2 Mount Veniaminof, AK

Active volcanoes emit gases into the atmosphere, and major eruptions release huge quantities of steam, sulfur dioxide, carbon dioxide, and volcanic ash. In contrast, weathering of rocks removes gas and moisture from the atmosphere. Precipitation accumulates on the land, where it can form standing water, groundwater, or erosion-causing runoff.

Atmosphere-Biosphere

01.06.a3 Indonesia

Plants and animals exchange carbon with the atmosphere in the form of CO_2, and use precipitation from the atmosphere. Some plants can extract moisture directly out of the air without precipitation. Large-scale circulation patterns in the atmosphere influence an area's climate, which controls the types of plants and animals that inhabit a region.

Hydrosphere-Lithosphere

01.06.a4 Glacier Parkway, Alberta, Canada

Channels within a stream generally bend back and forth as the water flows downhill. The water is faster and more energetic in some parts of the stream than in others, and erodes into the streambed and riverbank. In less energetic sections, sediment will be deposited on the bed, like the gravel in this photograph. The flowing water can dissolve soluble materials in bedrock along the channel or in loose stream sediment, and carry away the liberated chemical constituents.

Hydrosphere-Biosphere

01.06.a5 Indonesia

Oceans contain a diversity of life, from whales to algae, and everything in between. Coral reefs, shown above, represent an especially life-rich environment formed when living organisms extract materials dissolved in or carried by seawater to produce the hard parts of corals, shells, and sponges. At greater ocean depths, where waters are colder, shells and similar biologic materials dissolve, transferring material back to the seawater.

Lithosphere-Biosphere

01.06.a6 Near Badlands National Park, SD

The clearest interaction between the lithosphere and biosphere is the relationship between plants and soils. The type of soil helps determine the type of plants that can grow, and in turn depends on the type of starting materials (rocks and sediment), the geographic setting of the site (e.g., slope versus flat land), climate, and other factors. Plants remove nutrients from the soil but return material back to the soil through roots, annual leaf fall, or plant death and decay.

B To What Extent Do Humans Influence Interactions Between the Spheres?

Anyone who has flown in an airplane or viewed the landscape from a hill or building appreciates the amazing amount of human influence on the landscape. The intent of development is almost always to improve the human condition, but the complex chain reaction of impacts that cascade through the system can cause unintended and often harmful impacts elsewhere in one or more of the four spheres, as illustrated in the examples below. Some consequences of human impacts are not felt immediately but only appear much later, after the activity has continued for many years.

01.06.b1

Humans clear forests, a critical part of the biosphere, to provide lumber and grow food. In addition to the loss of habitat for plants and animals, deforestation reduces the amount of CO_2 that can be extracted out of the atmosphere and stored in the carbon-rich trunks, branches, and leaves of plants. Removing plant cover also causes increased runoff, which enhances soil erosion and leads to the additional loss of plant cover—an unintended consequence and a positive feedback.

01.06.b2 Grand Coulee Dam, WA

Over 80,000 dams exist in the U.S., providing water supplies, generating electricity, protecting towns from flooding, and providing recreational opportunities. Dams also alter the local water balance by interrupting the normal seasonal variations in flows of water and by capturing silt, sand, wood, and other materials that would normally go downstream. Construction and filling of the reservoir disrupts ecosystems, displaces people, and threatens or destroys plant and animal communities.

01.06.b3 Phoenix, AZ

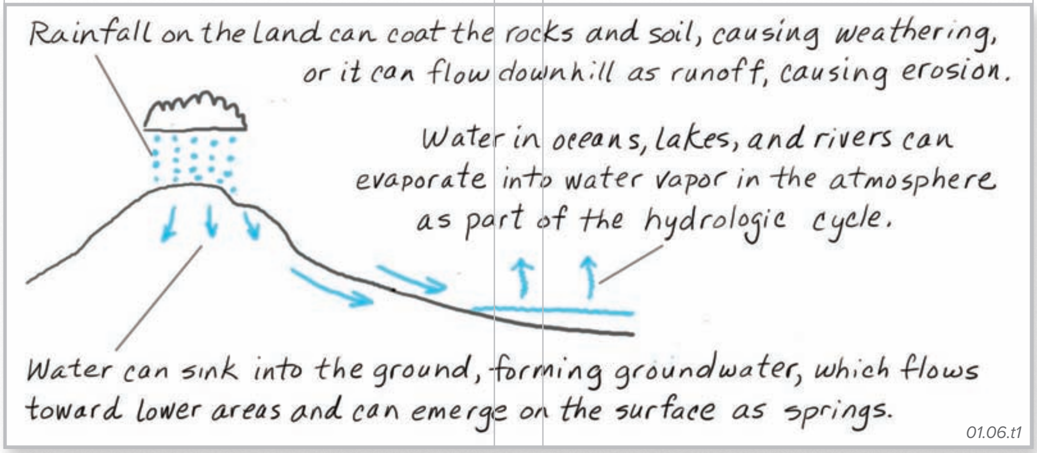
Local warming of the atmosphere occurs near cities because of normal urban activities (lighting, heating, etc.) and because many urban materials, like dark asphalt, capture and store more heat than natural open space. Heat is also released from car exhausts and industrial smokestacks. Non-natural drainage systems cause rapid accumulation and channeling of water. Development infringes on natural plant and animal communities, disturbs or covers soil, and alters erosion rates.

Learning with Concept Sketches

Earth science is a very visual science, relying on photographs, graphs, and many types of illustrations to show features and processes, and to represent how various earth systems operate. Suppose you wanted to summarize some of the interactions between Earth's spheres, as in the hydrologic cycle (introduced earlier in the book), which describes movement of water on our planet. It can be difficult to keep track of all the processes that are occurring, such as precipitation, runoff, and evaporation. We have a great suggestion to help you learn, retain, and apply any new information—construct a concept sketch!

A concept sketch, like the one shown below, is a simplified sketch annotated with labels and complete sentences that describe the features, processes, and relationships between different aspects. By constructing a concept sketch, you are putting the information into your own words and drawings. Research and our experience with teaching thousands of students show that this process greatly aids learning and improves student performance in the classroom, in labs, and on field trips.

To construct a concept sketch, begin by listing the important features, processes, and relationships you want to describe. Then, decide what features you need to show on your sketch in order to represent these features, processes, and relationships. Draw your sketch and write complete sentences describing the sketch, including labels and leader lines as needed. Try it—you will learn more and get better grades!



Before You Leave This Page

- ✓ Provide an example of an interaction between each pair of spheres.
- ✓ Describe examples of how humans can affect the natural system in each of the four spheres.
- ✓ Produce a concept sketch for some earth system in this chapter.

1.6

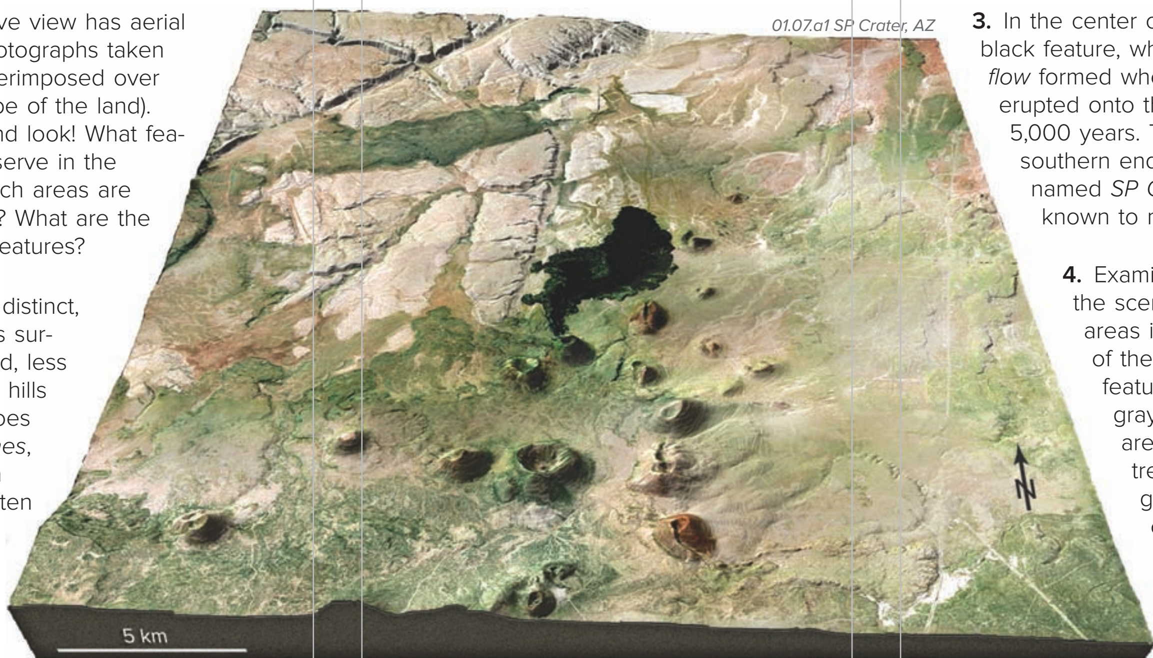
1.7 How Do We Depict Earth's Surface?

THE SURFACE OF EARTH displays various features, including mountains, hillslopes, and river valleys. We commonly represent such features on the land surface with *topographic maps* and *shaded-relief maps*. To depict the types of materials on Earth's surface, we use *satellite images* and *geologic maps*. A geologic map is the most important piece of geologic information for an area, because it shows the ages and types of rocks and sediment, as well as geologic features, some of which could pose a natural hazard.

A How Do Maps and Satellite Images Help Us Study Earth's Surface?

Satellite images and various types of maps are the primary ways we portray the land surface. Some maps depict the shape and elevation of the land surface, whereas others represent the materials on that surface. Views and maps of *SP Crater* in northern Arizona provide a particularly clear example of the relationship between geologic features, the land surface, and different types of maps.

01.07.a1 SP Crater, AZ



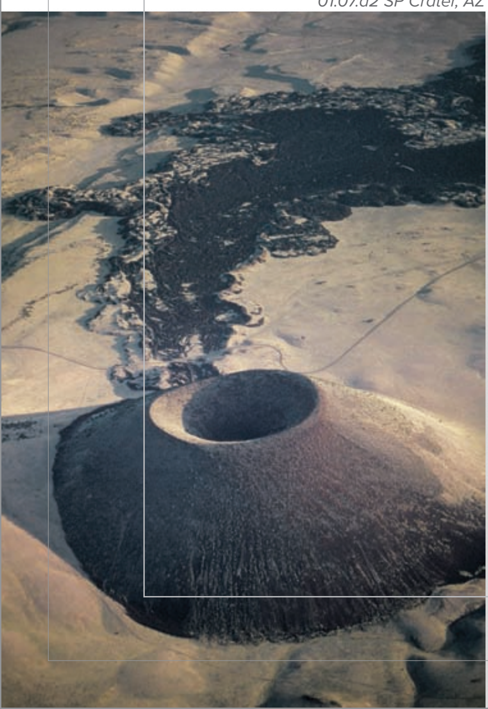
1. This perspective view has aerial photography (photographs taken from the air) superimposed over topography (shape of the land). Take a minute and look! What features do you observe in the topography? Which areas are high in elevation? What are the most distinctive features?

2. The area has distinct, cone-shaped hills surrounded by broad, less steep areas. The hills are small volcanoes called *scoria cones*, which form when fragments of molten rock are ejected into the air and settle around a volcanic vent.

3. In the center of the area is a nearly black feature, which is a solidified *lava flow* formed when fluid magma erupted onto the surface in the last 5,000 years. The scoria cone at the southern end of the lava flow is named *SP Crater*, and is well known to most geologists.

4. Examine other features in the scene. Note the light-gray areas in the upper left parts of the image, and the linear features that cut across the gray rocks. This entire area is dry, with few trees to obscure the geology. There is a clear correspondence between the topographic and geologic features.

01.07.a2 SP Crater, AZ



01.07.a3 SP Crater, AZ

5. This photograph (▲), taken from the large crater south of SP Crater, shows the crater (on the left) and several other scoria cones. The view is toward the north.

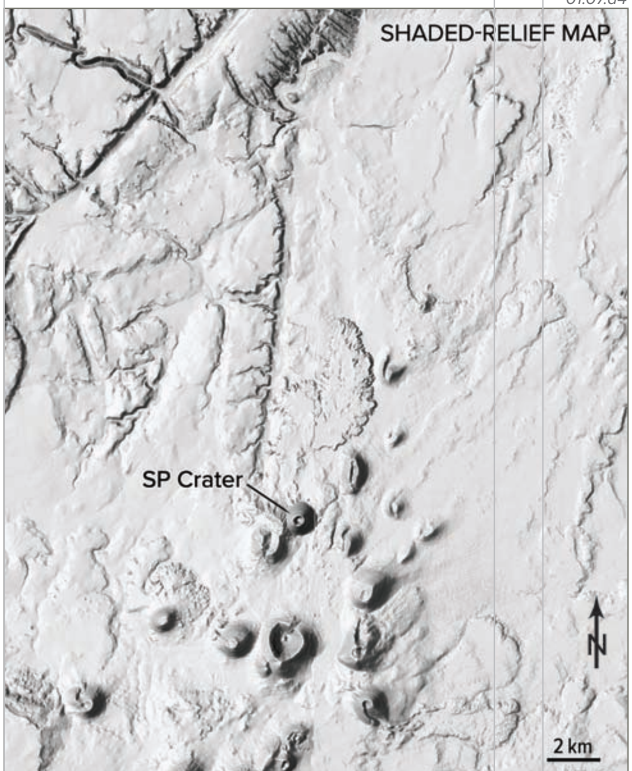
6. This photograph (◄), taken from the air, shows SP Crater and the dark lava flow that erupted from the base of the volcano.

Before You Leave These Pages

- ✓ Describe how each of the four types of maps and images depicts Earth's surface.
- ✓ Describe what contours on a topographic map represent and how contour spacing indicates the steepness of a slope.
- ✓ Briefly describe what a geologic map shows, using the area around SP Crater as an example.

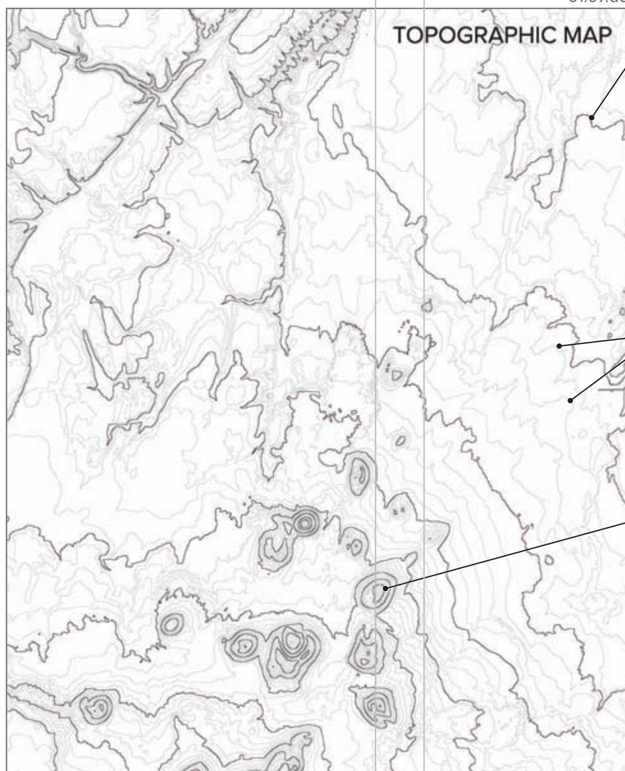
7. A *shaded-relief map* (▼) emphasizes the shape of the land by simulating light and dark shading on the hills and valleys. The individual hills on this map are *scoria cones*. The area is cut by straight and curving stream valleys that appear as gouges in the landscape. Simulated light comes from the upper left corner of the image.

01.07.a4



8. A *topographic map* (▼) shows the elevation of the land surface with a series of lines called *contours*. Each contour line follows a specific elevation on the surface. Standard shaded-relief maps and topographic maps depict the shape of the land surface but give no specific information about the types of earth materials on the surface.

01.07.a5



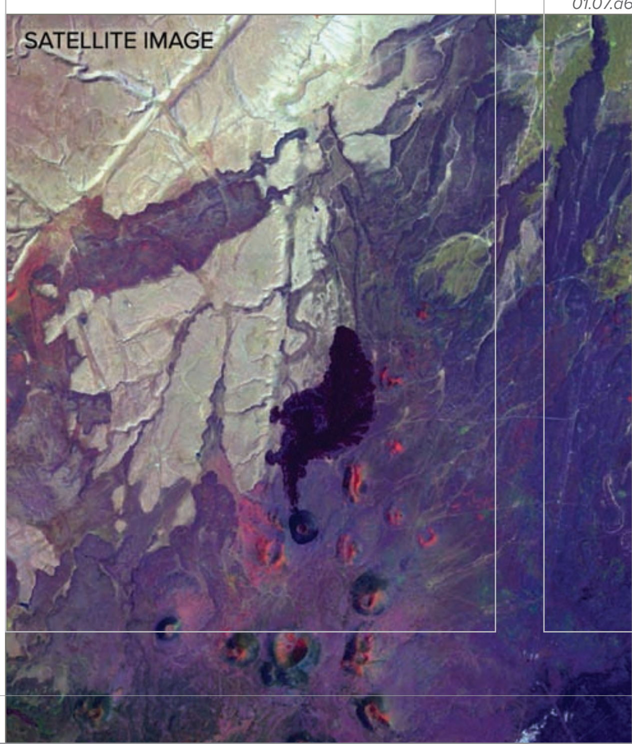
9. Most topographic maps show every fifth contour with a darker line, to help emphasize the broader patterns and to allow easier following of lines across the map. These dark lines are called *index contours*.

10. Adjacent contour lines are widely spaced where the land surface is fairly flat (has a gentle slope).

11. Contour lines are more closely spaced where the land surface is steep, such as on the slopes of the scoria cones. Note how the shapes of the contours reflect the shapes of the different scoria cones.

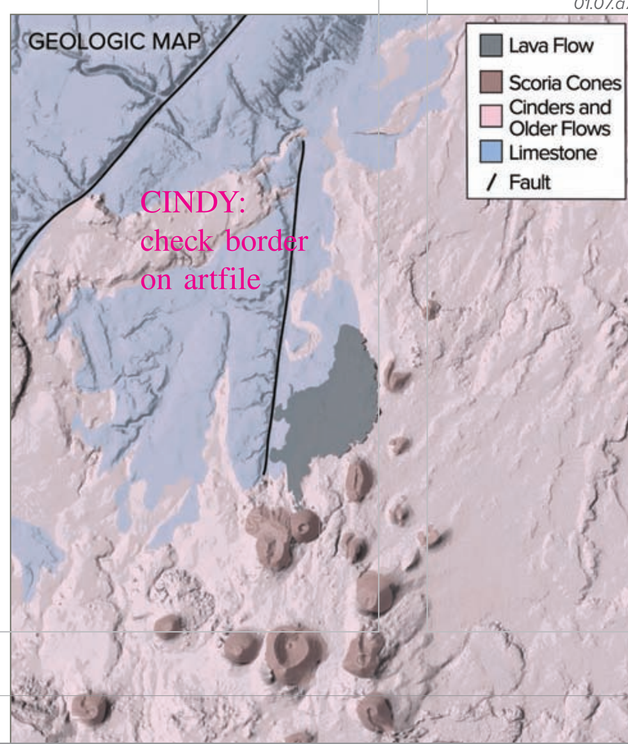
12. A *satellite image* (▼) commonly uses measurements of different wavelengths of light reflecting from a land surface. The computer-processed image below shows the distribution of different types of plants, rocks, and other features. The dark area in the center of the image is the black, solidified lava flow that erupted from the base of SP Crater, and reddish areas are scoria cones.

01.07.a6



13. A *geologic map* (▼) represents the distribution of rock units and geologic features exposed on the surface. This one shows SP Crater and its associated lava flow and older rock units. Compare the colored areas on this geologic map with the different areas visible on the satellite image to the left. Each color on this geologic map represents areas that have a certain type of rock or feature.

01.07.a7



14. The gray area in the center of the map marks the SP lava flow, and light pinkish-brown areas are scoria cones. Light pink represents volcanic cinders and older lava flows. Lavender indicates areas with light-colored rock (limestone) at the surface.

15. Compare the four maps to match specific features of the area. Which map or image gives you the best information about the shape of the landscape, and which gives you the best information about geology?

1.8 How Do We Depict Earth's Heights, Slopes, and Subsurface Aspects?

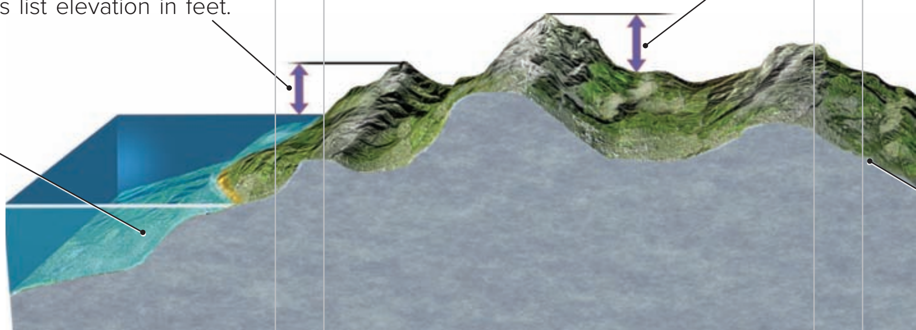
DIAGRAMS OF THE LAND SURFACE AND THE SUBSURFACE are essential tools for visualizing and understanding Earth. We use two-dimensional and three-dimensional diagrams to depict the steepness of slopes, the thickness and subsurface geometry of rock units, and how these units interact with the surface. Some diagrams show interpretations of how present-day landscapes formed via a sequence of geologic events.

A How Do We Refer to Differences in Topography?

Earth's surface is not flat and featureless but instead has high and low parts. The variation in the height and steepness of the land—that is, the shape of the land—is called *topography*. Topography is steep in some areas but nearly flat in others. We use common terms to refer to the height of the land and the steepness of slopes.

1. The height of a feature above sea level is its *elevation*. Scientists describe elevation in *meters* or *kilometers* above sea level, but some maps and most signs list elevation in feet.

2. Beneath water, we talk about ***depth***, generally expressing it as depth below sea level. We use *meters* for shallow depths and *kilometers* for deep ones.



01.08.a1

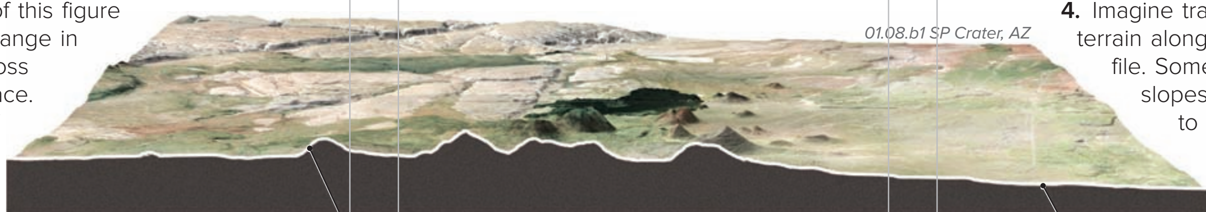
3. We also refer to the height of a feature above an adjacent lower area. The difference in elevation of one feature relative to another is ***topographic relief***. Like elevation, we measure relief in meters or feet; we refer to rugged areas as having *high relief* and to topographically subdued areas as having *low relief*.

4. Cliffs and slopes that drop sharply in elevation are *steep* slopes, whereas topography that is less steep is referred to as being *gentle*, as in a gentle slope.

B How Do We Represent Topographic Slopes?

We can depict steepness of the land surface with an imaginary slice through a terrain, like one through SP Crater and its surroundings (▼). This type of portrayal of ups and downs of the land surface is a *topographic profile*.

1. The front of this figure shows the change in elevation across the land surface. It is a type of topographic profile.



01.08.b1 SP Crater, AZ

4. Imagine traveling across this terrain along the line of the profile. Some parts (the gentle slopes) are relatively easy to travel across, whereas the steep slopes require more effort.

2. Steeper parts of the profile represent steep slopes on the sides of the small volcanoes. There is moderate relief between the peaks and surrounding plains.

3. Other parts of the profile are less steep, including lower elevation plains surrounding the volcanoes. There is only low relief from one part of the plains to another.

5. Some topographic profiles are simple plots of height of the topography versus distance across the land, like the black line that traces a profile across SP Crater (▶). The profile runs from west (on the left) to east (on the right), so it is an east-west profile. Most topographic profiles have such directions labeled directly on the plot, along with scales for elevation and for horizontal distances.

01.08.b2 SP Crater, AZ

6. We describe steepness of a slope in *degrees* from horizontal. The eastern slope of SP Crater has a 26-degree slope (26° slope). We also talk about *gradient*—a 26° slope drops 480 meters over a distance of 1,000 meters (one kilometer), which is typically expressed as 0.48, or 480 m/1,000 m.

C How Do We Represent Features in the Subsurface?

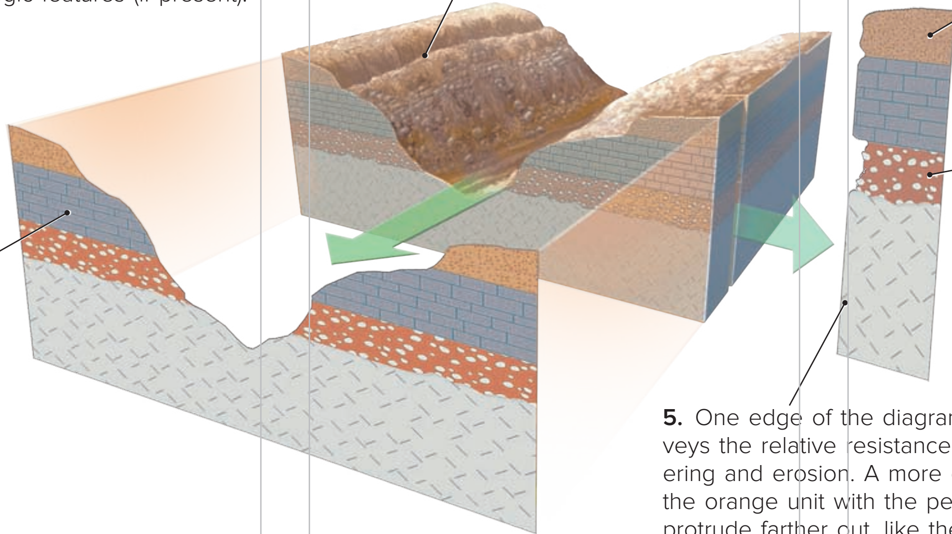
Most of our planet's geology is beneath Earth's surface, hidden from view. We are most aware of rock units and other earth materials if they are exposed in a natural exposure (an *outcrop*) on a mountainside or in a deep canyon, or perhaps in a roadside cut created during road construction (a *roadcut*). However, such units are also present beneath areas of relatively gentle topography that lack any natural or human-created exposures. To portray the surface and subsurface, we use diagrams, many specialized to earth science, to envision and understand the thicknesses, orientations, and subsurface distributions of materials. Such diagrams are important ways earth scientists document and communicate their understanding of an area.

Block Diagram

1. A *block diagram* portrays in three dimensions the shape of the land surface and the subsurface distributions of rock units. It also shows the location and orientation of faults, folds, and other geologic features (if present).

Cross Section

2. A *cross section* shows surficial and subsurface features as a two-dimensional slice through the land. This example is equivalent to the front-left side of the block diagram.



01.08.c1

Stratigraphic Section

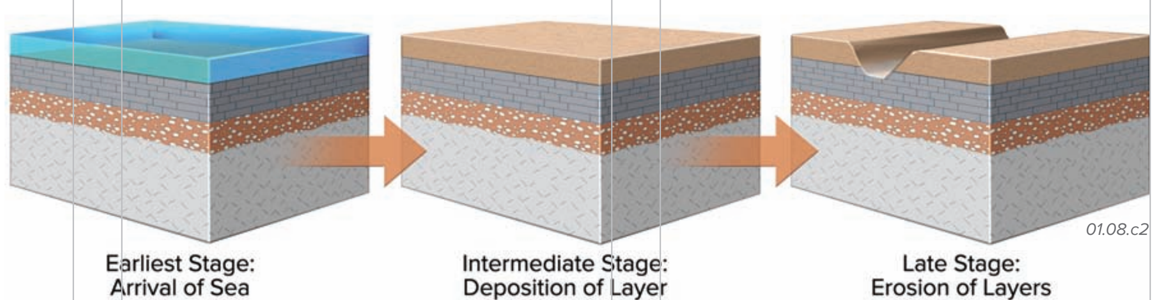
3. A *stratigraphic section* shows the rock units stacked on top of one another (with appropriate relative thicknesses).

4. Commonly, the patterns within each rock unit visually represent the character of the unit, such as the blocky fractures in the gray unit or the rounded pebbles in this orange-colored sedimentary unit.

5. One edge of the diagram (here the left edge) typically conveys the relative resistance of the different rock units to weathering and erosion. A more easily eroded unit is recessed, like the orange unit with the pebbles, whereas more resistant units protrude farther out, like the two gray units.

Evolutionary Diagrams

6. *Evolutionary diagrams* (▶) are block diagrams, cross sections, or maps that show the history of an area as a series of steps, proceeding from the earliest stages to the most recent one. Here, the upper tan rock layer depicted in the figures above is deposited on the gray layer and later eroded.

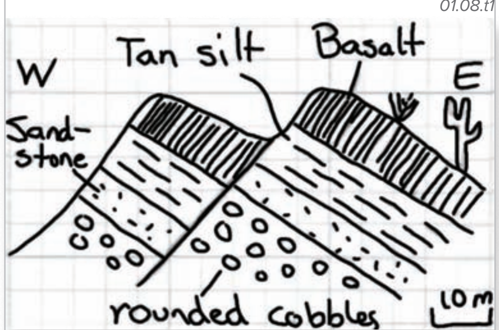


01.08.c2

Sketching the Earth

A challenge of earth science is trying to visualize how features exposed at the surface continue at depth. Sketches drawn in the field while studying landscapes and other natural features capture one's thoughts while they are still fresh and while ideas can be tested by making additional field observations. The sketch to the right is a simplified cross section drawn to summarize field relationships for some offset rock layers. A sketch is an excellent way to conceptualize and think about earth science—whether in the field, on a boat, looking through a telescope, or reading a textbook—because it highlights the most important features.

01.08.t1



Before You Leave This Page

- ✓ Sketch and describe what we mean by elevation, depth, relief, and slope.
- ✓ Sketch or describe the types of diagrams earth scientists use to represent subsurface geology and the sequence of rock units.
- ✓ Sketch or describe what is shown by a series of evolutionary diagrams.

1.9 How Do We Describe Locations on Earth?

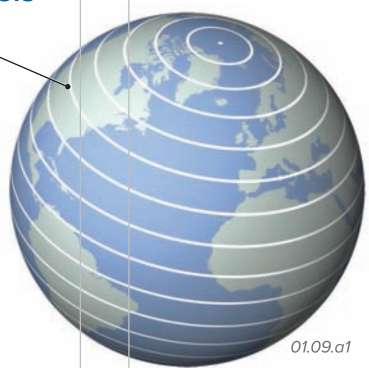
TO DESCRIBE LOCATION ON A SPHERE, we need a frame of reference—some specific features from which to reference any location. For Earth, that frame of reference involves the equator, the center of the Earth, and an imaginary north-south line through England. Using this frame of reference, we can devise systems of imaginary gridlines that encircle the Earth. The most commonly used imaginary gridlines are *latitude* and *longitude*, which are displayed on many maps and are provided by the location capabilities of many cellular phones.

A How Do We Represent Locations on a Globe?

If you were trying to convey the location of a specific place on a sphere, or the location of a city on our nearly spherical planet, a good place to begin visualizing the problem is to establish a framework of imaginary gridlines. Another important aspect is to consider how lines and planes interact with a sphere.

Parallels

1. We could draw lines that circle the globe, each staying the same distance from the North Pole or South Pole. The lines are parallel to one another and remain the same distance apart, and so are called *parallels*. In addition, these lines are parallel to imaginary cuts through the Earth, perpendicular to Earth's spin axis (which goes through the North and South poles). The parallel that is halfway between the North and South poles is the *equator*.



01.09.a1

Meridians

01.09.a2

3. Lines that encircle the globe from North Pole to South Pole are called *meridians*. Meridians do not stay the same distance apart and are not parallel. Instead, meridians are widest at the equator and converge toward each pole. A meridian would be the path you would travel if you took the most direct route from the North Pole to the South Pole, or from south to north.

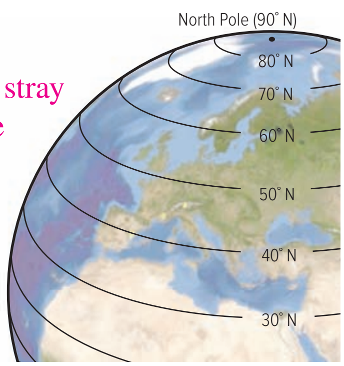
2. If we traveled along one of these lines (i.e., along a parallel), we would stay at the same distance from the pole as we encircled the planet. In other words, our position in a north-south framework would not change.

4. The term *meridian* comes from a Latin term for midday because, at any place, the Sun is along a meridian (i.e., is due south or north) at approximately noon. The terms A.M. (for before noon) and P.M. (for after noon) are also derived from this Latin term (e.g., post meridiem).

Latitude

5. The *latitude* of a location indicates its position north or south of the equator. Lines of latitude are *parallels* that encircle the globe east-west.

CINDY: check stray leader in artfile



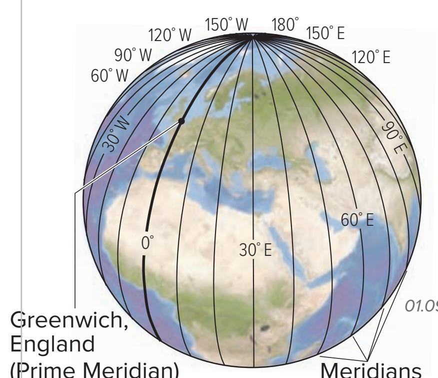
01.09.a3

6. The zero line of latitude is the equator, with the values increasing to 90 at the north and south poles. Locations near the equator are said to have a *low latitude*, and those near the pole are a *high latitude*; areas in between, such as central Europe, are in the *mid-latitudes*.

CINDY: The EPS file for this globe is not cropped

Longitude

7. The *longitude* of a location indicates its east-west position. Lines of longitude are *meridians* that encircle the globe north-south.

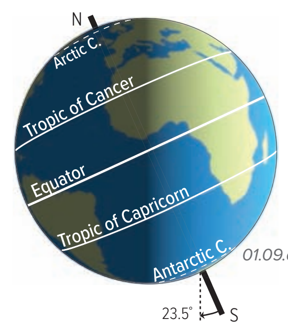


01.09.a4

8. For meridians of longitude, a starting, zero-degree longitude is defined as going through Greenwich, U.K. Meridians of longitude are widest at the equator and converge toward the poles. Starting at the zero longitude through Greenwich, values increase to 180° E and 180° W at the *International Date Line*, an imaginary line that runs through the middle of the Pacific Ocean (not shown; on the opposite side of the globe).

Important Lines of Latitude

9. In addition to the equator, there are a few lines of latitude that are especially important. These include the *Tropic of Cancer* and *Tropic of Capricorn*, which are 23.5° north and south of the equator, respectively. Areas near the equator are the *tropics* and those between the tropics and mid-latitudes are the *subtropics*.



01.09.a5

CINDY: I rescaled the third globe

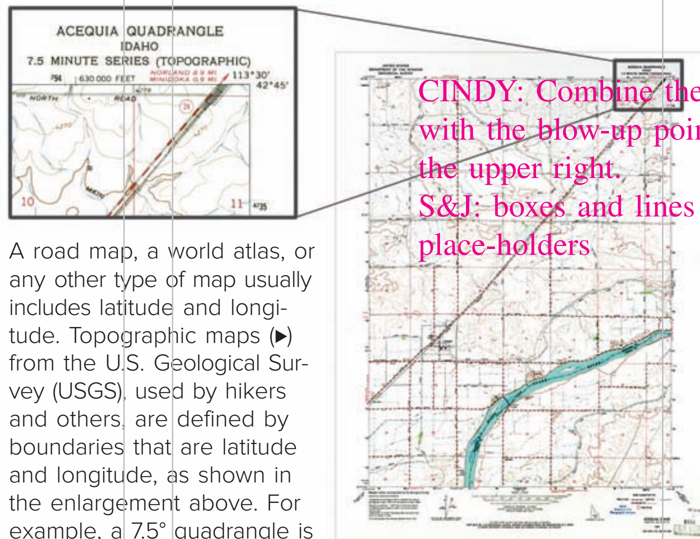
10. Other important lines of latitude are the *Arctic Circle* and *Antarctic Circle*, which are 66.5° north and south of the equator (23.5° away from the corresponding pole). Areas near the poles are described as *polar*. As discussed later, the 23.5° angle is how much Earth's axis is tilted with respect to the Sun.

B How Do We Use Latitude and Longitude?

If you were a pilot flying from New York City to Moscow, Russia, how would you know which way to go? We could describe locations using latitude and longitude, which are expressed in degrees. Fractions of a degree are expressed as decimal degrees (e.g., 9.73°) or as minutes and seconds, where there are 60 minutes (indicated by ') in a degree and 60 seconds (") in a minute (e.g., 9° 43' 48").

01.09.b1

This map (▸) illustrates the nature of the problem. If we want to navigate from New York to Moscow, we can tell from this map that we need to go a long way to the east and some amount to the north. These directions, although accurate, would not be good enough to guide us to Moscow. Fortunately, we can find on the Internet that the location of New York City, as given by latitude and longitude, is 40.7142° N, 74.0064° W. The location of Moscow is 55.7517° N, 37.6178° E. From these more precise ways of expressing location, we could fly from one city to another.



A road map, a world atlas, or any other type of map usually includes latitude and longitude. Topographic maps (▸) from the U.S. Geological Survey (USGS), used by hikers and others, are defined by boundaries that are latitude and longitude, as shown in the enlargement above. For example, a 7.5° quadrangle is 7.5° on a side.

01.09.b2

CINDY: Combine these two, with the blow-up pointing to the upper right.
S&J: boxes and lines are place-holders

C What Is GPS?

Most people think of GPS as a navigation system in our cars or embedded in our cellular telephones, or a handheld device used for location and guidance while hiking across the countryside. GPS, short for *global positioning system*, provides the accurate position on Earth's surface including latitude, longitude, elevation, and even how fast we are traveling. This information comes from a series of satellites orbiting Earth that send radio signals to ground-based receivers, like the ones on our dashboards, in our phones, or in our hand-held GPS when we go hiking.

01.09.c1

1. The U.S. government launches, controls, and monitors a constellation of dozens of satellites orbiting around Earth (◂). Two generations of satellites currently operate in the GPS constellation (▸). A third type will soon be deployed to improve the accuracy and reliability of satellite signals.

2. The time required for a radio signal from a satellite to reach a receiver on Earth is related to its distance to the receiver. A GPS receiver "knows" where each satellite is located in space at the instant the GPS unit receives the signal. Calculating the distances from four or more satellites allows the GPS unit to calculate its own position, commonly with a precision and accuracy of several meters (for a handheld GPS unit). Higher precision can be achieved by occupying a single site for a long interval of time and then averaging the measurements.

01.09.c2

01.09.c3

3. A handheld GPS device (◂) is a navigation tool for finding a location. These instruments operate on the same principles as all other GPS devices in that they receive radio signals from orbiting satellites that contain information about the position and distance of the satellite. GPS works best outside and with a clear view of the sky, but it can operate with reduced accuracy in forested areas, deep canyons, and other settings where parts of the sky, and therefore the view of the satellites, is partially blocked.

CINDY: Note new GPS photo

Before You Leave This Page

- ✓ Sketch and explain a parallel, meridian, latitude, and longitude, indicating where the zero value is for each measurement and identifying important lines of latitude.
- ✓ Briefly explain GPS.

1.10 How Do We Describe Time and Rates?

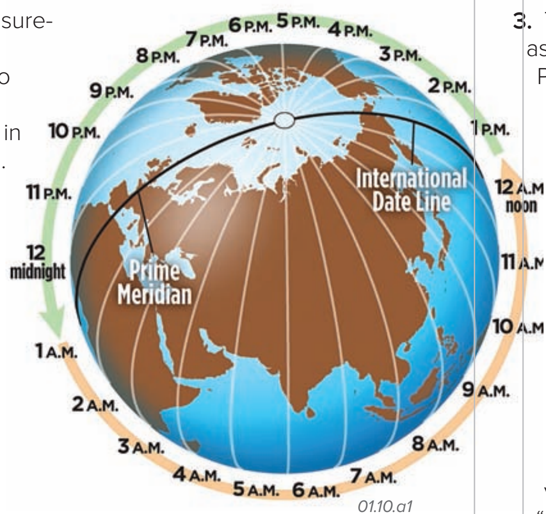
WE REFER TO TIME all the time in our daily lives. But how do we define time, and what do we mean when we say someone lives in a different time zone? The Earth rotates about its axis, causing locations on the surface to pass from day to night and back again. Not everyone witnesses sunrise at the same time, because Earth's rotation causes the Sun to rise at different times in different locations. The concept of longitude helps us understand these differences and describe time so that society can operate in a more orderly manner. Most of us think of time as the hours, minutes, and seconds on a clock, but much longer units of time are used when considering Earth's long history.

A How Do We Define Time Globally?

Some units of time, like a year or length of day, arise from natural progressions of the Earth as it orbits around the Sun in a year and completes a full daily rotation in 24 hours. Other expressions of time, such as "noon," depend on location, so in the 1800s the world agreed on an international system for defining time, based on the *Prime Meridian* and the *International Date Line*.

1. *Prime Meridian* is defined as the 0° longitude measurement on the Earth, passing through the British Royal Observatory in Greenwich, U.K. This location was also chosen as the reference point for world time, a time called *Greenwich Mean Time* (GMT). Time anywhere in the world is referenced relative to time at Greenwich. You may have seen the initials GMT when setting time on your computer, tablet, or cellular phone.

2. The globe shown here has meridians spaced equally apart so that there are 24 zones centered on the lines, one for each of the 24 hours in a day. If you could instantaneously travel from one meridian to the next, there would be a one-hour time difference. If political and other considerations did not intervene, the distribution of time zones could precisely follow lines of longitude, each 15° apart.



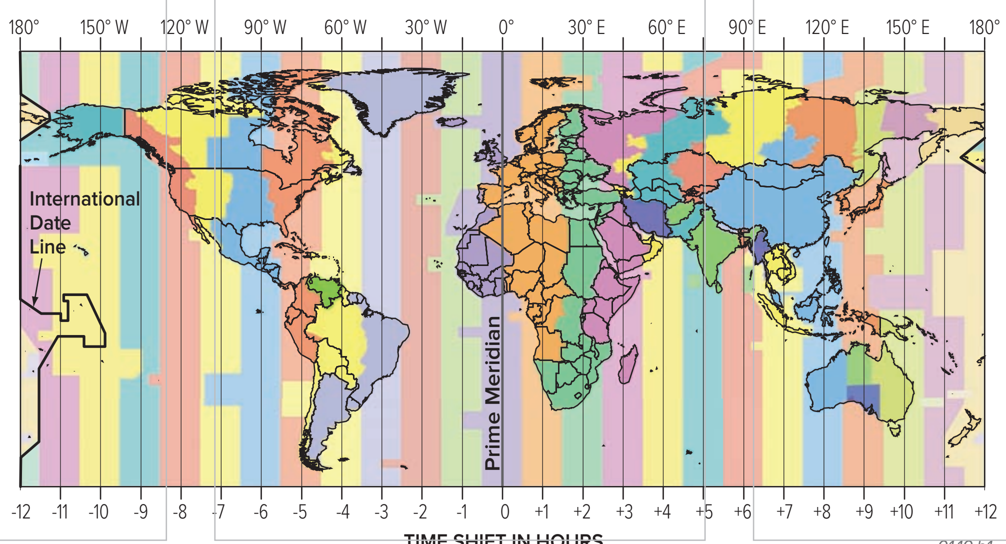
3. The *International Date Line* (IDL) is defined as the 180° measurement of longitude in the Pacific Ocean—the meridian on the exact opposite side of the Earth from Greenwich. Segments of the IDL have been shifted east and west to accommodate the needs of some nations in the Pacific so that travel and trade among those islands is less problematic.

4. If you cross the International Date Line, you cross into a different calendar day. Traveling westward across the IDL puts you one day later in the calendar, relative to immediately east of the IDL; this is described as "losing a day." Moving eastward across the line, you move to the previous day on the calendar, so we say you "gain a day."

B How Are Time Zones Defined?

The world is divided into 24 time zones, based loosely on longitude. This map color-codes these 24 time zones, most of which have irregular boundaries because they follow natural or political boundaries or try to keep some population center in a single zone. The boundaries between the four time zones covering the contiguous U.S. are mostly drawn along state or county boundaries or natural features.

As Earth rotates around its spin axis and the Sun remains stationary relative to Earth, the Sun illuminates different longitudes with the passage of time. Earth spins at a rate of 15° of longitude per hour, so we divide the planet into 24 time zones, each about 15° of longitude wide. Areas within a time zone adopt the same time, and there is a one-hour jump from one time zone to the next. If you are in one time zone, the time zone to the west is one hour earlier, and the time zone to the east is one hour later.



In most of the U.S. and Canada, clocks during the summer are set to one hour later for much of the year. This *Daylight Savings Time* (DST) provides daylight for an extra hour during the evening and one less hour of daylight in the morning. Some areas, like Saskatchewan and most of Arizona, do not observe DST, remaining instead on "standard time."

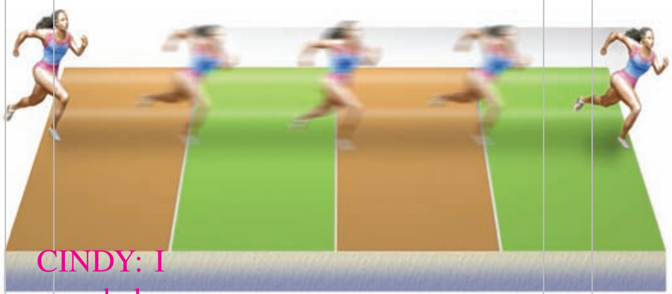
CINDY: The EPS file for this figure is not cropped

C How Do We Refer to Rates of Events and Processes?

Many aspects of earth science involve the *rates* of processes, such as how fast a hurricane is moving toward a coastline or how fast water in a stream is flowing. We calculate the rates of such processes in a similar way to how we calculate the speed of a car or a runner. Some rates, like wind velocities inside a tornado, are very rapid, whereas other rates, like the uplift of a mountain range, are very slow. For scientific work, units are metric, so we talk about millimeters per year, kilometers per hour, or similar units of distance and time.

Calculating Rates

1. A runner (▶) provides a good reminder of how to calculate rates. A rate is how much something changed divided by the time required for the change to occur. Generally, we are referring to how much distance someone or something travels in a given amount of time, but rate can also describe other processes, such as how fast air cools with increasing altitude.



01.09.c1

2. If this runner sprinted 40 meters in 5 seconds, the runner's average speed is calculated as follows:

distance/time = 40 m/5 s = 8 m/s

3. What is the runner's average speed if she runs 400 meters in 80 seconds? Go ahead, try it. We don't need to provide you the answer to this one.

Relatively Rapid Earth Processes

4. Some earth processes are relatively rapid, occurring within seconds, minutes, or days. Relatively rapid natural processes include the velocity of upper-level winds (100s km/hr), speeds of winds inside a severe storm (100s km/hr), motion of the ground during earthquakes (5 km/s), movement of an earthquake-generated wave (tsunami) across the open ocean (100s km/hr), and the catastrophic advance of an explosive volcanic eruption (100s km/hr).

01.10.c2-3 Seaside Heights, NJ

5. Hurricane Sandy, a huge and incredibly destructive storm that occurred in October 2012, is an example of a rapid natural process. Sandy originated as a tropical storm but migrated up the East Coast of the U.S. until it turned inland and struck New Jersey. While in the tropics, Sandy had winds estimated at 185 km/hr (115 mi/hr), but it had weakened considerably by the time the storm came ashore. The storm killed nearly 300 people along its path and caused damages of over $70 billion, mostly in New Jersey and New York.

6. The two photographs above show Seaside Heights, N.J., before and after the storm. The yellow and red arrows point to the same houses in both photographs. Although the photographs were taken several years apart, nearly all the damage occurred within a 24-hour period. In this short time, the shape of the coastline was extensively rearranged, houses were destroyed, and the entire neighborhood was covered in a layer of beach sand washed in by the waves. Such storm-related erosion and deposition of sediment (and houses) are rapid earth processes.

Relatively Slow Earth Processes

7. Other earth processes are very slow, occurring over decades, centuries, or millions of years. Natural processes that are fairly slow include movement of groundwater (m/day), motion of continents (cm/yr), and uplift and erosion of the land surface (as fast as mm/yr, but typically much slower). Although these processes are relatively slow, the Earth's history is long (4.55 billion years), so there is abundant time for slow processes to have big results, such as uplift of a high mountain range.

01.10.c4 Arches NP, UT

8. Observe this photograph of Delicate Arch, taken in Arches National Park, Utah. The arch is a remnant of a once-continuous rock layer that has been mostly eroded away. How long do you think it took natural erosion to erode away most of a hard rock layer, leaving this beautiful landform behind?

9. Several questions about the rates of processes come to mind. How old are the rock layers, and how long did it take to form all of the layers in the photograph? These layers are approximately 160 million years old, and accumulated slowly, one layer at a time, over millions of years. The landscape currently is being eroded, and this process has been occurring in this area for millions of years. Not much rock is eroded away each year, but even at very slow rates, significant erosion can occur in a million years. A final question might be about how long the arch will remain standing. This arch is relatively sturdy, but other arches in the region have collapsed in the last 100 years.

Before You Leave This Page

- ✓ Explain what GMT is and where the starting point is.
- ✓ Describe why we have time zones, and what influences time-zone boundaries and width.
- ✓ Explain how we calculate rates, giving some examples of relatively fast and slow natural processes.

1.11 What Is Earth's Place in the Solar System?

EARTH IS NOT ALONE IN SPACE. It is part of a system of planets and moons associated with the Sun, which together comprise a *solar system*. Our solar system is just one of countless solar systems in the many other galaxies in the universe. The Sun is the most important object for Earth and our solar system because it provides light and heat, without which life would be difficult if not impossible. Earth has a number of neighbors, including the Moon.

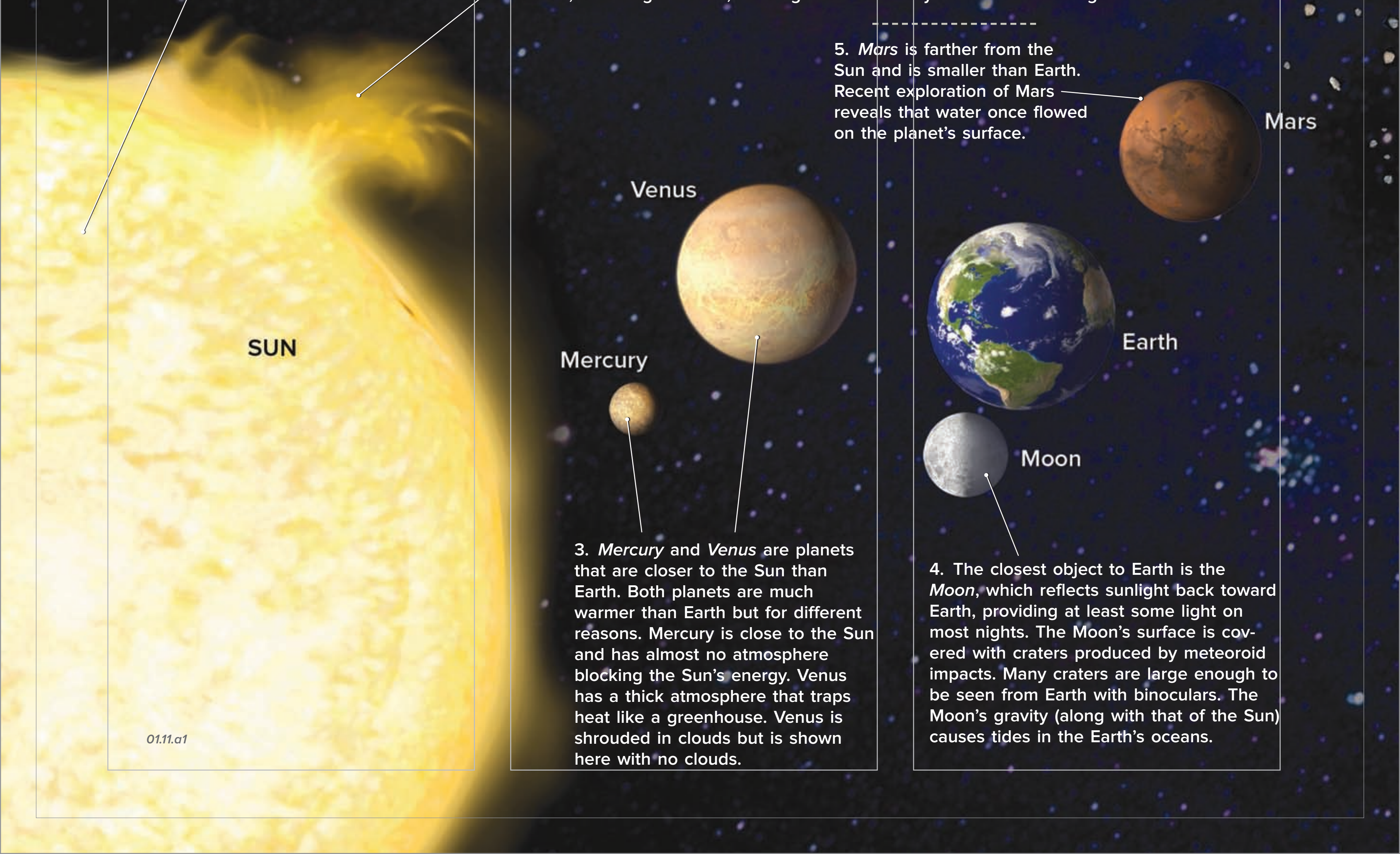
A What Are Earth's Nearest Neighbors?

Earth has five nearby neighbors—three other planets, one moon, and the Sun. The Sun and the Moon have direct effects on Earth. Both exert gravitational pull on our planet, and the Sun is our primary source of energy. The three planets (Mercury, Mars, and Venus), while not affecting us directly, provide glimpses of how Earth might have turned out. Earth and these three other planets are rocky and are called *terrestrial planets*, or simply the *inner planets*.

1. The *Sun* is the center of our solar system. It is by far the largest object in our solar system, but it is only a medium-sized star compared with other suns in our galaxy. The Sun's gravity is strong enough to keep all the planets orbiting around it. On Earth, a year is defined as the time it takes Earth to complete one orbit around the Sun.

2. The Sun creates light, heat, and other types of energy by fusing together hydrogen atoms in the process of *nuclear fusion*. This process is different than the process of nuclear fission, which causes atoms to break apart and is how Earth generates much of its internal heat. The Sun is the only object in our solar system that generates its own light—all the planets and moons, including our own, are bright because they reflect the Sun's light.

5. *Mars* is farther from the Sun and is smaller than Earth. Recent exploration of Mars reveals that water once flowed on the planet's surface.



3. *Mercury* and *Venus* are planets that are closer to the Sun than Earth. Both planets are much warmer than Earth but for different reasons. Mercury is close to the Sun and has almost no atmosphere blocking the Sun's energy. Venus has a thick atmosphere that traps heat like a greenhouse. Venus is shrouded in clouds but is shown here with no clouds.

4. The closest object to Earth is the *Moon*, which reflects sunlight back toward Earth, providing at least some light on most nights. The Moon's surface is covered with craters produced by meteoroid impacts. Many craters are large enough to be seen from Earth with binoculars. The Moon's gravity (along with that of the Sun) causes tides in the Earth's oceans.

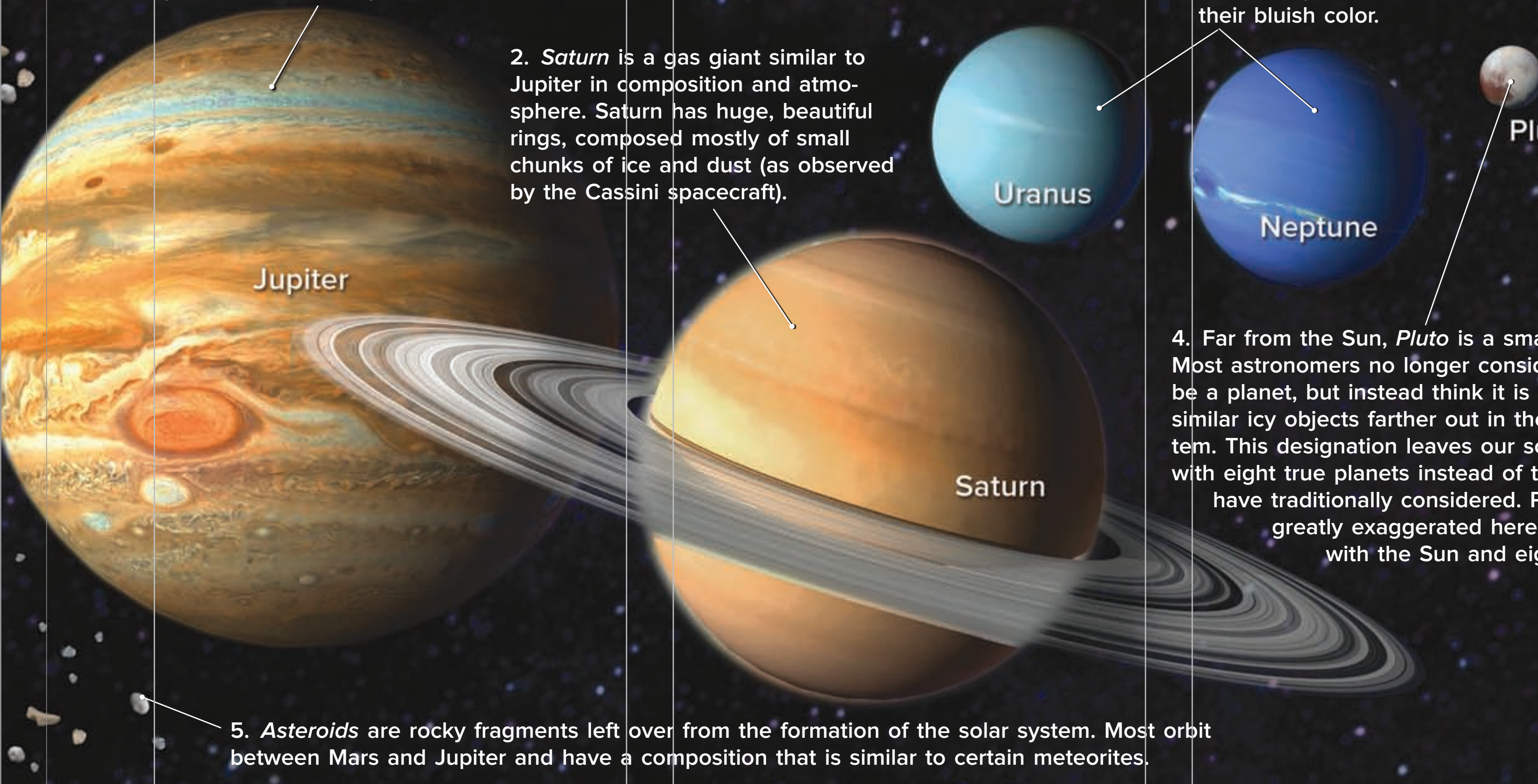
B What Are Some Characteristics of the Outer Planets?

The four outer planets, Pluto, and many asteroids are farther from the Sun than Mars. The outer planets are called *gas giants* because of their large size and gas-rich character. Pluto is a small, distant object that is no longer considered to be a planet by many astronomers.

1. Hundreds of times larger than Earth, *Jupiter* is the largest planet in the solar system. Like the Sun, Jupiter is composed mostly of hydrogen and helium. It has a distinctly banded, swirly atmosphere with what appears to be a huge red storm. Jupiter and the other gas giants are much larger than the inner planets.

2. *Saturn* is a gas giant similar to Jupiter in composition and atmosphere. Saturn has huge, beautiful rings, composed mostly of small chunks of ice and dust (as observed by the Cassini spacecraft).

3. *Uranus* and *Neptune* are smaller gas-giant planets, but these planets are still much larger than Earth. Their atmospheres contain significant methane, which causes their bluish color.



4. Far from the Sun, *Pluto* is a small, icy object. Most astronomers no longer consider Pluto to be a planet, but instead think it is related to similar icy objects farther out in the solar system. This designation leaves our solar system with eight true planets instead of the nine we have traditionally considered. Pluto's size is greatly exaggerated here compared with the Sun and eight planets.

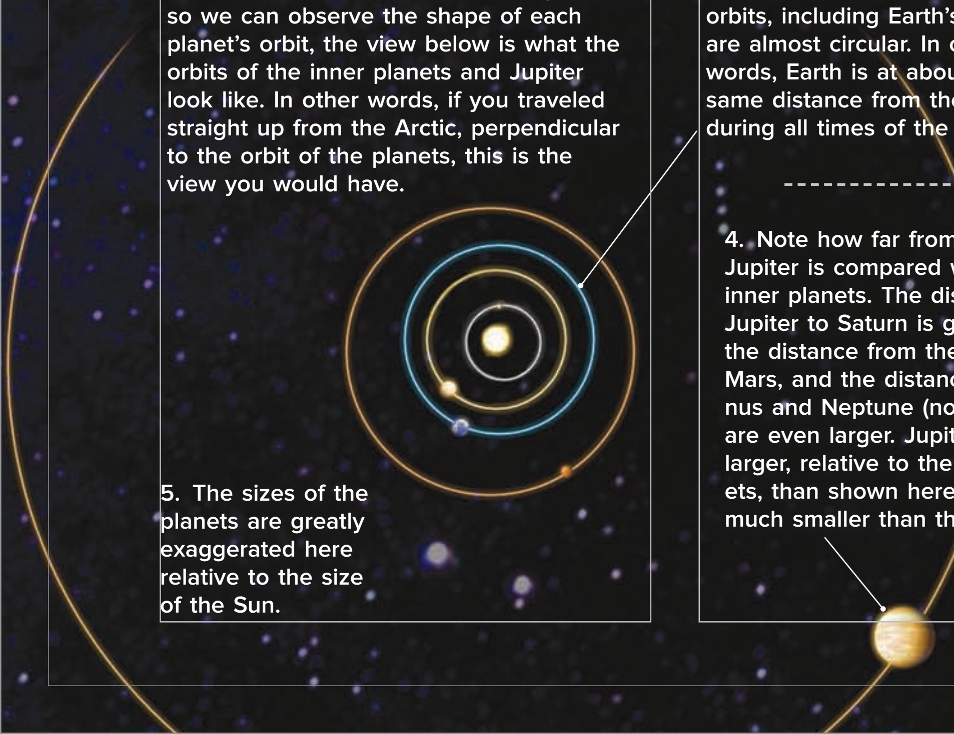
5. *Asteroids* are rocky fragments left over from the formation of the solar system. Most orbit between Mars and Jupiter and have a composition that is similar to certain meteorites.

C What Is the Shape and Spacing of the Orbits of the Planets?

1. If we step back from the solar system so we can observe the shape of each planet's orbit, the view below is what the orbits of the inner planets and Jupiter look like. In other words, if you traveled straight up from the Arctic, perpendicular to the orbit of the planets, this is the view you would have.

2. Observe that all of the planets' orbits, including Earth's orbit, are almost circular. In other words, Earth is at about the same distance from the Sun during all times of the year.

3. Earth's orbit is essentially *circular*, so Earth receives nearly the same amount of light and heat at all times of the year. Earth's seasons (summer and winter), therefore, are not caused by changes in the distance between Earth and the Sun. The seasons have another explanation, which involves the tilt of Earth's spin axis relative to its orbit, a topic we explore later in this book.



4. Note how far from the Sun Jupiter is compared with the inner planets. The distance from Jupiter to Saturn is greater than the distance from the Sun to Mars, and the distances to Uranus and Neptune (not shown) are even larger. Jupiter is much larger, relative to the other planets, than shown here, but is much smaller than the Sun.

5. The sizes of the planets are greatly exaggerated here relative to the size of the Sun.

Before You Leave This Page

- ✓ Sketch a view of the solar system, from the Sun outward to Jupiter.
- ✓ Explain why the Sun and the Moon are the most important objects to Earth.
- ✓ Summarize how the outer planets are different from the inner planets.

1.12 How Do We Approach Earth Science Problems?

EARTH SCIENTISTS APPROACH PROBLEMS in many ways, asking questions about Earth's features and processes and then collecting data that help document what is there and what is happening. Some questions can be addressed by making general observations with our human senses, whereas others require *quantitative* data, which are numeric and are typically visualized and analyzed using data tables, calculations, equations, and graphs.

A What Is the Difference Between Qualitative and Quantitative Data?

01.12.a1 Augustine Island, AK

When Augustine volcano in Alaska erupts, earth scientists make various types of observations and measurements. Some observations are *qualitative*, like simple descriptions, and others are measurements that are *quantitative*. Both types of data are essential for documenting natural phenomena.

01.12.a2 Augustine Island, AK

Qualitative data include descriptive words, labels, sketches, or other images. We can describe this picture of Augustine volcano with phrases like "contains large, angular fragments," "releases steam," or "the rocks are mostly gray." Such phrases can convey very important information about the site.

01.12.a3 Augustine Island, AK

Quantitative data involve numbers that represent measurements. Most come from scientific instruments, such as this thermal camera that records temperatures on Augustine volcano, or from simple measuring devices like a thermometer. We can collect quantitative data in many settings.

B What Quantitative Properties Do We Directly Measure While in the Environment?

Earth scientists often describe features qualitatively, but they also collect quantitative data, which consist of numeric values measured with scientific tools or instruments. Some measurements are collected out in the environment.

01.12.b1 Lake Pleasant, AZ

◀ ORIENTATION: Geologists observe and measure the orientation of geologic features, such as layers, fractures, and folds. In this view, a geologist is using a level on a handheld compass to measure how much the sedimentary layers have been tilted.

01.12.b2 Kyrgyzstan

▶ SURFACE FEATURES: Most earth scientists use topographic and other maps to mark locations of data, but some, especially those earth scientists who study landscapes, use precise surveying instruments to study landforms. Such measurements can document the movement of the land surface before or after an earthquake or volcanic eruption.

01.12.b3 NASA Global Hawk Aircraft

◀ GAS COMPOSITION: Understanding of atmospheric processes is strengthened by having precise estimates of the amount of water vapor and other gases in the atmosphere, as is being measured by this airplane.

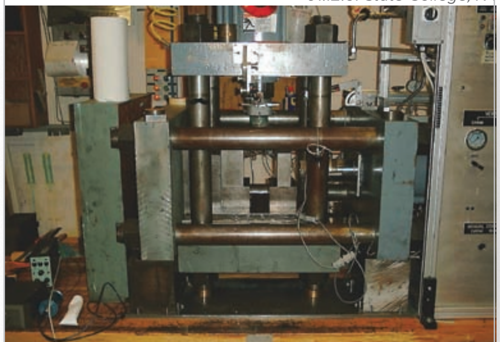
01.12.b4 Yellowstone NP, WY

▶ WATER FLOW AND CHEMISTRY: We can measure the velocity and volume of flowing water in streams and groundwater. Chemical analyses, including some performed in the field, document what the water contains.

C What Quantitative Properties Do We Measure Using Laboratories and Sensors?

Some data collection is done in laboratory environments, by collecting data with sensors on satellites, or by observing through telescopes. These data often include quantitative measurements done with sophisticated scientific instruments that can measure physical properties, chemical composition, light spectra, and ages of rocks, soils, and other materials.

01.12.c1 State College, PA



PHYSICAL PROPERTIES: Density, strength, and other physical properties of earth materials, as measured in the laboratory, form the basis for evaluating how rocks behave when subjected to forces, such as during earthquakes.

01.12.c2 Solar Dynamics Observatory, NASA

COMPOSITION: We conduct chemical analyses on samples of earth materials, water, and air, and also use telescopes and satellites to analyze remote objects. This image shows our Sun, as viewed in ultraviolet frequencies.

01.12.c3 Syracuse, NY

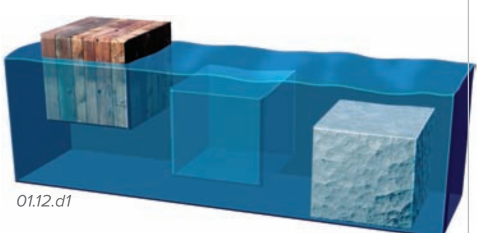
AGE: Certain materials can be dated using precise analytical instruments that measure the ratios between different types of radioactive elements. These can be on materials from the Earth, Moon, or meteorites.

D How Do We Calculate Density, and How Does It Differ from Weight?

Density is a very important quantitative property for understanding the Earth and other objects in the solar system and universe. It controls regional elevations and causes forces that result in earthquakes. It is a key aspect in the rising and sinking of air in the atmosphere and water in oceans and lakes. It influences the gravitational attraction between objects in space. We determine or estimate density by directly measuring a material in the laboratory, by using instruments to measure the pull of gravity, or by numerically analyzing how fast seismic waves pass through materials.

Density

1. *Density* refers to how much mass (substance) is present in a given volume. Below, a wooden block, a "cube" of water, and a stone block all have the same shape and volume but different amounts of mass. The wood is less dense than water and floats, but the stone is more dense and sinks. The cube of water has the same density as the surrounding water and so does not sink to the bottom or float on the surface.



01.12.d1

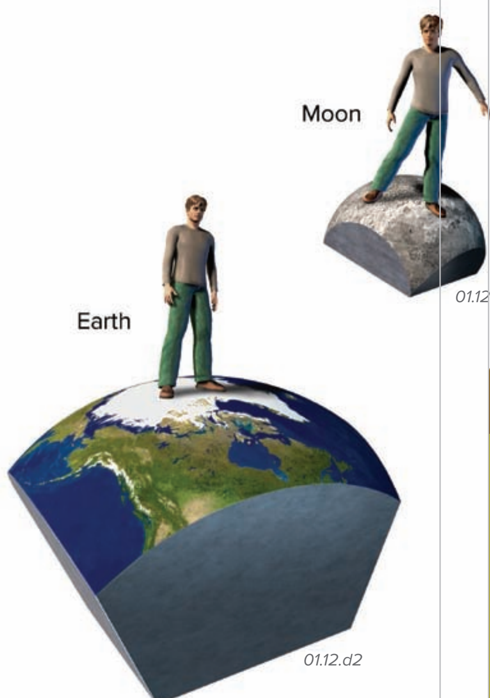
2. We calculate density using the following formula:

density = mass/volume

We measure mass in grams or kilograms, and volume in cubic centimeters, cubic meters, or liters. Density is therefore in units of g/cm^3 or g/L. Water has a density of 1 g/cm^3 at room temperature and pressure, whereas ice, which floats on water, is slightly less dense at 0.92 g/cm^3. Granite has a higher average density of 2.65 g/cm^3.

Weight

3. The *weight* of an object is how much downward force it exerts under the pull of gravity. Weight depends on how much mass the object contains and the strength of the gravity field.



01.12.d3

01.12.d2

4. A person has the same mass, whether standing on Earth or on the Moon. If the person weighs 180 pounds on Earth, the person will weigh only 30 pounds on the Moon (because of the Moon's lower gravity). When addressing scientific issues, scientists rarely talk about weight, instead referring to mass, generally using metric-system units like g/cm^3.

Before You Leave This Page

- ✓ Explain how qualitative data differ from quantitative data.
- ✓ Describe some types of quantitative data that earth scientists use.
- ✓ Describe what density is, how it is calculated, and how it differs from weight.

1.13 How Do We Develop Scientific Explanations?

EARTH SCIENCE IS A FIELD OF SCIENCE that aims to explain Earth's features and processes. Every land region, ocean basin, part of the atmosphere, and planetary object has a wealth of interesting questions with answers of importance to society. To answer the questions, earth scientists use their senses and scientific instruments to observe features and processes on Earth and elsewhere in the universe. They use the resulting observations to answer questions and then, through a series of logical steps, build from observations to explanations.

A What Are Observations?

We learn about our world by making *observations*. We look, listen, smell, and feel so we can record and analyze what is around us. Scientific instruments provide additional information about aspects of the world that we cannot sense, and they allow us to discriminate fine details. For example, we might sense that the temperature outside is near freezing, but if we use a thermometer we can measure a precise value. Every day we make judgments about whether our observations are worth remembering and reliable enough to plan a course of action.

1. Scientists take special care to make valid *observations*, such as when examining these layers of volcanic ash. An observation that is judged to be valid becomes a piece of *data* that can be used to develop possible explanations.

01.13.a1 Gray Mtn., AZ

2. Scientific instruments provide quantitative information, provided they are checked and calibrated to ensure that measurements represent valid and trustworthy data. This typically involves reanalysis of standard materials for which the physical properties have already been well determined. Once the instruments are calibrated, scientists can measure and record data in a field notebook, tablet, or computer and collect samples to permit later reexamination and analysis.

3. Evaluating the validity of observations is critical, so scientists commonly repeat measurements to compare values. They may invite other scientists to check and discuss their observations, measurements, and ideas (▼).

01.13.a2 Gray Mtn., AZ

B How Are Interpretations Different from Data?

Data by themselves are not very useful until we analyze them in the context of existing ideas. Perhaps the data will confirm old ideas, or perhaps they will point out a need for a new interpretation. The recent history of volcanic eruptions near Yellowstone National Park illustrates the difference between data and interpretations.

DATA: This map shows a belt of relatively smooth, lower elevation terrain that trends northeast across the mountains of southern Idaho and northern Nevada. It contains mostly volcanic rocks.

INTERPRETATION: Some process related to volcanism formed a belt of low topography and volcanic rocks in the belt outlined in red.

01.13.b1

DATA: The belt of smooth topography ends near Yellowstone, a recently active volcanic area in the northwestern corner of Wyoming.

INTERPRETATION: Recent volcanism at Yellowstone may be related to the process that smoothed the topography of the belt.

DATA: Samples of volcanic rock analyzed in the laboratory provide ages for when the rock formed. The ages, shown in white as millions of years (m.y.), get younger toward the northeast, from 15 million years in Nevada to less than one million years near Yellowstone.

INTERPRETATION: The very recent volcanism at Yellowstone occurred for the same reasons as the older volcanism to the southwest.

C What Is an Explanation?

When scientists examine a collection of related data, several interpretations may fit together to make a coherent story or *explanation.* The table below summarizes data-interpretation pairs from part B. The bottom row in the table is a new piece of data obtained from other studies. These data and interpretations combine to form a possible explanation, or *hypothesis*, for how the belt of smooth topography formed.

Data	Interpretation	A Possible Explanation
A belt of smoothed topography, mostly in volcanic rocks, extends in a northeast direction and cuts across the region.	The belt of smoothed topography is related to some process that also produced volcanic eruptions.	For 15 million years, North America and its lithosphere have been moving southwest over a deep thermal disturbance called a *hot spot*. The hot spot involves melting of rocks at depth, resulting in volcanism on the surface. As North America moves southwestward over the hot spot, new volcanoes erupt and then become inactive once that area moves past the hot spot. If North America continues to move southwestward, the hot spot may cause new volcanoes northeast of Yellowstone.
The belt ends at Yellowstone National Park.	Volcanism at Yellowstone is related to the smoothed topography.	
Volcanic rocks along the belt get younger to the northeast.	The smoothed belt did not form all at once but rather sequentially, from southwest to northeast.	
The North American continent is moving slowly to the southwest based on satellite observations, and the age progression of volcanism is related to this motion.	There is a source of magma beneath Earth's crust. The continent has moved over the magma source, causing volcanic activity to occur in a narrow belt. Volcanism initially occurred in the southwest but migrated to the northeast over time as North America moved to the southwest.	

D What Is Happening at Yellowstone National Park?

Geoscientists have long recognized that several huge volcanic eruptions occurred in Yellowstone during the past two million years. Geoscientist Bob Smith studied Yellowstone for decades and in 1973 noticed that lake levels along the southern side of Yellowstone Lake had risen, drowning trees. How did he investigate his observations?

1. To check his observation, Smith and colleagues conducted a new, detailed survey of the area's topography using high-precision surveying equipment.

01.13.d1 Yellowstone NP, WY

2. This view shows Yellowstone Lake, with north to the left. When Smith compared the new survey with the last survey done in 1920, he discovered that the elevation of the area shaded orange had increased (the area had risen) in a remarkably short period of time. What was causing this area along the north side of the lake to rise in elevation?

01.13.d2

3. Smith concluded that the rising area north of the lake caused the lake to spill over its southern shoreline, drowning trees in the areas shown in purple.

Observations, Interpretations, and Hypotheses

Discovery of drowned trees along Yellowstone Lake and the follow-up studies illustrate how we develop and investigate questions. An observation (the drowned trees) led to the question, *What is going on here?* The question led to a possible interpretation that parts of the land around the lake may be actively rising or sinking. An explanation that is developed to explain observations and that allows testing is a *hypothesis*. To test his predictions, Smith used precise surveying equipment to collect new observations of the land surface. He scrutinized and validated the new data and proposed a new hypothesis that rising land beneath the northern part of the lake had displaced water that drowned trees along the southern shore.

This example illustrates the strategy of considering different types of data and different scales of observation. Smith interpreted local uplift north of Yellowstone Lake to be the result of a large magma chamber beneath the surface. One interpretation is that the magma originated by deep melting related to a hot spot in the mantle. As the North American continent and lithosphere moved over the hot spot, volcanism and faulting formed the belt of smoothed topography along the *Snake River Plain.* Many geoscientists accept this explanation but still consider and test other explanations.

Before You Leave This Page

- ✓ Explain what observations are and how they become valid.
- ✓ Describe how data differ from an interpretation, and provide one example of each.
- ✓ Summarize how data and interpretations lead to new explanations.
- ✓ Describe how a series of observations led to an explanation for regional and local processes at Yellowstone.

1.14 How Do Scientific Ideas Get Established?

HOW DOES A SCIENTIFIC EXPLANATION move through the steps from an initial idea to a testable hypothesis and finally to a widely accepted *theory* supported by a rigorous body of knowledge? Scientists begin with observations, propose possible explanations (hypotheses), make predictions based on each hypothesis, and conduct investigations to test each prediction. Science is a way to evaluate which hypotheses are most likely to be correct and which are not. It is a body of knowledge based on supported hypotheses and on accepted theories that have been examined and tested many times.

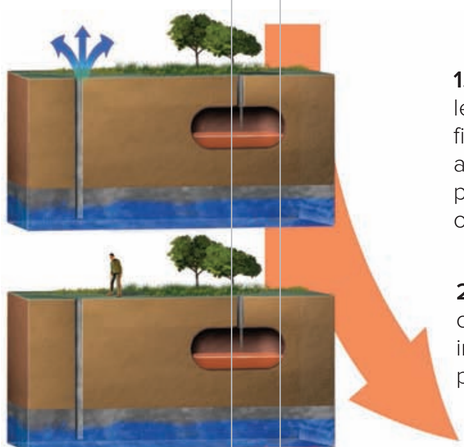
A How Do We Test Alternative Explanations?

Science proceeds as scientists explore the unknown—making observations and then systematically investigating questions that arise from observations that are puzzling or unexpected. Often, we try to develop several possible explanations and then devise ways to test each one. The normal steps in this process are illustrated below, using an investigation of groundwater contaminated by gasoline.

Steps in the Investigation

Observations

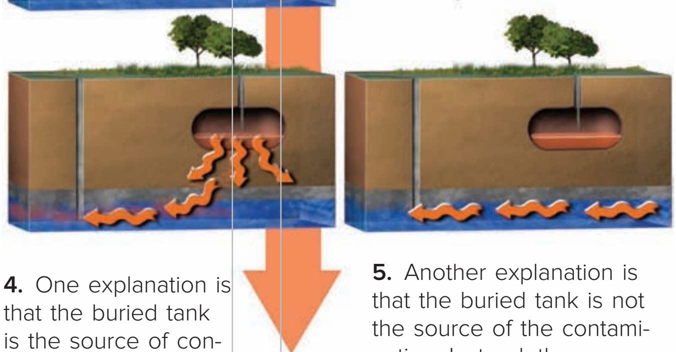
Questions Derived from Observations



1. Someone makes the *observation* that groundwater from a local well (on the left side of the figure) contains gasoline near an old buried gasoline tank. The first step in any investigation is to make observations, recognize a problem, and state the problem clearly and succinctly. Stating the problem as simply as possible simplifies it into a more manageable form and helps focus our thinking on its most important aspects.

2. The observation leads to a *question*—Did the gasoline in the groundwater come from a leak in the buried tank? Questions may be about what is happening currently, what happened in the past, or, in this case, who or what caused a problem.

Proposed Explanations and Predictions from Each Explanation



3. Scientists often propose several explanations, referred to as *hypotheses*, to explain what they observe. A hypothesis is a causal explanation that can be tested, either by conducting additional investigations or by examining data that already exist. Drawing a sketch or other type of figure often helps us better conceptualize the alternatives.

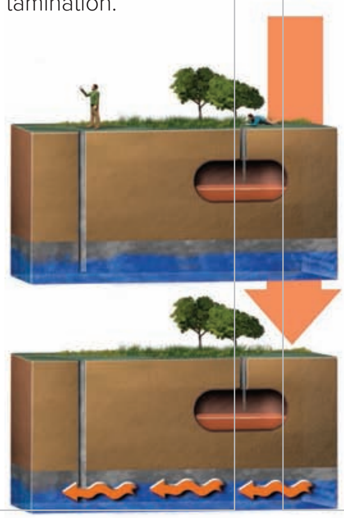
4. One explanation is that the buried tank is the source of contamination.

5. Another explanation is that the buried tank is not the source of the contamination. Instead, the source is somewhere else, and contamination flowed into the area.

6. We develop *predictions* for each explanation. For the first option, the tank should have some kind of leak and should be surrounded by gasoline. Also, the type of gasoline in the tank should be the same as in the groundwater. Next, we plan some way to *test* the predictions, such as by inspecting the tank or analyzing the gasoline in the tank and groundwater.

Results of Investigation

Conclusions



01.14.a1

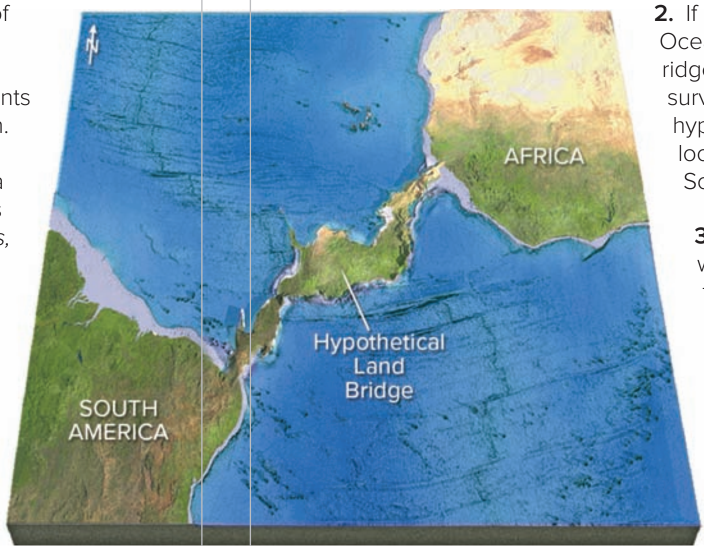
7. The investigation discovered no holes in the tank or any gasoline in the soil around the tank. Records show that the tank held unleaded gasoline, but gasoline in the groundwater is leaded. We compare the results of any investigation with the predictions to determine which possible explanation is most consistent with the new data.

8. Data collected during the investigation support the conclusion that the buried tank is not the source of contamination. Any explanation that is inconsistent with data is probably incorrect, so we pursue other explanations. In this example, a nearby abandoned gas station may be the source of the gasoline. We can devise ways to evaluate this new hypothesis by investigating the site near the older gas station. We also can revisit the previously rejected hypothesis if we discover a new way in which it might explain the data.

B How Does a Hypothesis Become an Established Theory?

A hypothesis that survives scientific scrutiny can be elevated to the higher standard of acceptability of a *theory*. Like a hypothesis, a theory explains existing data and helps predict data not yet collected, but a theory encompasses a more extensive body of knowledge. The scientific process rejects many hypotheses, and few hypotheses survive the intense investigation, experimentation, and testing of predictions to become theories accepted by a majority of scientists. The testing and rejecting of ideas distinguishes science from ways of knowing based on faith.

1. Scientists found fossils of the same land animals in South America and Africa, even though these continents are separated by an ocean. To explain these observations, scientists proposed a hypothesis that long ridges of land, called *land bridges,* once linked the two continents but were now under water. The hypothetical land bridges would have allowed land animals to walk from one continent to the other. According to the hypothesis, the bridges later collapsed or were submerged beneath the oceans.



01.14.b1

2. If the land bridges once existed, then the South Atlantic Ocean should contain submerged ridges, or remnants of ridges, that once connected the two continents. When surveys of the ocean floor failed to find land bridges, the hypothesis had to be abandoned. So scientists had to look for another way to explain the similarity of fossils in South America and Africa.

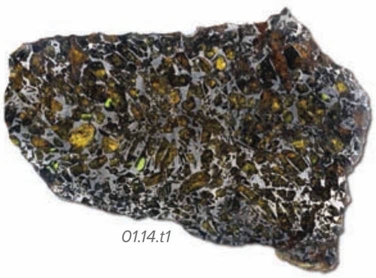
3. A land-bridge hypothesis was also proposed as a way to explain the migration of animals and humans from Asia to North America during the Ice Ages. This hypothesis, unlike the hypothesis about the Atlantic Ocean, is supported by a lot of data and by a credible explanation of why a land bridge existed. A submerged ridge does link Alaska and Asia, and it would have been dry land when the growth of glaciers lowered sea level. So the hypothesis that a land bridge existed off Alaska evolved into a theory, while the hypothesis that one existed in the South Atlantic was rejected.

How and Why Scientific Understandings Change Over Time

Science is a way of investigating the world around us. It is an evolving framework of knowledge and methods, not a static collection of facts. Explanations and theories accepted by the scientific community can change over time as new data, new scientific instruments, and new ideas become available.

Although many scientific explanations are considered to be "correct" and are supported by many lines of evidence, the history of science warns us not to trust any explanation as "final truth." There is so much evidence supporting some theories that they probably will never be shown to be wrong. On the other hand, scientific scrutiny has caused many proposed hypotheses or theories to be rejected or greatly modified based on new data. Some accepted scientific explanations needed only to be revised slightly to account for new data or other scientific advances. In other cases, the science of the time was not sophisticated enough to produce explanations that could hold up under scrutiny. Scientists operate under the principle that no explanation in science is ever *proven*, but some are eliminated. There are no final answers, but science proceeds through a series of logical steps toward a well-tested explanation that best explains all the available observations and other data.

In the 1700s, for example, the most influential scientists of the time could not accept that stones (*meteorites*), such as the one shown here, fell out of the sky. For a time, scientists and others believed that meteors and meteorites resulted from lightning that fused dust with other particles in



01.14.t1

the air. This explanation was rejected when chemists noted that some meteorites consisted of iron-nickel alloys that were not found in any Earth rocks. Also, some meteorites fell in plain view when there were no lightning storms. Stones really were falling from the sky!

We have gained much understanding using the methods of science, but we still do not know many things about the universe. There are countless interesting questions left to investigate, and many important theories left to imagine. We not only lack reasonable explanations for many scientific phenomena, in many cases we do not yet know the right questions to ask or what data to collect. Some hypotheses we currently accept will be proven wrong by future studies. There is still much to learn.

Before You Leave This Page

- ✓ Explain the logical steps taken to evaluate an explanation.
- ✓ Describe how a hypothesis becomes an established theory.
- ✓ Describe what causes changes in scientific understandings, and discuss why scientific explanations are never proven to be "true."

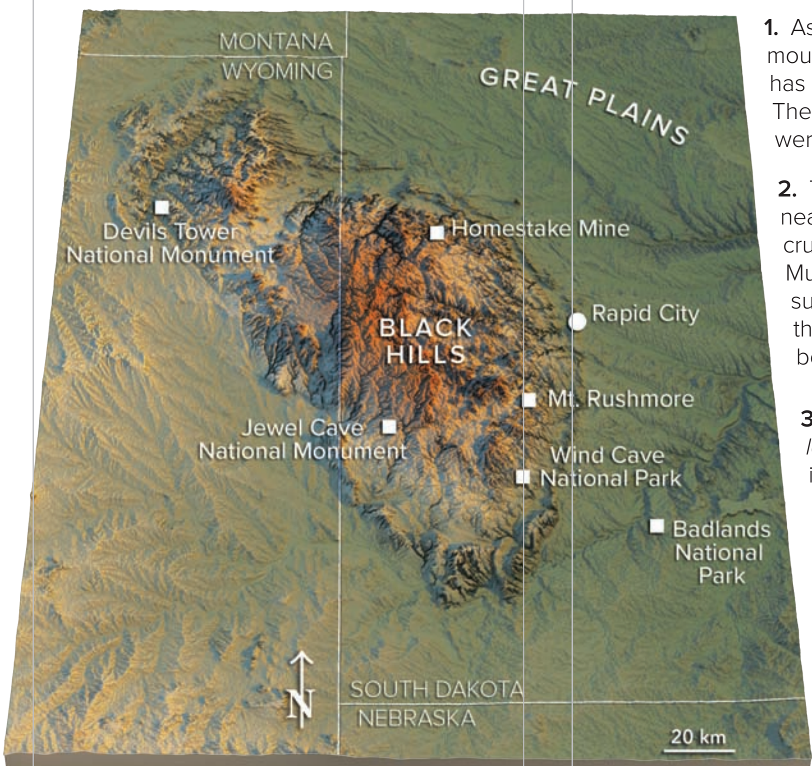
1.14

CINDY: update rock specimen drop-shadow style

How Are Earth-System Processes Expressed in the Black Hills and in Rapid City?

THE BLACK HILLS OF SOUTH DAKOTA AND WYOMING are a natural wonder. The area is home to three national parks and one national monument. It is famous for its gold and for the presidents' faces carved into granite cliffs at Mount Rushmore. Rapid City, at the foot of the mountains, was devastated by a flash flood caused by unstable atmospheric conditions. In this region, the impacts of nature are dramatic and provide an opportunity for us to examine how concepts presented in this chapter connect together and how they apply to a real place.

A What Is the Setting of the Black Hills?



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1. As seen in this shaded relief perspective (◀), the *Black Hills* are an isolated mountainous area that rises above the surrounding *Great Plains*. The region has a moderately high elevation, more than 1,000 m (3,000 ft) above sea level. The highest parts of the Black Hills consist of erosionally resistant rocks that were uplifted to the surface.

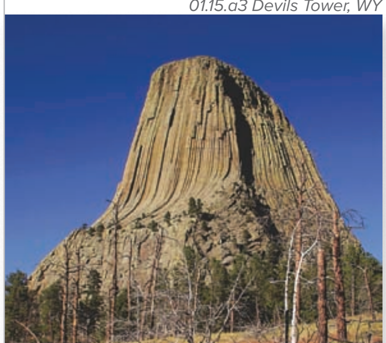
2. The famous gold deposits of the *Homestake Mine* formed on the seafloor nearly 1.8 billion years ago. The rocks were then buried deep within the crust, where they were heated, strongly deformed, and metamorphosed. Much later, uplift of the Black Hills brought the rocks and gold closer to the surface. The Homestake Mine produced 39 million ounces of gold, more than any other mine in the Western Hemisphere. The deep mine has also been used as a site to measure high-energy particles from space.

3. Rapid City is on the eastern flank of the Black Hills. To the south, *Badlands National Park*, known for its intricately eroded landscapes, is carved into soft sedimentary rocks. The Black Hills is home to many caves, including at *Wind Caves National Park* and *Jewel Caves National Monutment.*

01.15.a2 Mount Rushmore, SD

4. The presidents' faces at *Mount Rushmore* (▶) were chiseled into a granite that solidified in an underground magma chamber 1.7 billion years ago. The granite and surrounding metamorphic rocks were cooled, uplifted, and overlain by a sequence of rock layers. More recently, the rocks were uplifted to the surface when the Black Hills formed 60 million years ago.

01.15.a3 Devils Tower, WY



5. *Devils Tower* (◀) is a well-known landmark that rises out of the Black Hills. The rock formed by solidification of a magma chamber at depth, followed by uplift and erosion to bring the rocks to the surface. The distinctive columns are the result of fracturing as the hot rock cooled.

6. This figure (▼) shows the geometry of rock units beneath the Black Hills. The Black Hills rose when horizontal forces squeezed the area and warped its rock layers. As the mountains were uplifted, erosion stripped off upper layers of sedimentary rock (shown in purples, blues, and greens), exposing an underlying core of ancient igneous and metamorphic rocks (shown in brown). Rapid City is near the boundary between the hard, ancient bedrock in the center of the mountains and younger sedimentary rocks of the plains.

01.15.a4

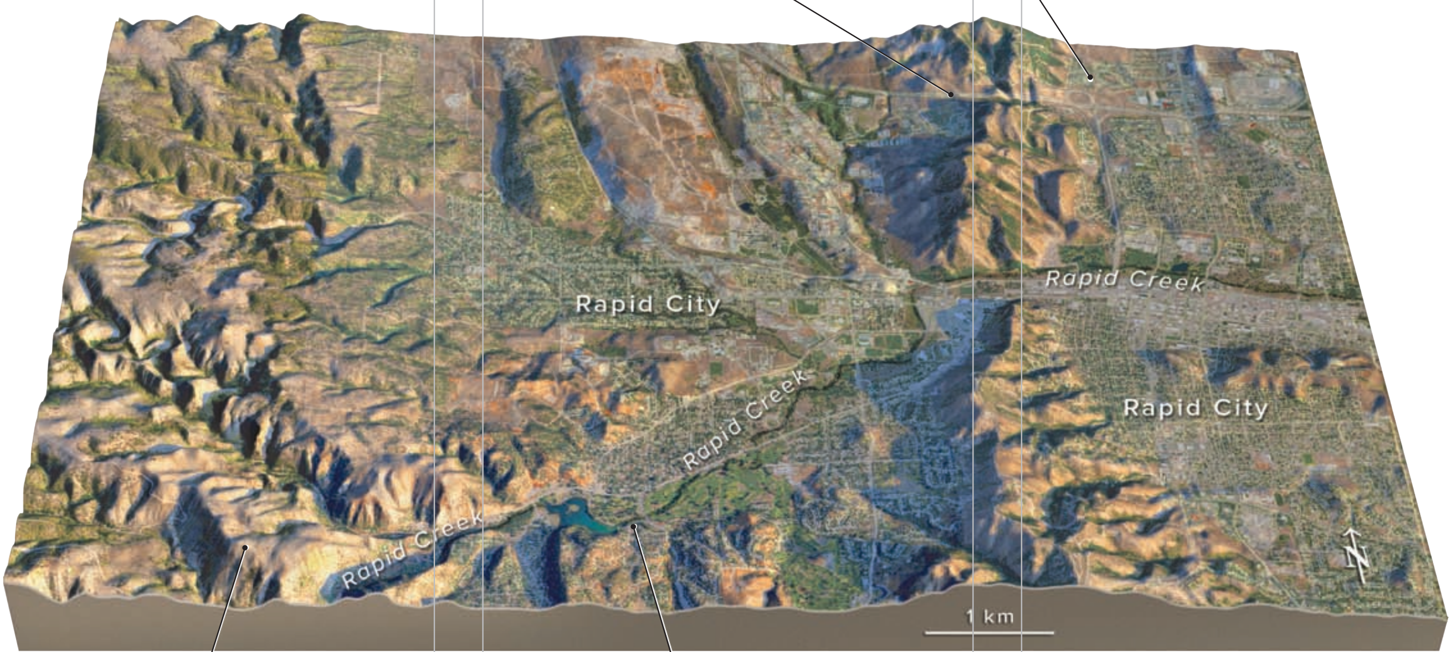
B What Geologic Processes Affect the Rapid City Area?

This view of Rapid City is an aerial photograph superimposed over topography. Where do you think erosion is occurring? Where is sediment being deposited? Which places are most susceptible to landslides? Examine this scene and think about the earth processes that might be occurring in each part of the area.

1. Rapid City is located along the mountain front, partly in the foothills and partly on the plains. Some parts of the city are on low areas next to Rapid Creek, which begins in the Black Hills and flows eastward through a gap in a ridge and then through the center of the city.

2. Upturned rock layers form a ridge that divides the city into two halves. Some of the homes are right along the creek, whereas others are on the steep hillslopes.

3. The plains contain sedimentary rocks, some of which were deposited in a great inland sea and then buried by other rocks. With uplift of the mountains and erosion, the rocks came back to the surface where they are weathered and eroded today.



01.15.b1

4. This part of the Black Hills consists of hard igneous and metamorphic rocks that form steep mountains and canyons. Farther northwest (not in this view) is the world-famous *Homestake Mine*, a former producer of gold. The underground mine is no longer operating, but it reached depths of more than 2.5 km (8,000 ft)!

5. *Rapid Creek* drains a large area of the Black Hills and flows through the middle of Rapid City. A small dam forms Canyon Lake (the blue-green area) just above the city.

6. A flash flood in 1972 destroyed buildings, bridges, and roads along Rapid Creek, leaving the creek littered with shattered houses and other debris, an example of the hazards of living too near flowing water. After the flood, the city decided to restrict building in areas most likely to be flooded, instead turning the flood-prone areas into parks and trails as part of a greenbelt along the creek, a wise and less risky use of such space.

The Rapid City Flash Flood of 1972

In June 1972, winds pushed moist air westward up the flanks of the Black Hills, forming severe thunderstorms. The huge thunderstorms remained over the mountains, where they dumped as much as 15 inches of rain in one afternoon and evening. This downpour unleashed a *flash flood* down Rapid Creek that was ten times larger than any previously recorded flood on the creek. The swirling floodwaters breached the dam at Canyon Lake, which increased the volume of the flood downstream through Rapid City. The floodwaters raced toward the center of the city. They killed 238 people, destroyed more than 1,300 homes, and caused $160 million in damage. Most of the damage occurred along the creek channel, where many homes had been built too close to the creek, and in areas low enough to be flooded by this large volume of water. Since the flood, the city has removed buildings on many flood-prone sites and developed a wide greenbelt in the areas most likely to flood. Some buildings were allowed to remain in flood-prone areas, but many were raised above likely levels of future floods. As for all streams, the occurrence of an exceptionally large flood causes us to reassess what size floods are possible and how often such floods are likely to reoccur.

Before You Leave This Page

- ✓ Briefly sketch the landscape around Rapid City and explain how earth processes affect this landscape.
- ✓ Identify and explain ways that earth features and processes affect the people of Rapid City.
- ✓ Describe the events that led to the Rapid City flood and explain why there was so much damage.

1.15

1.16

How Are Earth Processes Affecting This Place?

EARTH SCIENCE HAS A MAJOR ROLE, from global to local scales, in the well-being of our society. The image below shows an aerial photograph superimposed on topography for an area near St. George, Utah. In this investigation, you will observe and identify some landscape features, consider possible earth processes operating in this region, and think about how the landscape, weather, climate, and various processes affect the people who live here.

Goals of This Exercise:

- Determine where important earth processes are occurring.
- Interpret how earth processes are affecting the people who live here.
- Identify a relatively safe place to live that is away from geologic hazards, such as volcanism, earthquakes, landslides, and flooding.

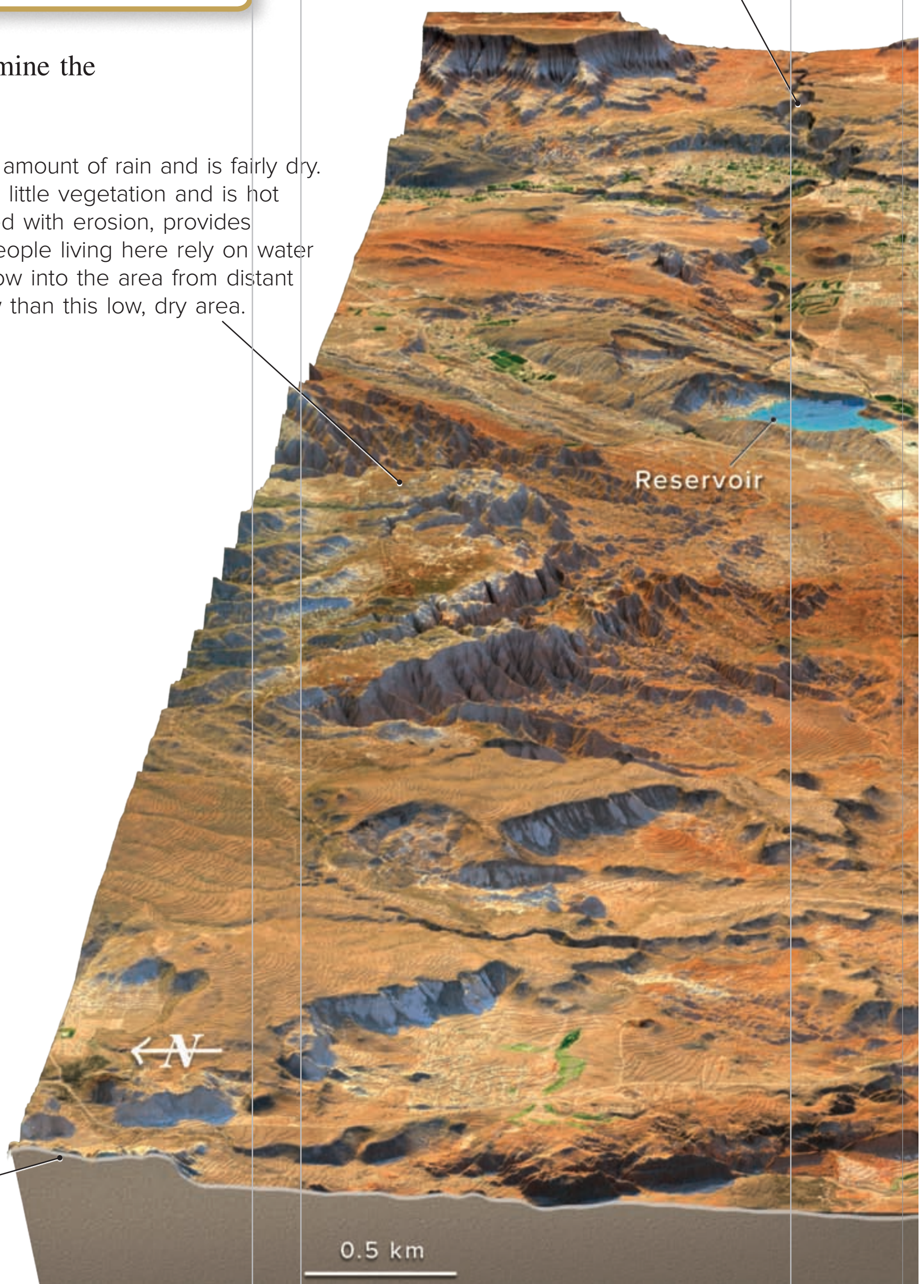
1. The main feature is the Virgin River, which receives water from precipitation in mountains around Zion National Park. It enters the valley through a narrow gorge. Hot springs provide recreation at the end of the gorge, where the river flows through the cliffs.

Begin by reading the procedures list on the next page. Then examine the figure and read the descriptions flanking the figure.

2. Most of this region receives only a small amount of rain and is fairly dry. The low areas are part of a desert that has little vegetation and is hot during the summer. The dry climate, coupled with erosion, provides dramatic exposures of the various rocks. People living here rely on water from wells, reservoirs, and the rivers that flow into the area from distant mountains that receive more rain and snow than this low, dry area.

3. A high, pine-covered mountain range and steep, rocky cliffs flank the valley. The cliffs and mountains receive abundant winter snow and torrential summer rains, which cause flash flooding down canyons that lead into the valley. This photograph (▼) shows the valley, mountains, and cliffs, viewed toward the northwest. The high mountains in the photograph are outside of the area shown in the main figure. They commonly have some puffy clouds over their peaks, while the sky over the valley has few or no clouds. As a result of its lower elevation and fewer clouds, the valley is much hotter and drier than the mountains.

01.16.a2 St. George, UT



4. This figure exaggerates the height of the land surface to better show the features. It shows the mountains twice as high and twice as steep as they really are. Exaggerating the topography in this way is called *vertical exaggeration*.

Procedures

Use the figure and descriptions to complete the following steps. Record your answers in the worksheet, which will be provided by your instructor in paper form, as a printable file, or as an activity you complete online.

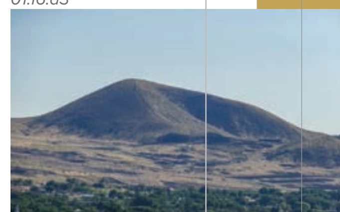
A. Using the image below, explore this area. Make observations about the landscapes and earth processes that are likely on land and in the atmosphere. Next, mark on the provided worksheet at least one location where the following processes would likely occur: locally intense rainfall, weathering, erosion, transport of sediment, deposition of sediment, volcanic activity, landsliding, and flooding.

B. Using your observations and interpretations, indicate on the worksheet all the ways that earth processes might influence the lives of the people who live here. Think about each landscape feature and earth process, and then decide whether it has an important influence on the people. Where would you look for water? Is there a higher potential for a certain type of natural hazard (flooding, earthquakes, etc.) in a particular part of the area? How might the mountains influence the amount of clouds and rainfall?

C. Using all your information, select a location away from natural hazards that would be a relatively safe place to live compared to more hazardous sites in the area. Mark this location on your worksheet with the word *Here*.

01.16.a1

01.16.a3



5. Several dark, lumpy hills are volcanoes (▶) that erupted in the recent geologic past (last several million years). When the volcanoes erupted, they poured molten rock (lava) onto the surface and launched hot volcanic projectiles into the air.

01.16.a4

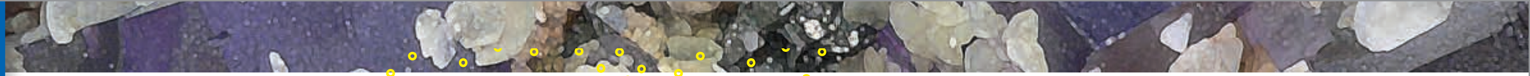
6. The Hurricane Cliffs mark the location of the Hurricane fault, a huge crack through the crust. Movement along this fault uplifted rocks on the east side, forming the cliffs (▶). The fault is active and has caused a few small and moderate-sized earthquakes.

01.16.a5

7. Along the valley, the rock layers are warped upward like a bunched-up rug (▶). Petroleum formed when organic-rich layers were buried and slightly heated, liberating the oil. The oil rose until it became trapped within the rock layers at depth. It is pumped to the surface in a nearby oil field that is not on the map but is in a geologic setting similar to the area labeled here as a possible oil field.

01.16.a6

8. Early pioneers and more recent inhabitants sited farms (▶) next to the river because there is a year-round supply of fresh water and because floodwaters deposit mud that replenishes the fertile soils. The river occasionally overflows its banks, flooding the farms and other low areas, so most houses are away from the river or on areas that are high enough to avoid most floods. Farms were placed next to the rivers, and towns were built near the farms.



CHAPTER 2

Minerals and Mineral Resources

EARTH'S SURFACE IS COMPOSED of many kinds of materials: black lava flows, white sandy beaches, red cliffs, and gray granite hills. Such landscapes are composed of rocks, sediment, and soil, which are all largely composed of *minerals*. Some regions of Earth provide a treasury of gemstones and other mineral resources, many of which are essential to modern society. What kinds of materials are common on Earth, and how did the less common ones, such as gemstones, form? Here we explore minerals, from landscapes to atoms.

This perspective view (▶) shows satellite data superimposed over topography for southernmost California and adjacent Baja California, Mexico. The Peninsular Ranges, a forested mountainous area east of San Diego, are in greens and browns in the center of the image. The white line across the image, added for reference, marks the border between the United States and Mexico.

What are the rocks that make up the hills and mountains of the Peninsular Ranges (▼)?

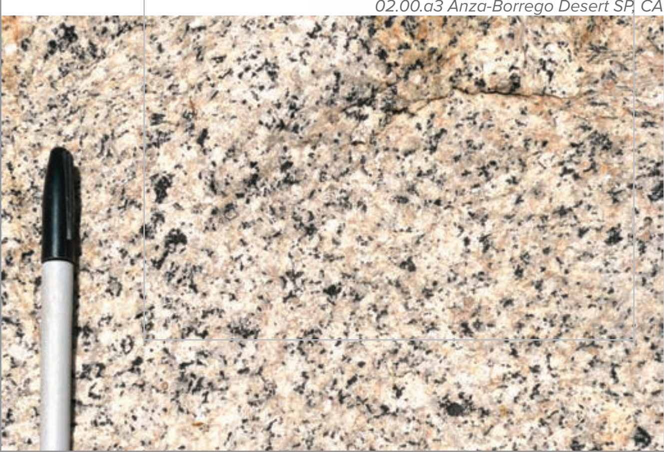
02.00.a1

02.00.a2 Jacumba, CA

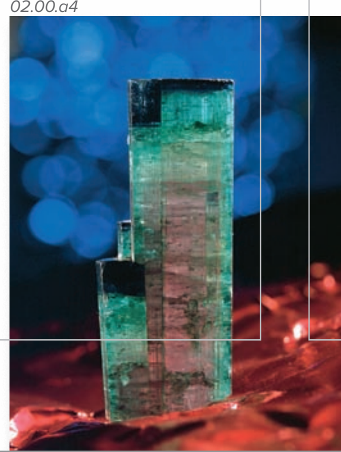
The Peninsular Ranges contain many outcrops of grayish-colored rocks, most of which are igneous rocks like granite. When viewed up close (▼), the granite displays four different kinds of crystals: whitish, light pink, transparent gray, and black.

What are rocks made of, and what controls the color and other properties of a rock?

02.00.a3 Anza-Borrego Desert SP, CA



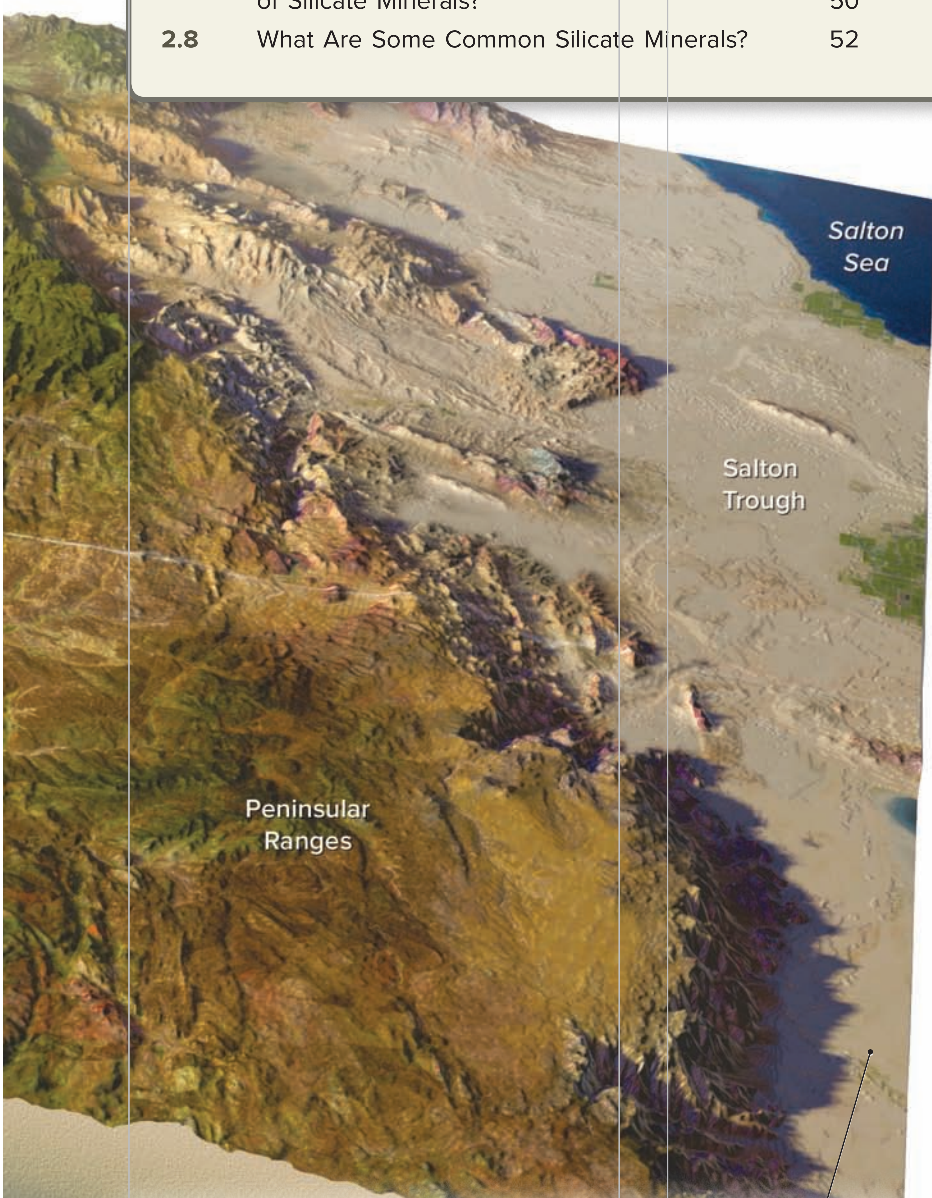
02.00.a4



San Diego County is a famous source of beautiful minerals, including tourmaline crystals (◀), that can be pink, purple, green, or all three colors.

What are crystals, how do they form, and where do we find them?

TOPICS IN THIS CHAPTER



East of the Peninsular Ranges, the land drops down into the lowlands of the Salton Trough, which is characterized by sandy deserts, farmlands of the Imperial Valley, and several large, salty lakes, including the blue Salton Sea. The sand and pebbles in the Salton Trough were eroded from the adjacent mountains and carried to the area by streams or strong winds.

What are most sand grains composed of?

The Peninsular Ranges

The area called the Peninsular Ranges is a broad, upland region that stretches 1,500 km across southernmost California and southward into the Baja Peninsula of Mexico. In this image, the mountains appear green because they are mostly covered by forests and other types of vegetation. The lowlands of the Salton Trough east (right) of the mountains receive much less rain and have a lighter color in this image because vegetation is sparse, and sand and rocks cover the surface.

The contrast between the Peninsular Ranges and the Salton Trough illustrates some important aspects to consider when observing and thinking about landscapes. First, landscapes develop from the materials that are available. The mountains contain granite because that is the type of rock that was there, long before the mountains were uplifted. The mountains would have a different appearance if they instead consisted of a material much weaker than granite and, in this case, might not even be mountains today. In addition to the type of materials, the geometry of the rock units and other materials can also impart a distinct style to the landscape. An appropriate place to begin thinking about landscapes is, therefore, to examine the repertoire of earth materials, starting with minerals.

Once the materials are at the surface, they are acted on by the atmosphere, moisture in the soil, and other components of the environment that tend to break down rocks into loose materials. The kind of climate greatly influences this loosening process. Once loosened, these materials can be stripped off the land surface and transported away by running water, wind, and ice, eventually being deposited as sediment someplace else, such as sedimentary rocks in the Salton Trough, as in the photograph below. This sequence of events is what shaped the mountains of the Peninsular Ranges and also deposited the resulting loose materials in the Salton Trough. These processes are still occurring, so the landscape continues to evolve.

02.00.a5 Rancho Vallecito, CA

What Is the Difference Between a Rock and a Mineral?

WHAT MATERIALS MAKE UP THE WORLD around us? What do we see if we look closely at a rock outcrop? How does the rock look when viewed with a magnifying glass or microscope? We investigate these questions using the beautiful scenery of Yosemite National Park in California.

A What Materials Make Up a Landscape?

1. Observe this photograph of Yosemite Valley, the heart of Yosemite National Park in the Sierra Nevada range of California. What do you notice about the landscape?

2. This landscape is dominated by dramatic cliffs and steep slopes of massive gray rock perched above a green, forested valley. The valley is famous for waterfalls and huge rock faces. The appropriately named Half Dome is in the right side of the photograph. What would we see if we got closer to this landscape?

02.01.a1 Yosemite NP, CA

02.01.a2 Yosemite NP, CA

3. From several meters away, the rock forming Yosemite's cliffs looks fairly homogeneous. It all seems to be the same kind of gray rock, a kind of igneous rock called *granite*. The granite is cut by fractures.

02.01.a3 Sierra Nevada, CA

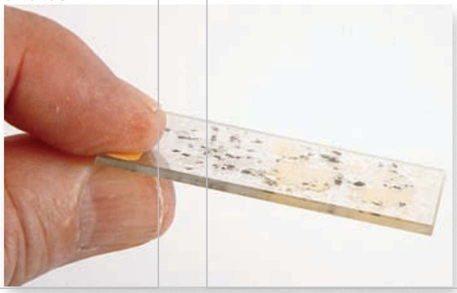
4. Closer examination reveals several different-colored grains in the rock: whitish, pinkish, clear gray, and black. To better observe a rock at this scale, a geoscientist may collect a hand-sized piece, called a *hand specimen*.

02.01.a4

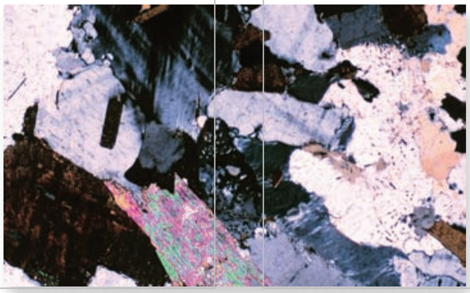
5. When examined with a magnifying glass or *hand lens*, the rock contains different minerals with distinct appearances. The clear gray crystals all have similar chemical composition and physical properties, and so represent one kind of *mineral*. The whitish crystals are a different kind of mineral, as are the pink and black crystals.

6. To examine the rock in even more detail, a geoscientist will cut a very thin slice from a hand specimen and glue it to a glass slide to make a *thin section*. The slice is so thin that light can pass through it. Geoscientists then examine the thin section using a microscope that has polarizing filters.

02.01.a5



02.01.a6



7. When polarized light shines through a thin section and optical filters, the internal structure of crystals interacts with the light in ways that allow us to observe diagnostic characteristics, to identify minerals, and to estimate percentages of each mineral.

B What Is and What Is Not a Mineral?

What characteristics define a mineral? To be considered a mineral, a substance must fulfill all of the criteria listed below. A mineral is a naturally occurring, inorganic, crystalline solid with a relatively consistent composition.

Natural

02.01.b1 Apophyllite/Stilbite

02.01.b2

1. A mineral must be *natural*. Crystals on the left grew naturally from warm water flowing through a rock, but synthetic crystals on the right grew in a laboratory. Natural diamonds are minerals, but synthetic diamonds grown in the lab are not.

Inorganic

02.01.b3 Calcite

02.01.b4

2. The crystal on the left is *inorganic* and a mineral. The shells on the right have the same composition as the crystal, but they were made by creatures; the shells are not considered to be a mineral by most geoscientists because the shells are not inorganic.

Solid

02.01.b5

02.01.b6

3. All minerals are *solid*, not liquid or gaseous. Ice, a solid, is a mineral, but liquid water is not, even though it has the same composition. Liquid mercury, although natural and found in rocks, is not considered a mineral.

Ordered Internal Structure

02.01.b7 Calcite

02.01.b8 Obsidian

4. A mineral has an *ordered internal structure,* which means that atoms are arranged in a regular, repeating way. Such substances are considered to be *crystalline*, and they can form well-defined geometric crystals. The mineral on the left is crystalline, and the shape of the crystals reflects the internal arrangement of its atoms. The volcanic glass (obsidian) on the right is not crystalline. Its atoms are arranged in a random way, so volcanic glass is not a mineral.

Specific Chemical Composition

02.01.b9 Halite and Table Salt

02.01.b10 Conglomerate

5. Minerals are homogeneous and so have specific chemical compositions that do not depend on the size of the sample that is analyzed. Table salt, which is the mineral *halite*, contains atoms of the chemical elements *sodium* (Na) and *chlorine* (Cl) in equal proportions, no matter how big or small the specimen. The rock on the right is not a mineral because different parts of the rock have very different compositions. Most minerals have a specific chemical formula, like NaCl for halite.

Rocks, Minerals, and "Minerals"

When we hear the word *mineral* used in the context of *vitamins and minerals*, are these minerals the same as the minerals described above? The answer is *no*. In a kitchen or pharmacy, the term *mineral* refers to a chemical *element*, such as potassium (K). This type of (nutritional) mineral is different from the crystalline mineral of geoscientists.

In earth science, most minerals consist of at least two different chemical elements, i.e., naturally occurring chemical compounds, such as the *sodium* (Na) and *chlorine* (Cl) that make up the mineral *halite* (salt). Many minerals have three, four, or even more chemical elements. A few minerals, however, include only one chemical element, and these are called *native elements*. The mineral *diamond*, for example, consists entirely of the element *carbon*.

Some rocks contain only a single mineral. Limestone may be 100% of the mineral calcite. Sandstone may be 100% quartz. Most rocks, like the granites from Yosemite National Park, include several different minerals, and each mineral is made of one or more elements. So, rocks are made of minerals, and minerals are made of elements. Although the vitamin pill you take with breakfast may not contain any geologic minerals, most of the nutritional elements in the pill were extracted from geologic minerals.

Before You Leave This Page

- ✓ Explain the relationship between rocks, minerals, and chemical elements.
- ✓ Explain each characteristic that a material must have to be a mineral, listing an example that is a mineral and an example that is not.
- ✓ Explain the difference between a mineral in a vitamin pill and a geologic mineral.

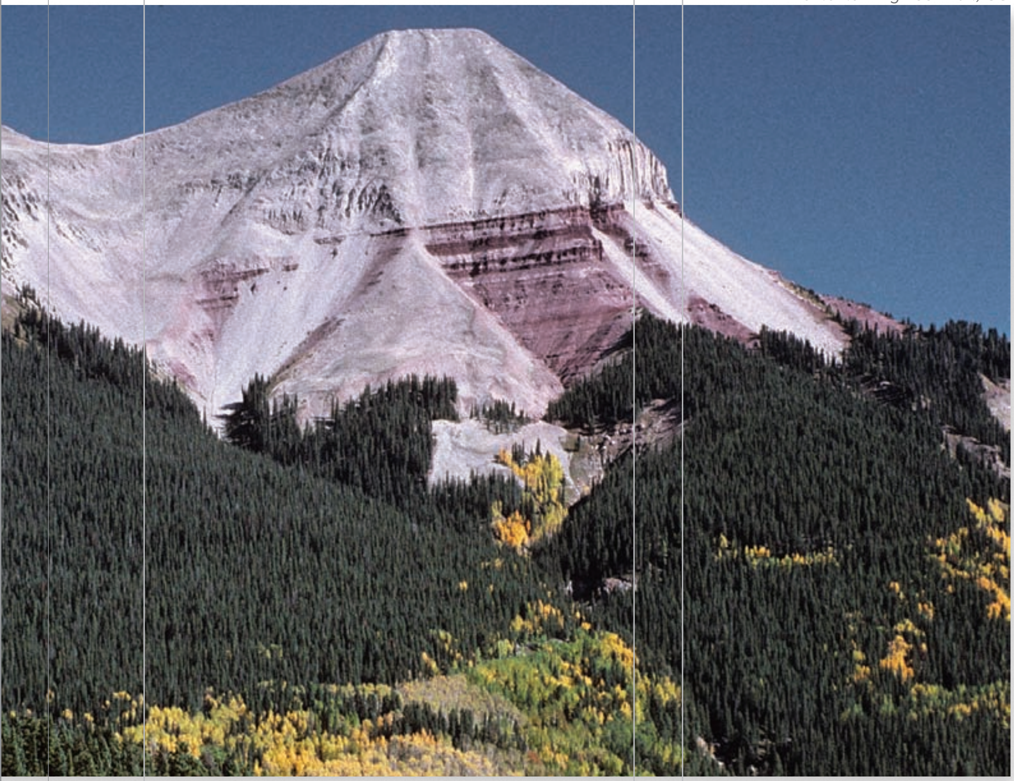
How Are Minerals Put Together in Rocks?

THERE ARE MANY KINDS OF ROCKS, varying greatly in texture, color, and the minerals they contain. Geoscientists use the term *texture* to refer not only to the roughness or smoothness of a rock, but also to the way its grains and minerals are arranged. What controls the texture of a rock? How are minerals in a rock connected to one another? What can we determine about a rock, including how it formed, from its texture and the types of minerals it contains?

A How Are Minerals Put Together in Rocks?

Minerals compose igneous, sedimentary, metamorphic, and hydrothermal rocks. The beautiful and geologically interesting Engineer Mountain in the San Juan Mountains of southwestern Colorado contains two different types of rocks, providing examples of the two main ways that minerals occur in rocks.

02.02.a1 Engineer Mtn., CO



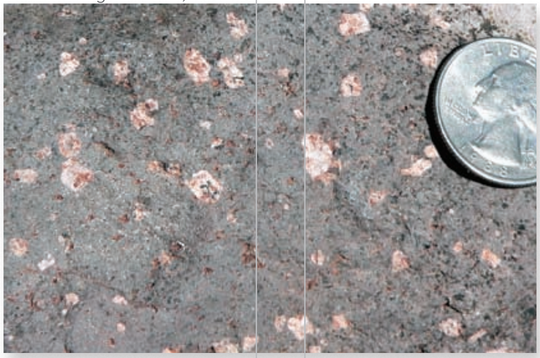
1. The main mountain has an upper gray part and a lower reddish-brown part (◀). Loose pieces of the upper gray part tumble down the hillside, forming gray slopes that cover some of the red rocks.

02.02.a2 Engineer Mtn., CO

2. A closer view of the mountainside (▲) reveals differences between the gray and reddish parts. Both parts contain vertical fractures, but the reddish-brown part also has well-defined, nearly horizontal layers, whereas the gray part does not.

Two Types of Rocks

02.02.a3 Engineer Mtn., CO



3. *Crystalline*—The gray rock displays light-colored crystals surrounded by a gray, fine-grained material (called a *matrix*) with crystals too small to see in this photograph. A rock composed of interlocking minerals that grew together is a *crystalline rock*. Crystalline rocks typically form in high-temperature environments by crystallization of magma, by metamorphism, or by precipitation from hot water. Some crystalline rocks consist of crystals formed from the precipitation of minerals in cooler waters, such as when a lake evaporates.

02.02.a4 Engineer Mtn., CO

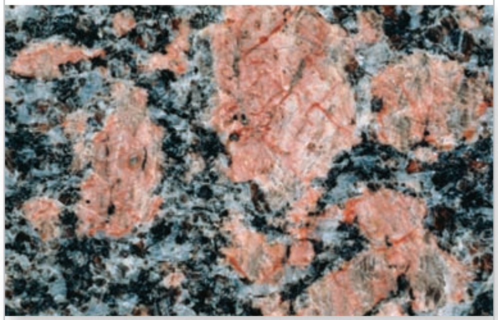
4. *Clastic*—A close look at the reddish-brown layer reveals that it includes distinct pieces of rock derived from older weathered and eroded rocks. These pieces, called *clasts*, range from small sand grains to larger pebbles. A rock consisting of pieces derived from other rocks is a *clastic rock*. Most clastic rocks form on Earth's surface in low-temperature environments, such as sand dunes, streams, glaciers, and beaches—any place sediment is deposited. Clasts also compose some volcanic rocks, including those formed by explosive volcanic eruptions.

B What Different Attributes Do Rocks Display?

Crystalline rocks and clastic rocks can have various attributes, depending on the sizes and shapes of crystals and clasts in the rocks and on how the crystals and clasts are arranged. The photographs below display some common rock textures. Some are of natural exposures of rocks and some are cut and polished rock slabs, like you would find on a kitchen countertop. The parts of the slabs shown are 5 to 30 cm (2 to 12 in.) across.

Crystalline Rocks

Clastic Rocks


02.02.b1 Brazil

Types of Minerals

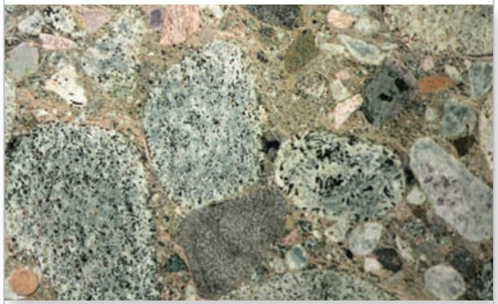
Rocks can consist of one mineral or many minerals, but most contain more than one mineral. This crystalline rock (◀) is an igneous rock with several types of minerals, each having a distinctly different color. This clastic sedimentary rock (▶) also includes different types of minerals, including small, partially rounded pebbles of quartz in various shades of gray.

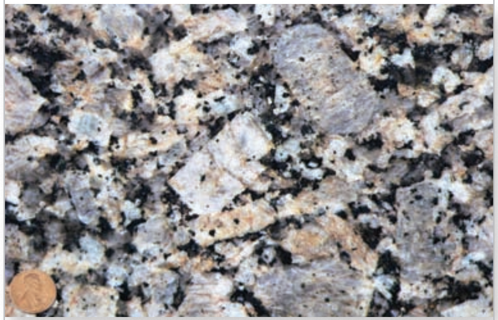

02.02.b2 Moab, UT


02.02.b3 Alaska

Sizes of Crystals or Clasts

Rocks can contain various sizes of crystals and clasts. This granitic crystalline rock (◀) has coarse crystals, including some whitish ones that are more than 5 to 10 cm (2 to 4 in.) in diameter. This clastic sedimentary rock (▶) includes various sizes of larger clasts in a matrix of smaller pebbles and sand.


02.02.b4 Brazil


02.02.b5 Brazil

Shapes of Crystals or Clasts

Crystals and clasts in rocks can have various shapes. This crystalline igneous rock (◀) includes some large, nearly rectangular crystals surrounded by smaller, more irregularly shaped crystals. This clastic sedimentary rock (▶) includes mostly rounded pebbles (clasts) in a matrix of sand and smaller clasts. Some clastic rocks contain clasts that are sharp and angular.


02.02.b6 Smoky Mtns., TN


02.02.b7 Stone Mtn. SP, GA

Layers or No Layers

Crystalline rocks and clastic rocks may or may not have distinct layers. Most granites (◀) do not have obvious layers or compositional variations. In contrast, this clastic rock (▶), which is mostly composed of sand grains, displays a sequence of layers. An important first observation about any rock is whether it has layers and a variable composition or lacks layers or variation.


02.02.b8 Gaviota Beach, CA

Before You Leave This Page

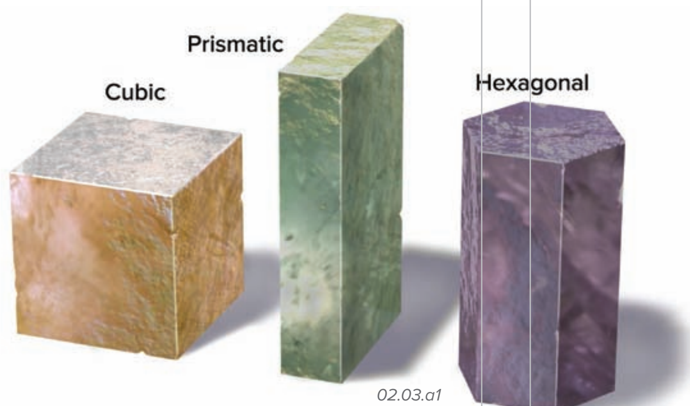
- ✓ Explain the difference between a clastic rock and a crystalline rock and the differences between the general environments in which clastic and crystalline rocks form.
- ✓ Describe or sketch four general characteristics to observe in crystalline and clastic rocks.

How Do We Distinguish One Mineral from Another?

MINERALS HAVE MANY PROPERTIES that allow us to distinguish them from each other. Some properties are reflected by the shape of the mineral or the way the mineral breaks. Others are physical properties, like hardness and magnetism, that we can evaluate with simple tests.

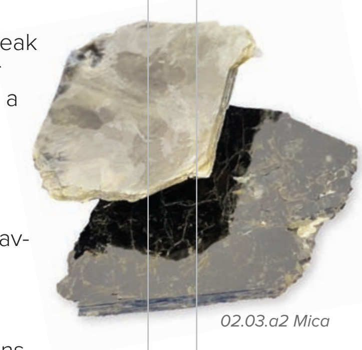
A What Clues Does the Appearance of a Mineral Provide?

The first thing that we notice about a mineral is usually its outward appearance. We may note its size, shape, color, or how light reflects from its surface. These properties provide clues about the identity of a mineral. The figures below illustrate some physical properties that are relevant for identifying a mineral.



02.03.a1

1. *Crystal Shape*—A mineral that grows unobstructed by its surroundings can have a distinctive geometric shape. The shape of the crystal reflects the arrangement of atoms within the mineral and therefore provides a clue about the mineral's identity. Common crystal shapes include, but are not limited to, cubes, rectangular prisms, and hexagons (six-sided shapes).



02.03.a2 Mica

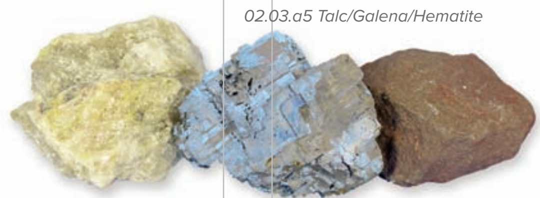
2. *Cleavage*—Some minerals break in specific ways because of their internal arrangement of atoms. If a mineral breaks preferentially along a specific set of planes, the mineral has *cleavage*. Some minerals, like the ones shown here, break along one set of cleavage planes and cleave into thin sheets, but other minerals break along several sets of cleavage planes having different orientations.

02.03.a3 Quartz

3. *No Cleavage*—Some minerals have an internal atomic arrangement that does not contain planes along which the mineral breaks. These minerals do not have cleavage but instead break along *fractures*. Fractures in minerals tend to have rough, irregular surfaces, like ones shown here cutting a quartz crystal. In contrast, cleavage planes tend to be more planar and regular.

02.03.a4 Quartz

4. *Color*—The color of a mineral is a useful, but not always reliable, property for mineral identification. Bright or unique colors are easily noticed, but a mineral can occur in several color varieties, such as the different-colored versions of quartz shown here. Other minerals always have the same color. It is the color and the crystal shape that make some minerals so beautiful and so highly valued as gemstones or mineral specimens.



02.03.a5 Talc/Galena/Hematite

5. *Luster*—The way that light bounces off a mineral is a property called *luster*. A mineral can be highly reflective, dull, or somewhere in between. It can be partially transparent or opaque. It can look like metal, a pearly shell, a silky material, or a simple piece of earth. The names of different types of luster reflect the quality and intensity of the reflection. Luster terms include metallic, nonmetallic, glassy, pearly, silky, resinous, and earthy.

02.03.a6 Olivine/Pyroxene

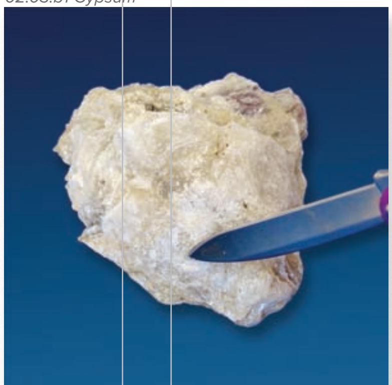
6. *Microscopic Observations*— To identify minerals in rocks, especially fine-grained rocks, we often examine a *thin section* (◀) using a microscope. When a thin section is viewed between two polarizing filters, light shining through the thin section causes the different minerals to exhibit distinctive and diagnostic colors.

B What Tests Can We Perform to Help Us Identify a Mineral?

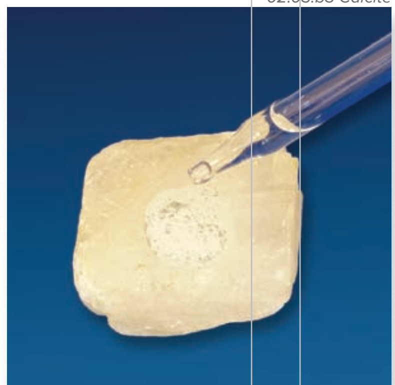
We determine some mineral properties by conducting tests. We may touch a mineral with a magnet to check its magnetism, or we may try to scratch it to determine its hardness.

1. *Hardness*—Some minerals are very hard, and some are quite soft. A mineral can be scratched by a material that is harder than the mineral but not by one that is softer. To estimate mineral hardness, we often conduct scratch tests using common objects, such as a fingernail, penny, or knife blade. We may also use other minerals of known hardness for comparison.

02.03.b1 Gypsum



02.03.b3 Calcite



3. *Effervescence*—If a drop of dilute hydrochloric acid (HCl) is placed on a mineral, a reaction may cause vigorous bubbling, or *effervescing*. The mineral *calcite*, which is the main mineral in limestone, effervesces strongly with HCl, but no other common minerals do. Any sample that effervesces when tested with hydrochloric acid is most likely to be calcite.

2. *Streak*—If a mineral is rubbed against an unglazed porcelain plate (called a streak plate), it may leave a trail of powdered material called a *streak*. Some minerals have a diagnostic streak color. The iron-oxide mineral *hematite,* for example, has a reddish streak.

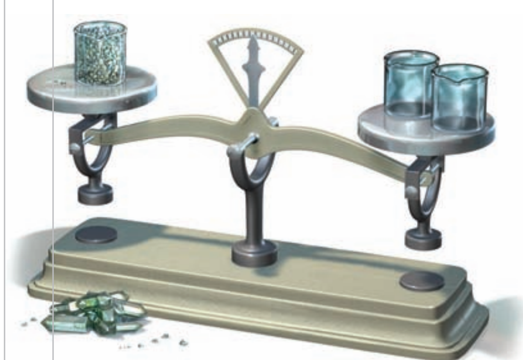
02.03.b2 Hematite

02.03.b4 Magnetite

4. *Magnetism*—A few iron-bearing minerals are naturally magnetic. The mineral *magnetite* is the strongest natural magnet. It is attracted to other magnets, and its magnetism can be strong enough to deflect a compass needle. Other magnetic minerals are less magnetic than magnetite, but magnetism may still help identify them.

5. *Density*—Some minerals are more dense than others. This property can often be detected by simply holding a mineral and noting how heavy it feels. We call this approach a *heft test.* In the lab, scientists precisely determine the ratio of the density of a substance to the density of freshwater, a property called *specific gravity*.

6. In this example (▶), crushed crystals are placed into a glass beaker on one side of a balance scale and weigh as much as two beakers of water. This sample of dry, crushed crystals is therefore twice as dense as water and has a specific gravity of 2. It would be more dense if it were a solid crystal without air between the crushed pieces. A typical specific gravity of rock is 2.7 (i.e., 2.7 times more dense than freshwater).



02.03.b5

Mohs Hardness Scale

Mohs Hardness Scale (▶) consists of 10 familiar minerals ranked in order of hardness, from 1 to 10. The softest mineral (talc) is 1, and the hardest mineral (diamond) is 10. These numbers describe the *relative* hardnesses of the minerals, but the numbers do not provide a real comparison of their actual hardnesses. Quartz (hardness of 7) is twice as hard as apatite (hardness of 5), and diamond (hardness of 10) is about five times as hard as corundum (hardness of 9).

Hardness and Mineral		Common Objects
1	Talc	
2	Gypsum	Fingernail (2.5)
3	Calcite	Copper wire (3.5)
4	Fluorite	
5	Apatite	Window glass or knife blade (5.5)
6	K-feldspar	
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	

Before You Leave This Page

- ✓ Explain the properties of a mineral that can be observed without using a test.
- ✓ Describe how to test for hardness, streak, effervescence, and magnetism.
- ✓ Explain the meaning of a mineral's specific gravity.
- ✓ Explain the Mohs Hardness Scale.

What Controls a Crystal's Shape?

CRYSTALS CAN HAVE BEAUTIFUL SHAPES. The outward shape of a crystal reflects a combination of factors, including the arrangement of atoms in the crystal and how the crystal's growth was affected by the material around it. What, at an atomic scale, controls the shape of a crystal?

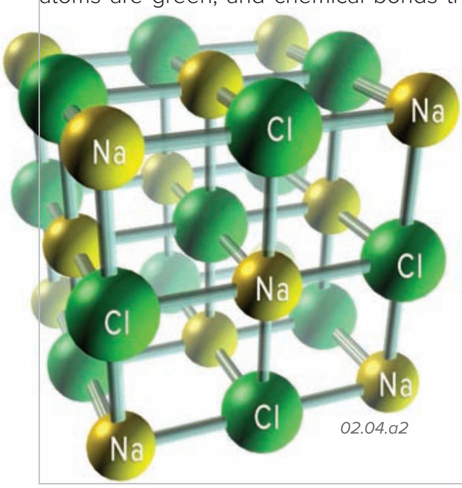
A How Is the Shape of a Mineral Related to Its Internal Structure?

If the growth of a mineral is unconstrained by surrounding materials, the outward shape of the crystal mimics the mineral's internal structure of atoms. The relatively simple outward shape and internal structure of halite nicely illustrate this relationship between the interior and the exterior of a mineral.

1. The photograph below shows natural crystals of table salt, which is the mineral *halite* (NaCl). These crystals grew together and look like a number of cubes connected together.

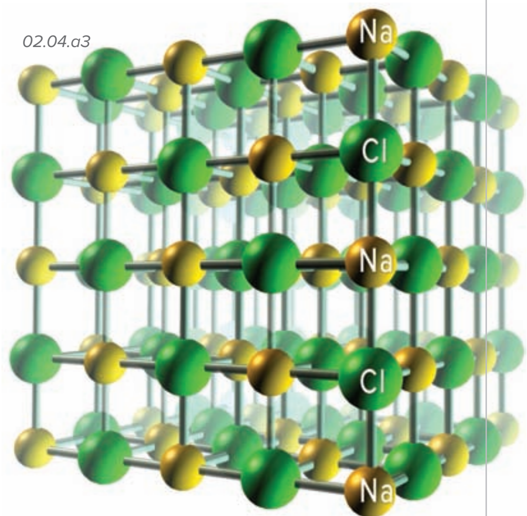
02.04.a1 Halite

2. Mineralogists (geologists and other scientists who study minerals) have documented that halite consists of equal proportions of sodium (Na) and chlorine (Cl) atoms. It has the chemical formula NaCl. Mineralogists have investigated the atomic arrangement of atoms within halite and find that sodium and chlorine atoms have a geometric arrangement that is like a cube. In the figure below, sodium atoms are yellow, chlorine atoms are green, and chemical bonds that link adjacent atoms are represented by stick-like connectors. Note that the green chlorine atom in the center of the structure is surrounded by and bonded with six sodium atoms. Other minerals have more complicated shapes or chemical formulas, but we use halite here because it is so simple.



02.04.a2

3. In a crystal, one part of the atomic arrangement repeats indefinitely to make the entire crystal. In halite, the smallest part is one pair of sodium (Na) and chlorine (Cl) atoms. Sodium and chlorine atoms alternate in three perpendicular directions. Note that in this figure, whether you go up-down, left-to-right, or front-to-back, Na and Cl alternate in the crystalline structure.



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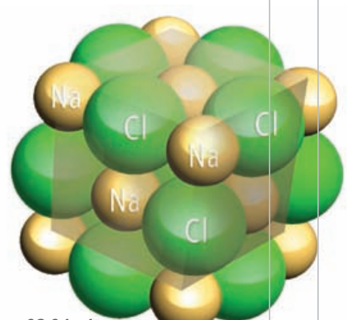


02.04.a4

4. A different way to represent crystals is to show atoms as spheres that fit together and touch (◀). This type of model more accurately represents the relationship between adjacent atoms and their electrons, but it is more difficult to see the internal structure. Note that for halite, the relative sizes of sodium (Na) and chlorine (Cl) atoms allow them to pack together tightly in a cube-shaped arrangement. The atoms in halite are so tiny that a one-inch cube of halite contains more than 100,000,000,000,000,000,000,000 [10^{23}] pairs of Na and Cl atoms.

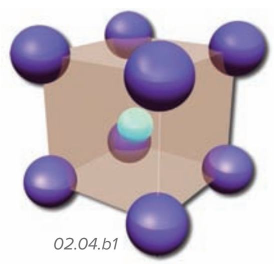
5. In addition to growing as cubic crystals, halite will also cleave into cube-shaped or shoebox-shaped fragments. If you examine table salt with a magnifying glass, you will observe that most salt grains are tiny cubes or slightly elongated boxes, like the halite crystal shown here. Note the cube-shaped to rectangular "steps" where pieces have broken off the front corner of the crystal, a result of the cleavage characteristic of halite.

02.04.a5 Halite

B How Are Atoms Arranged in a Mineral?

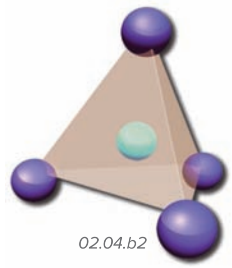
Atoms fit together in a limited number of ways. How closely atoms can be packed together depends on their electrical charge (positive versus negative) and the relative sizes of different kinds of atoms (e.g., smaller Na atoms fit between larger Cl atoms). A single atom typically bonds to 3, 4, 6, 8, or even more atoms. Atoms of similar charge repel each other, whereas atoms of opposite charge attract, and so atoms are generally arranged in geometric patterns. Three common arrangements of atoms are shown below, but other, more complicated arrangements are common.

Atoms can be arranged in the shape of a cube. This type of structure is referred to as *cubic*.



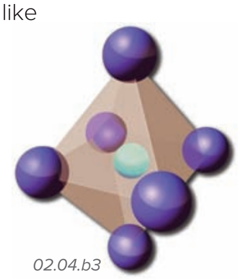
02.04.b1

One atom can be surrounded by four other atoms, arranged as a pyramid with three sides and a base. This arrangement and four-sided shape is called a *tetrahedron* (tetra = four).



02.04.b2

Atoms can be arranged in a shape that is like two oppositely pointing, four-sided pyramids joined at their bases. This shape is an *octahedron* (octa = eight).



02.04.b3

C How Is the Shape of a Crystal Affected by the Environment in Which It Grows?

For a crystal to attain a perfect shape, it must grow unimpeded by surrounding material. Most nicely shaped crystals grew in an open space, in water or in magma; their growth was not constrained by other, preexisting crystals. When crystals grow within solid rock or around preexisting crystals, they generally do not have such well-formed shapes.

These crystals have well-defined shapes, flat crystal faces, and sharp ends called *terminations*. Most such crystals grew into a space filled with hot or cold water rather than solid rock.

02.04.c1 Calcite

02.04.c2 Polished Slab

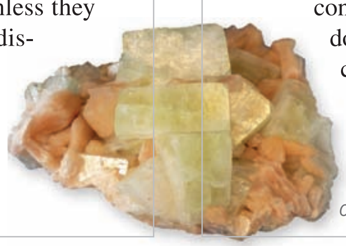
In this rock, partially transparent gray quartz is in irregularly shaped masses that fill the spaces between and around the white and red minerals. The quartz grew after the other minerals were already there, so it had to conform to their shapes.

States of Matter: Solids, Liquids, and Gases

The most fundamental attribute of a material is its *state of matter:* whether it is a solid, liquid, or gas. Materials that are *solid* have a relatively fixed shape and volume because their atoms are packed closely together and connected, or bonded, to one another, like the crystals shown below. Rock, minerals, and volcanic glasses are solids and retain their shape and volume unless they are being actively deformed, dissolved, or perturbed in some other way.

In contrast, a *liquid* easily changes shape, conforming to its surroundings, as when water fills a glass. Atoms in a liquid are held together, but weakly enough that the material is mobile and can change shape. A liquid maintains a relatively constant volume, unless it is subjected to changes in temperature (heated or cooled) or in pressure, as occurs to waters below the earth's surface.

In a gas, atoms and molecules are even less connected and more mobile. A gas does not have a constant shape or constant volume; it will conform to the shape of its container and expand or contract according to how much space is available.



02.04.t1 Apophyllite/Stilbite

Before You Leave This Page

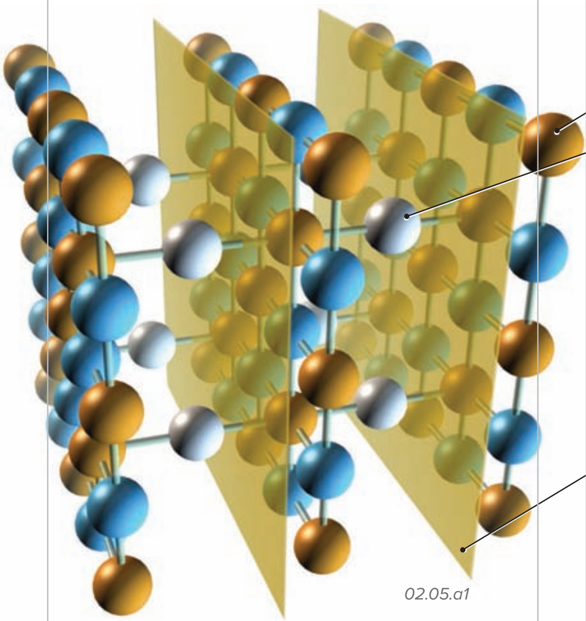
- ✓ Explain what it means to say that crystals have an ordered atomic arrangement, using the crystal form of halite as an example.
- ✓ Sketch and describe three common ways in which atoms are arranged in a mineral.
- ✓ Explain how the shape of a crystal is affected by the environment in which the crystal grows.
- ✓ Summarize the three states of matter.

What Causes Cleavage in Minerals?

CLEAVAGE IS THE TENDENCY OF MINERALS TO BREAK along parallel planes. Some minerals cleave into cubes, and others cleave into thin sheets. Still other minerals break along irregular fractures instead of cleavage planes. Cleavage is controlled by the arrangement of atoms in a mineral and the strengths of the bonds between atoms.

A What Happens at an Atomic Scale When a Mineral Cleaves?

The same orderly arrangement of atoms that causes crystals to form with specific shapes can also affect the way crystals break. Breaking a mineral requires applying enough force to break the links—bonds—between adjacent atoms. In many minerals, different bonds have different strengths, so the mineral breaks preferentially (cleaves) along the easiest directions and through the weakest bonds.



02.05.a1

1. This mineral consists of three kinds of atoms shown here in brown, blue, and gray.

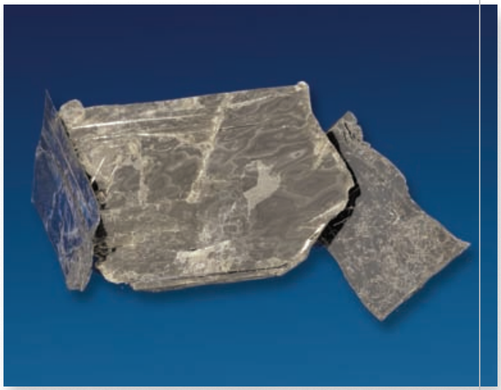
2. The brown atoms are linked with (bonded to) the blue atoms, forming flat sheets.

3. Adjacent sheets are joined together by long bonds between the gray atoms and the brown atoms in the sheets on either side.

4. Bonds between the brown and blue atoms (within the sheets) are stronger than bonds between the brown and gray atoms (linking the sheets). If the mineral is subjected to sufficient force, the force will break the weakest bonds (those between the brown and gray atoms). The breaks will occur along the cleavage planes shown in yellow.

5. With this type of arrangement of atoms and bonds, the mineral will cleave along one set of planes, splitting into thin sheets, like the cleaved pieces of mineral shown here (▶).

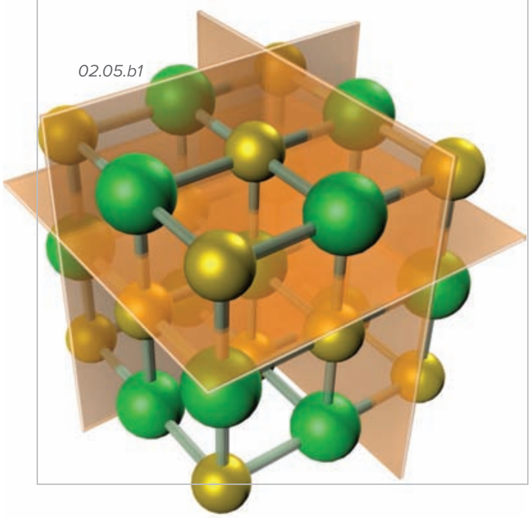
02.05.a2 Biotite



B What Happens if All of the Bonds Have the Same Strength?

In the example above, one set of bonds is relatively weak and so forms a natural place for breaking across the mineral. How does the mineral break if all the bonds have similar strengths or if the arrangement of atoms and bonds does not allow the crystal to break along any planes?

02.05.b1



The bonds in this mineral (◀) all have a similar strength but are arranged in such a way that the mineral can break along three sets of planes without passing through an atom. In this example, the three planes are mutually perpendicular (at 90° to each other).

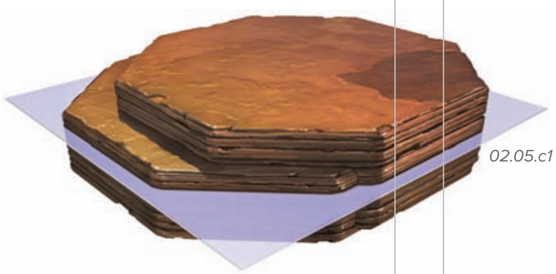
02.05.b2 Quartz

The bonds in this mineral (◀) are not arranged into a configuration that allows any cleavage planes to form. Instead, the crystal has broken like glass, along irregular curved *fractures* instead of along cleavage planes. A crystal that fractures in this irregular way can still contain well-defined planes, called *crystal faces*, that formed during the growth of the crystal. In such minerals, the way in which the crystal grows can be different than the way in which it breaks.

C What Are Some Common Types of Cleavage?

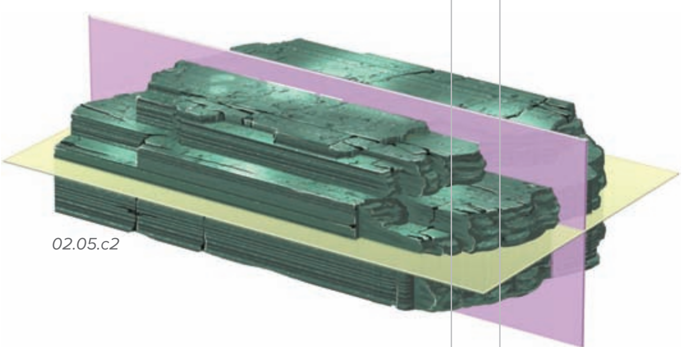
If a mineral has cleavage, it can cleave along one or more sets of parallel planes. Two sets of planes might be perpendicular (90°) to one another or might intersect at some other angle. In the diagrams below, colored planes show the orientation of possible cleavage planes. The specific mineral groups mentioned below are shown and described on later pages.

One Direction of Cleavage



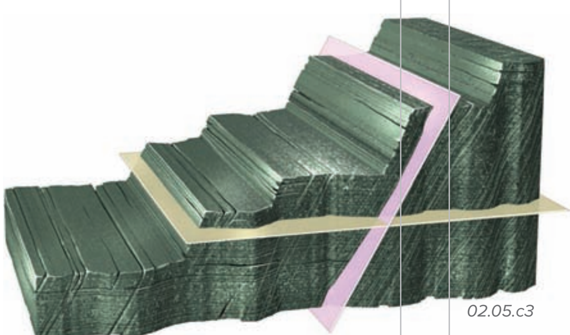
If a mineral has a single direction of cleavage, it cleaves along one set of parallel planes, forming thin sheets. Examples of a single direction of cleavage are members of the mica group of minerals.

Two Perpendicular Directions of Cleavage



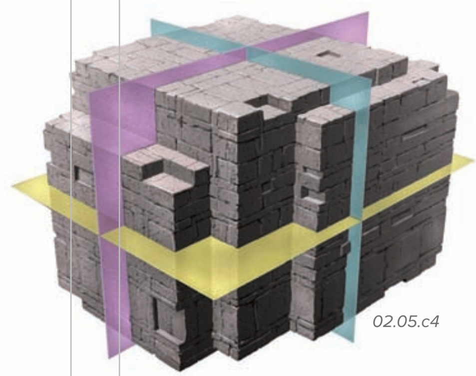
Many minerals cleave along two sets of planes that are perpendicular to one another. This type of cleavage results in right-angle (90°) steps along broken crystal faces. The pyroxene mineral group has right-angle cleavage.

Two Non-Perpendicular Directions of Cleavage



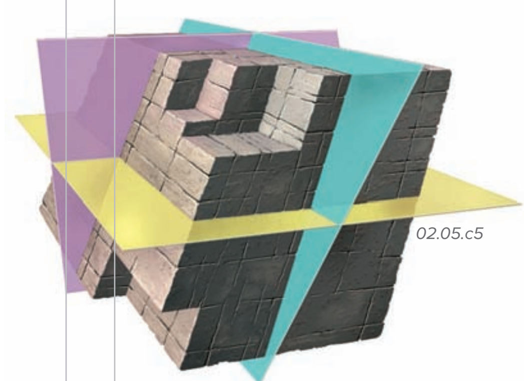
Two planes of cleavage can intersect at angles other than 90°. Minerals with this type of cleavage can break into pieces having corners that do not form right angles. The amphibole group of minerals has this type of cleavage.

Three Perpendicular Directions of Cleavage



If a mineral cleaves along three perpendicular sets of planes, broken faces have a stair-step geometry and the mineral commonly breaks into cubes, as is typical of halite.

Three Non-Perpendicular Directions of Cleavage



Minerals that cleave along three directions of planes that are not mutually perpendicular break into pieces that are shaped like a *rhomb*, or a sheared box. Calcite is the most common mineral that cleaves into rhombs.

Before You Leave This Page

- ✓ Explain or sketch the relationship between cleavage and the arrangement and strengths of bonds.
- ✓ Explain what happens if a mineral lacks planes along which it may cleave.
- ✓ Sketch and describe five types of cleavage.

How Are Minerals Classified?

WITH NEARLY 100 NATURALLY OCCURRING ELEMENTS, it should not be a surprise that there are thousands of different minerals. Some minerals are so rare that they occur only in unusual environments, but others are so common they are almost everywhere on Earth's surface. Here, we concentrate on minerals that are very common and are critical to our understanding of Earth's landscapes and processes.

A How Are Similar Chemical Elements Grouped in the Periodic Table?

Chemical elements are the fundamental building blocks of minerals, so we classify minerals into several *mineral groups* based on the main chemical components within those minerals. Before discussing these mineral groups, we take a tour of the chemical elements via the *Periodic Table*, a useful way to organize the elements.

1. Each element in the Periodic Table has an *atomic symbol*, one or two letters representing the name of the element (commonly the name in *Latin*) and an *atomic number* (shown to the upper left of the symbol). Elements that share a background color on the table share some similar chemical properties.

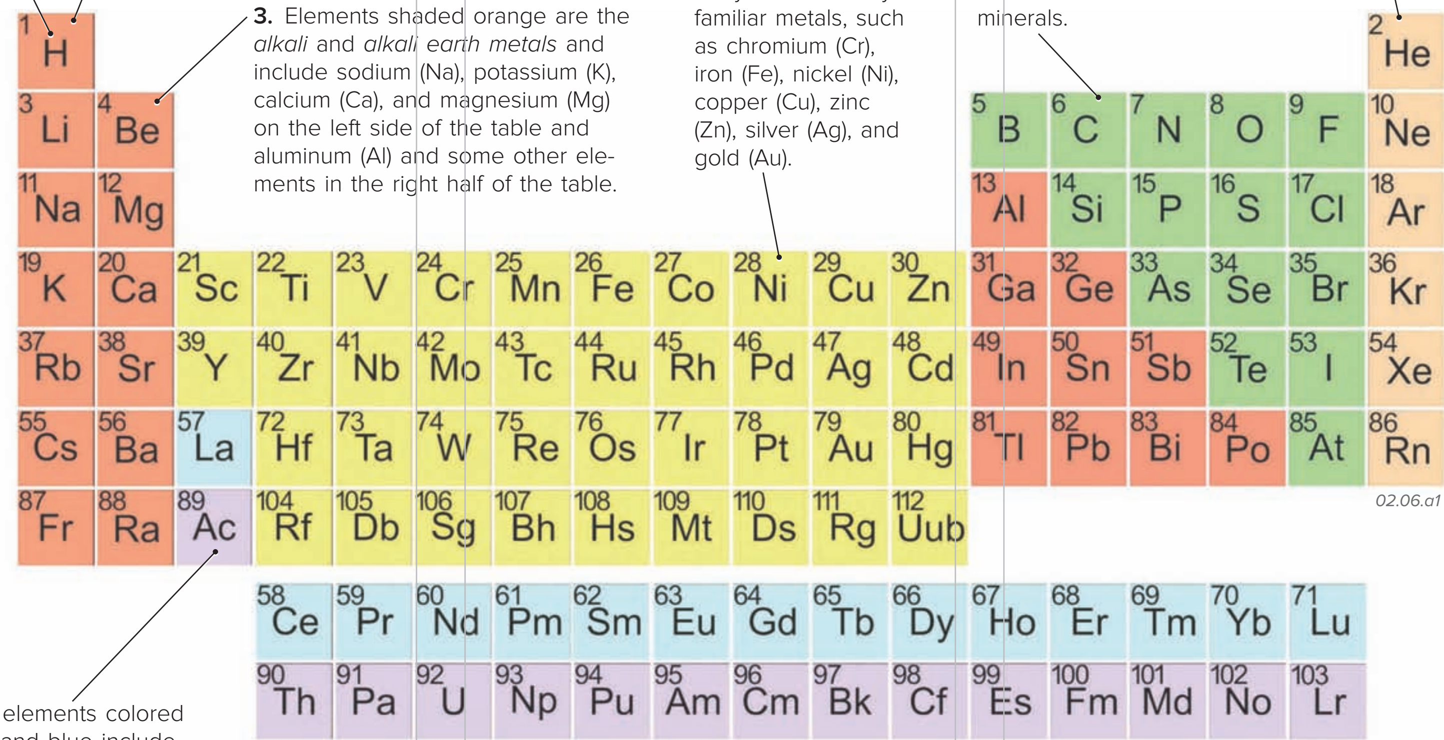
2. The table begins with hydrogen (H), the lightest element, and advances to higher atomic numbers and heavier elements from left to right and from top to bottom.

3. Elements shaded orange are the *alkali* and *alkali earth metals* and include sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) on the left side of the table and aluminum (Al) and some other elements in the right half of the table.

4. Elements colored yellow are called *transition metals.* They include many familiar metals, such as chromium (Cr), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), silver (Ag), and gold (Au).

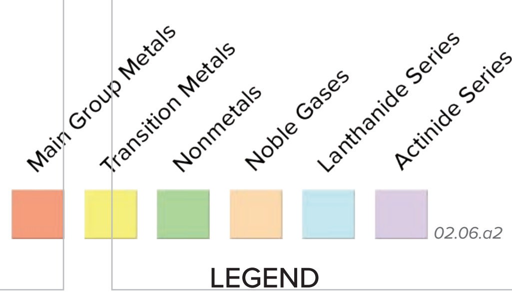
5. The elements colored green are *nonmetals* and include carbon (C), silicon (Si), and oxygen (O). The nonmetals typically bond with both types of metallic elements to form minerals.

6. The last column includes elements called *noble gases* because they are gases that do not readily combine with other elements.



7. The elements colored purple and blue include some familiar elements, such as uranium (U), and many that are less familiar. Elements with atomic numbers higher than 92 are not known in natural settings (these are produced only in the laboratory), except for plutonium (Pu), which is produced naturally only in unusual circumstances by natural nuclear reactions.

8. The lightest and simplest elements, hydrogen (H) and helium (He), are the most abundant elements in the universe. The elements oxygen (O) and silicon (Si) make up 74% of Earth's crust, with the rest being mostly aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg). Consequently, the most common minerals that we see are made of oxygen and silicon, with lesser amounts of the other common elements.



B What Are the Major Classes of Rock-Forming Minerals?

The most important rock-forming minerals can be divided into several classes based on their chemistry. The Periodic Table provides a useful framework.

02.06.b2 Quartz

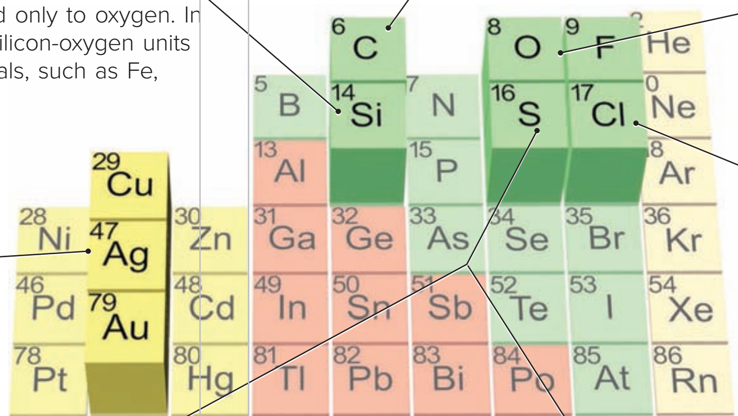
1. *Silicates*, including the mineral *quartz* (◀), are the most important mineral group on Earth. They contain silicon and oxygen, the two most abundant elements in the crust, and so are very common. In silicates, each silicon atom is bonded only to oxygen. In most silicate minerals, the silicon-oxygen units are linked by bonds to metals, such as Fe, Mg, Na, K, Ca, and Al.

2. *Carbonates* contain carbon and oxygen bonded together in a triangular arrangement. The triangles are linked together by other elements, most commonly the metal calcium (Ca). An example is the mineral *calcite* ($CaCO_3$). ▶

02.06.b3 Calcite

02.06.b4 Hematite

3. *Oxides* consist of oxygen bonded with a metal, such as iron in the mineral *hematite* (Fe_2O_3). ▶



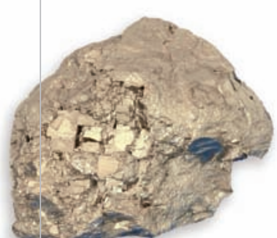
02.06.b1

4. *Halides* contain chlorine (Cl) or fluorine (F), both of which are nonmetals that typically bond with a metal from the left side of the table. *Halite* (NaCl) is a halide mineral (▶).

02.06.b5 Halite

7. *Native minerals* are minerals that contain only a single element. The metals copper (Cu), silver (Ag), and gold (Au) can occur as native minerals or in combinations, called *alloys*, with other metals. Nonmetallic elements that occur as native minerals include sulfur (S) as *native sulfur* and carbon (C) as *graphite* and *diamond*.

6. *Sulfides* contain sulfur (S) bonded with a metal, such as iron (Fe) or copper (Cu). The mineral *pyrite* (FeS_2), also called "fool's gold," is a common sulfide (▶).



02.06.b7 Pyrite

5. *Sulfates* contain sulfur (S) that is only bonded to oxygen. The sulfur-oxygen units are bonded to a metal, such as calcium (Ca) or iron (Fe). *Gypsum* ($CaSO_4 \cdot 2H_2O$) is a common sulfate (▶).

02.06.b6 Gypsum

Asbestos: The Importance of Mineral Classification

Asbestos has long had the reputation of being a dangerous material. Asbestos was used on pipes, ceilings, and ships because of its excellent fire-retarding and insulating properties. Some health studies have shown that asbestos dust, when inhaled, can cause cancer and other serious health problems. But what is asbestos, and is the health story simple?

The term *asbestos* does not refer to a single mineral, but instead refers to a number of silicate minerals whose common characteristic is that they tend to form fibers. Five types of asbestos belong to a group of silicate minerals called *amphiboles*, including a variety known as "blue" asbestos, which forms individual, straight fibers. Medical studies have shown conclusively that "blue" asbestos poses a severe health risk.

In contrast, the type of asbestos most commonly used in the United States is *chrysotile*, a fibrous form of the silicate mineral *serpentine*. Chrysotile has a totally different mineral structure than the other types of asbestos and occurs in fibers that are curved and form interlocking bundles. Studies of this "white" chrysotile asbestos indicate that it is much less hazardous than blue asbestos, mostly causing problems if breathed in large amounts for a long time, as occurs with chrysotile miners. The medical community and Environmental Protection Agency (EPA) are at odds with many scientists because the medical studies and the EPA traditionally have lumped all asbestos into the same category rather than considering the health risks of each kind separately. As a result, hundreds of billions of dollars may be spent, perhaps needlessly, removing *chrysotile* asbestos from schools, businesses, and other facilities.

Before You Leave This Page

- ✓ Describe the Periodic Table, including the locations of the main groups of chemical elements (metals, transition metals, nonmetals, and noble gases).
- ✓ List the major classes of minerals and discuss the main chemical characteristic of each class.
- ✓ Describe two types of asbestos and the health controversy over asbestos.

What Is the Crystalline Structure of Silicate Minerals?

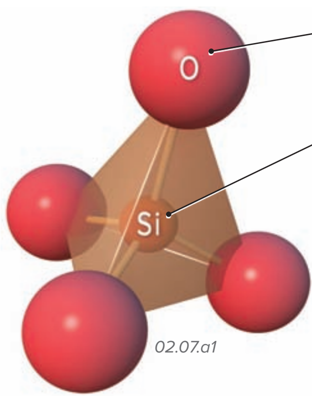
SILICATE MINERALS ARE THE MOST IMPORTANT rock-forming minerals because they comprise most of Earth's crust and mantle. There are different groups of silicate minerals, and the different groups have distinctive cleavage and other mineral characteristics. Here, we explore the types of silicate minerals, from atoms to crystals.

A What Do Silicate Minerals Contain?

In most silicates, one silicon atom is bonded with four oxygen atoms to form the negatively charged SiO_4^{4-} complex. This SiO_4^{4-} complex has a very important shape, called a *tetrahedron*, that controls many aspects of silicate minerals. The silicon-oxygen tetrahedron forms a building block for the vast majority of the minerals on Earth.

Silicon-Oxygen Tetrahedron

1. The four oxygen atoms and one silicon atom combine in an SiO_4^{4-} complex, which can be represented by a four-pointed pyramid called a *tetrahedron*.



02.07.a1

2. An oxygen atom is at each corner of the pyramid.

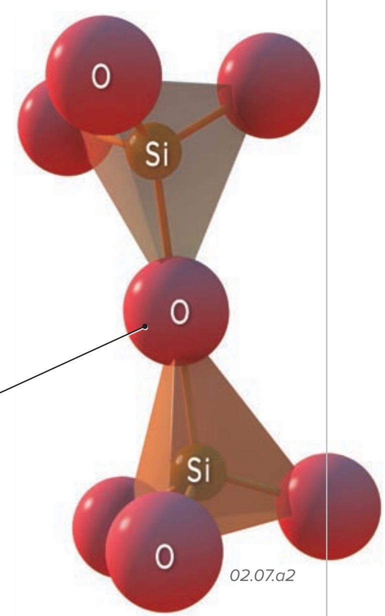
3. A much smaller silicon atom is in the center of the pyramid.

4. The SiO_4^{4-} complex takes the shape of a tetrahedron because the four oxygen atoms have similar atomic charges and so repel each other. The oxygen atoms move as far as possible from each other, taking positions that define the shape of a tetrahedron.

Linked Silicon-Oxygen Tetrahedra

5. A silicon-oxygen tetrahedron has a negative electric charge that allows it to bond with other tetrahedra. Each oxygen atom in the tetrahedron is a naturally protruding site ready to bond to other elements and chemical complexes.

6. An oxygen atom can be shared by two adjacent tetrahedra. In this manner, silicon-oxygen tetrahedra can link together to form different types of silicate minerals.

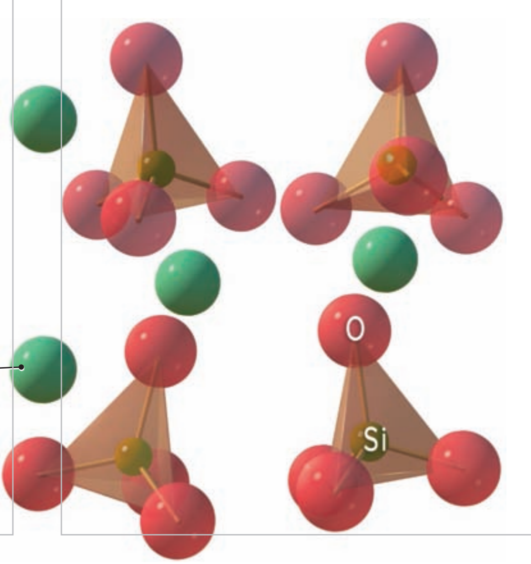


02.07.a2

Silicon-Oxygen Tetrahedra and Metallic Elements

7. In addition to bonding to one another, silicon-oxygen tetrahedra bond with other elements, such as the green atoms shown in this figure. The bonds to the green atoms are not shown.

8. Silicon-oxygen tetrahedra have a negative electrical charge and so attract positively charged atoms, called *cations* (the green atoms).



02.07.a3

9. A huge variety of minerals results from the ability of silicon-oxygen tetrahedra to bond with other silicon-oxygen tetrahedra, with various cations, and with other chemical substances. There are thousands of known minerals, but most are uncommon to rare. Several dozen minerals, many of which are silicate minerals, compose most rocks we encounter at the surface. A typical rock contains one to five main minerals, with a small number of less abundant minerals, many of which are visible only under a microscope. So learning only a few minerals helps you to identify most rocks.

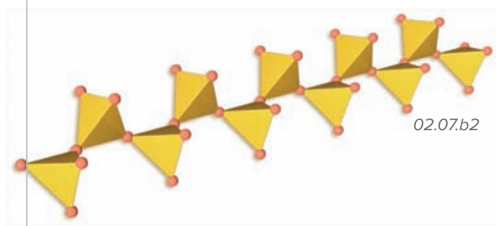
B What Are the Different Types of Silicate Minerals?

Silicon-oxygen tetrahedra can be connected in five main ways, each producing a major group of silicate minerals that share common characteristics. Bonds that link one tetrahedron to another are strong, but bonds to other elements between tetrahedra provide planes of weaker bonds, allowing most silicate minerals to cleave. A silicate mineral's cleavage, or lack of cleavage, reflects how the tetrahedra are arranged. The silicon-oxygen tetrahedra are shown below with the oxygen atoms on each corner.

Independent Tetrahedra

1. Some minerals contain silicon-oxygen tetrahedra that are bonded to other elements (not shown), but not to other tetrahedra. Minerals in this group, including *olivine*, do not break along clearly defined planes because bonds are more or less equally strong in all directions.

Single Chains

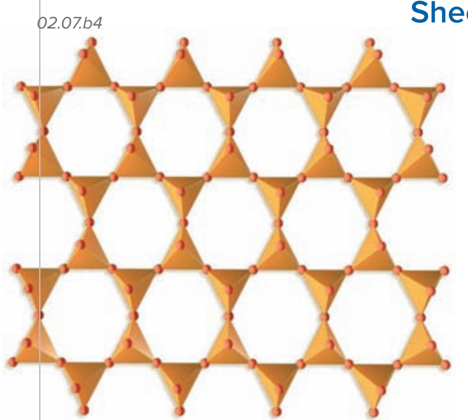


2. Tetrahedra may form *single chains* by sharing two oxygen atoms. The chains are strongly bonded and difficult to break, so cleavage cuts parallel to, rather than across, the chains. This results in two planes of cleavage that are nearly perpendicular (90° angle) to each other. Minerals that belong to this group are called *pyroxene minerals,* or simply *pyroxenes.*

Double Chains

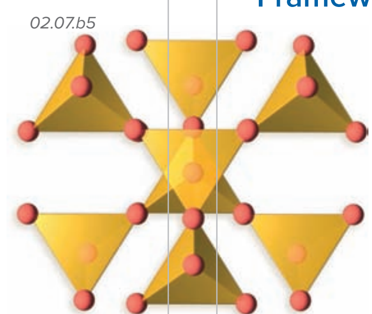
3. Tetrahedra can also form *double chains* if half the tetrahedra share two oxygen atoms and half share three, as shown here. Such minerals cleave parallel to the double chains and along two planes of cleavage separated by angles of 60° and 120°. Minerals of this group are called *amphibole minerals,* or simply *amphiboles.*

Sheets



4. In *sheet silicates*, tetrahedra share three oxygen atoms to form continuous sheets. Other elements and water molecules can fit between the sheets, forming minerals with layered structures. Bonds between sheets are weak, so these minerals have one main direction of cleavage parallel to the sheet structure. The most common sheet-silicate minerals are *micas* and *clay minerals*.

Frameworks



5. Tetrahedra in *framework silicates* share all four oxygen atoms, forming a structure bonded well in three dimensions. *Quartz*, and a few rarer framework silicates, contain only silicon-oxygen tetrahedra bonded to each other. Quartz is hard and has no cleavage, so it fractures instead. Some framework silicates have other elements in the structure between the silicon-oxygen tetrahedra, providing several planes of cleavage. Minerals belonging to the *feldspar group* are good examples of framwork silicate minerals with cleavage.

Silicon, Silica, and Silicone

These three similar words can be confusing, so let's explore what each one means.

Silicon is the fourteenth element of the Periodic Table, having atomic symbol Si. The name silicon also is used for a *synthetic* material—a material produced by humans that does not occur naturally. Synthetic silicon is a semiconductor used to make computer chips.

Silica refers to a compound containing only silicon and oxygen in a ratio of 1:2, so it has the formula SiO_2. Quartz is 100% silica. Although each silicon atom in quartz is bonded to four oxygen, each oxygen is shared between two silicon, so the ratio Si:O is 1:2. Geoscientists speak about silica more than about silicon because silicon is nearly always bonded with oxygen in rocks and minerals.

Silicone is a *synthetic* material in which carbon is bonded to silicon atoms to keep the material in long chains. These chains make silicone a material that can be used as a type of grease or as caulk for sealing around windows and doors.

Before You Leave This Page

- ✓ Sketch or explain a silicon-oxygen tetrahedron and how one can join with another tetrahedron or a cation.
- ✓ Explain or sketch how silicon-oxygen tetrahedra link in five different geometries to produce five silicate mineral groups.
- ✓ Explain the differences between silicon, silica, and silicone.

What Are Some Common Silicate Minerals?

SILICATE MINERALS ACCOUNT FOR OVER 90% of the minerals in Earth's crust. Most silicate minerals also contain other elements, commonly aluminum (Al), calcium (Ca), sodium (Na), potassium (K), iron (Fe), and magnesium (Mg). The presence and amounts of these elements influence the crystalline structure, which in turn determines mineral properties, such as color and cleavage.

A What Are Some Light-Colored Silicate Minerals?

The most common silicate minerals in the upper part of the continental crust have light colors and typically are white, light gray, and light pink. Some of these minerals are almost transparent, and some have a reflective, silvery color. Light-colored silicate minerals predominate in the upper continental crust and are present in smaller amounts in rocks of the oceanic crust and the mantle. Such light-colored silicate minerals are called *felsic*, a term combining the words "feldspar" (a family of minerals described below) and "silica."

02.08.a1

Quartz—This very common mineral, with a formula of SiO_2, is generally transparent to nearly white, but it can be pink, brown, or purple. Its silicon (Si) and oxygen (O) atoms are strongly bonded in a tight, three-dimensional *framework*, so quartz is hard (Mohs hardness of 7) and does not cleave. Instead, it breaks along fractures that have irregular or smoothly curving surfaces that are described as being *conchoidal*, as on the broken, front face of the right crystal. The front crystal has well-developed crystal faces that formed during growth of the crystal, but the bottom is a rough fracture.

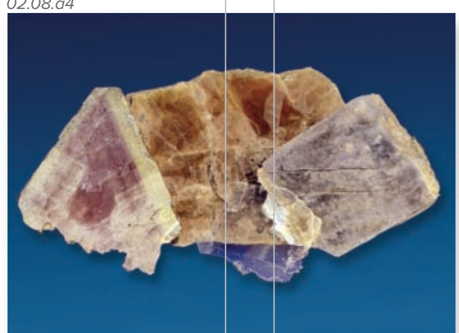
02.08.a2

Potassium Feldspar— Potassium feldspar, often just called *K-feldspar*, contains potassium (K), aluminum (Al), silicon, and oxygen, with lesser amounts of sodium (Na) and calcium (Ca). It generally is a pink-to cream-colored mineral, but in volcanic rocks, it can be nearly transparent. Many K-feldspar crystals display two directions of cleavage, and some show wavy, light-colored lines on crystal surfaces, as shown here. K-feldspar is abundant in all granites, and it is common in many other igneous, sedimentary, and metamorphic rocks.

02.08.a3

Plagioclase—Plagioclase is one of the two most common feldspar minerals. Feldspars are a group of framework silicates that contain varying amounts of potassium (K), sodium (Na), calcium (Ca), and aluminum (Al), in addition to silicon and oxygen. In plagioclase, the potassium content is close to zero percent. Plagioclase exhibits a complete gradation from Na-rich varieties, which are nearly white to cream colored, to Ca-rich varieties, which are dark gray or brown. However, most plagioclase has a whitish to light-gray color. Some crystal faces display straight lines called *striations*, as shown on the left front crystal here.

02.08.a4



Muscovite—This sheet-silicate mineral is part of the *mica* family, whose members all have one direction of cleavage and so break into flakes and sheets. It typically is partially transparent, a clear to silvery-gray color, and somewhat shiny because the flat surfaces of the sheets reflect light. Muscovite contains potassium (K) and aluminum (Al), in addition to silicon and oxygen. Its atomic structure contains a component of water, expressed in its chemical formula as $(OH)^-$. The bonds holding the sheets together are stronger than the bonds between sheets, so sheets can be peeled apart with your fingers.

Before You Leave These Pages

- ✓ Describe the main light- and dark-colored silicate minerals, including their general characteristics, such as cleavage and main elements.
- ✓ Discuss the characteristics of clay minerals and how they form.

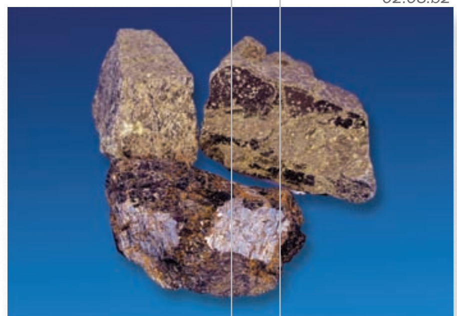
B What Are Some Dark-Colored Silicate Minerals?

Dark silicate minerals predominate in dark igneous and metamorphic rocks and also are many of the dark crystals scattered within otherwise light-colored rocks. They form most of the oceanic crust and the mantle and are present in variable amounts in continental crust, especially the lower crust. Dark-colored silicate minerals are also called *mafic minerals* to acknowledge their high magnesium (Mg) and iron (Fe) content.

02.08.b1

Amphibole—The term *amphibole* refers to a group of related silicate minerals. Amphibole minerals can contain magnesium, iron, calcium, sodium, and aluminum, in addition to silicon and oxygen. They can be black, dark green, pale green, or nearly white. They commonly form crystals that are long compared to their width, like the long green crystals that are present in the back specimen. Amphiboles are double-chain silicates and so cleave along planes that meet to form angles of 60° and 120°.

02.08.b2



Pyroxene—The term *pyroxene* refers to a group of single-chain silicate minerals that share a similar crystal structure. Pyroxene minerals can include various amounts of calcium, sodium, aluminum, iron, and magnesium in addition to silicon and oxygen. Their color can be black, dark brown, green, or nearly white. Most pyroxenes tend to form crystals that are roughly *equant*, meaning that all dimensions are about the same. Pyroxenes have two nearly perpendicular directions of cleavage (90° angles), which helps distinguish them from amphiboles.

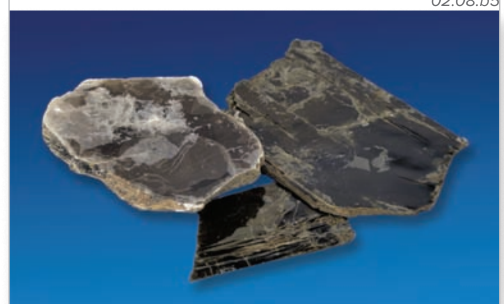
02.08.b3

Olivine—Olivine is the most common mineral in the upper mantle and usually has a distinctive olive-green color. It has independent tetrahedra linked by iron or magnesium, and no cleavage. Its composition varies between iron-rich and magnesium-rich end members, but samples from the mantle are magnesium rich.

02.08.b4

Garnet—Garnets are silicates that can be just about any color, but a deep red color is very common. The crystals are distinctive, having 12 diamond-shaped faces when perfectly formed. The reason color is so variable is because chemistry is variable. Garnets contain silica with variable amounts of calcium, iron, magnesium, manganese, and aluminum.

02.08.b5



Biotite—Biotite is a dark-colored mica (sheet silicate) that is typically black or brown. All biotite contains potassium, aluminum, silicon, and oxygen, with variable amounts of iron and magnesium. Brown biotite, commonly having a tint of bronze, is rich in magnesium and contains little iron. Like all micas, biotite has one dominant direction of cleavage.

Clay Minerals

The term *clay* is used in two ways in earth science. It refers either to a family of minerals or to any very fine sedimentary particles that are less than 0.002 millimeters in diameter. Clay minerals have a sheet-silicate structure similar to that of mica, but the bonds holding the atoms together are much weaker. The sheets in clays are weakly held together, so they easily slip past one another, giving clays their slippery feel. When some clay minerals get wet, water pushes apart the weakly bonded sheets, causing some clay minerals to expand.

02.08.t1

Most clay minerals have light colors but may appear dark if mixed with other material, especially dark minerals or organic debris. Most clay minerals form by weathering of rocks at Earth's surface or from chemical reactions that occur when hot water interacts with rocks containing feldspar, volcanic ash, and other reactive materials. Fine grain size and low density mean that clay particles are easily transported. Fine particles of clay can be picked up by wind and water and then transported long distances. Clay can be deposited on land by streams, wind, and other agents of transport, but some clay makes it to the open ocean, where it finally settles to the ocean floor, forming extensive deposits of submarine mud.

What Are Some Common Nonsilicate Minerals?

MANY MINERALS DO NOT INCLUDE SILICON and so are classified as *nonsilicates*. Some of the most common nonsilicate minerals are *carbonates* and *halides,* which typically form by precipitation from water. *Oxides* and *sulfides* form when metal atoms bond with oxygen or sulfur, respectively. Nonsilicate minerals are an important resource for our society and are used widely in industry, highways, and homes.

Carbonates

Carbonate minerals contain a metallic element, such as calcium (Ca) or magnesium (Mg), linked with a carbon-oxygen combination called *carbonate* $(CO_3)^{2-}$. The most common carbonate minerals are *calcite* and *dolomite*. Others include *malachite* and *azurite*, striking green and blue copper carbonates. *Trona*, a sodium carbonate, is an important mineral used to manufacture many products. Carbonates typically precipitate from water or have an organic origin (e.g., corals).

02.09.a1

Calcite—This mineral is the most common calcium-carbonate mineral ($CaCO_3$) and occurs in a variety of water-related environments. It may be almost clear but commonly has a cream to light gray color. It is the only common mineral that effervesces with dilute hydrochloric acid (HCl) because HCl breaks bonds in calcite and releases carbon dioxide (CO_2) gas.

02.09.a2

Dolomite—This mineral is similar to calcite, but magnesium (Mg) substitutes in the structure for some calcium (Ca). It has the formula $CaMg(CO_3)_2$. The mineral is cream-colored, light gray, tan, or brown and may not effervesce with HCl unless pulverized into a fine powder. A rock composed mostly of the mineral dolomite is a *dolostone*. Rocks that contain dolomite also commonly contain calcite.

02.09.a3 Hunt Valley, MD

Most limestones are nearly 100% calcite, and some carbonate rocks contain a mix of calcite and dolomite. Carbonate minerals also occur in coral and shells, including the mineral *aragonite*, which has the same composition as calcite but a different atomic arrangement. When limestone is heated and metamorphosed, calcite grows into larger crystals and the limestone becomes *marble* (▲).

Oxides

Oxide minerals consist of oxygen bonded with iron (Fe), titanium (Ti), aluminum (Al), or other metals. Iron-oxide minerals are the most common oxides, except for ice, which is a hydrogen-oxide mineral (the solid phase of H_2O).

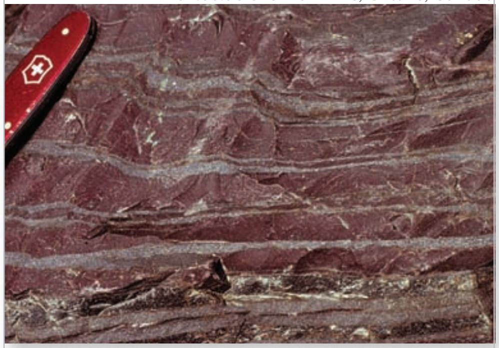
02.09.a4

Hematite—This iron oxide (Fe_2O_3) can be black, brown, silvery gray, or earthy red, but it consistently has a red streak. Hematite is the red color in rust, provides color in some paints, and is responsible for many red-rock landscapes. It commonly forms when other iron-bearing minerals oxidize.

02.09.a5

Magnetite—This iron oxide (Fe_3O_4) is typically black and is strongly magnetic, here attracting a circular magnet. It is present as small black grains in many kinds of igneous, sedimentary, and metamorphic rocks, as well as in beach sands and other sediments.

02.09.a6 Sherman Mine, Ontario, Canada



Magnetite and hematite occur together in beautifully layered sedimentary rocks called *banded iron formations*. Some Precambrian iron formations are mined for iron in the Great Lakes region of the United States and Canada and elsewhere.

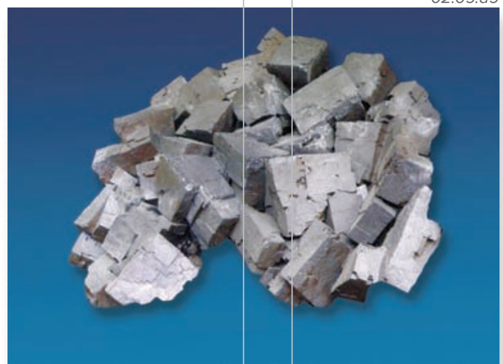
Sulfides

Sulfide minerals contain sulfide ions $(S)^{2-}$ bonded with iron (Fe), lead (Pb), zinc (Zn), or copper (Cu). Sulfide minerals, including the copper-iron sulfide mineral *chalcopyrite*, are the principal metal ores in many large mines. Most sulfide minerals have a metallic luster and can occur as well-formed crystals or irregular masses.

02.09.a7

Pyrite—Pyrite is a common iron-sulfide mineral (FeS_2). It has a pale bronze to brass-yellow color for which it earns the name "fool's gold." It commonly forms cube-shaped crystals with faces showing straight lines (*striations*).

02.09.a9



Galena—This mineral is a lead sulfide (PbS). It forms distinctive metallic-gray cubes with a cubic cleavage. It has a high density (specific gravity), which can be felt easily by picking up a sample (i.e, a heft test). In the United States, many galena crystals are from lead mines near the Mississippi Valley.

02.09.a8, Nova Scotia, Canada

Small crystals of brass-colored pyrite, as shown here, are commonly deposited by hot (hydrothermal) water. Weathering of pyrite can cause adjacent rocks to become coated with yellow and orange, sulfur-rich material, like the stained quartz on the left side of this photograph.

02.09.a10

There are many other important sulfide minerals, including iron sulfides, copper sulfides, lead sulfides, and zinc sulfides. We mine sulfides because of their high metal contents. Most sulfide-rich mineral deposits formed when hydrothermal fluids passed through rock.

Salt and Related Minerals (Halides and Sulfates)

Halide minerals (salts) consist of a metallic element, such as sodium (Na) or potassium (K), and a halide element, usually chlorine (Cl). *Sulfate minerals*, especially *gypsum*, commonly occur with salt. They consist of an element such as calcium (Ca) and a sulfur-oxygen complex ion called sulfate $(SO_4)^{2-}$. Many halides and sulfates form when water evaporates in a lake or from precipitation in a shallow sea with limited connection to the ocean.

02.09.a11

Halite—Halite (NaCl) has cubic cleavage and a salty taste. It generally forms from the evaporation of salty water, such as a drying lake or a part of a sea that becomes cut off from the rest of the oceans. When concentrated in thick beds to make a rock, it is called *rock salt.* We use salt for many household and industrial applications.

02.09.a12

Gypsum—This hydrated calcium-sulfate mineral ($CaSO_4 \cdot 2H_2O$) is typically gray, white, or clear and can be scratched with a fingernail. Most gypsum forms in environments similar to those in which halite forms (evaporation of salty water), and the two minerals commonly occur together. Gypsum also precipitates from hot or warm water that circulated underground through fractures in rocks. Like salt, it is an important mineral to society, being used in wall board to sheath framed walls, in plaster, and as a component of certain types of cement.

Before You Leave This Page

- ✓ Discuss the key chemical constituents for each of the five nonsilicate mineral groups.
- ✓ Describe the major nonsilicate minerals, including their general characteristics such as color, cleavage, and any diagnostic attributes.

What Are the Building Blocks of Minerals?

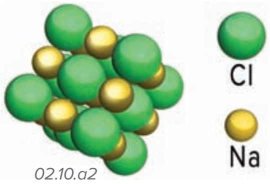
MINERALS ARE COMPOSED OF CHEMICALLY BONDED ELEMENTS. An element is a type of atom that has a specific number of protons (e.g., all hydrogen atoms have one proton, whereas all oxygen atoms have eight protons). The mineral halite can be broken into smaller pieces of halite, but if separated into its chlorine and sodium atoms, it is no longer halite.

A How Are Minerals Related to Elements and Atoms?

An atom is the smallest unit of an element that retains the characteristics of the element. Atoms are made of even smaller particles (including electrons, protons, and neutrons), but if, for example, a single atom of gold could be broken apart, its pieces would no longer be gold.

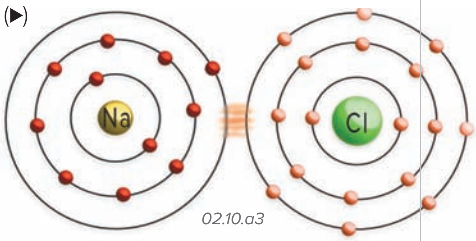
02.10.a1 Halite

◄ The mineral halite consists of atoms of two chemical elements—chlorine and sodium. If halite is dissolved in water, it dissolves (►) to produce salt water containing individual atoms of chlorine and sodium.



02.10.a2

Chlorine (Cl) and sodium (Na) atoms (►) each have a small central nucleus surrounded by electrons at various distances from the nucleus.



02.10.a3

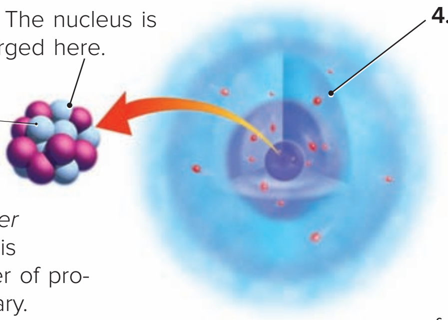
B What Is a Model for the Structure of an Atom?

Atoms are too small to observe, so we use conceptual models to visualize them. The simple two-dimensional model of atoms shown in the previous figure does not fully represent atoms, which are three-dimensional spheres.

1. Atoms have a tiny central core called the *nucleus*. The nucleus is much smaller than the entire atom but is shown enlarged here.

2. The nucleus has two kinds of fundamental particles—*protons* and *neutrons*. Protons, shown in blue, have a positive (+) electrical charge, and neutrons, shown in reddish purple, do not have a charge.

3. The number of protons is called the *atomic number* of an element. The number of neutrons and protons is the atom's *atomic mass*. For any element, the number of protons is consistent, but the number of neutrons can vary.



02.10.b1

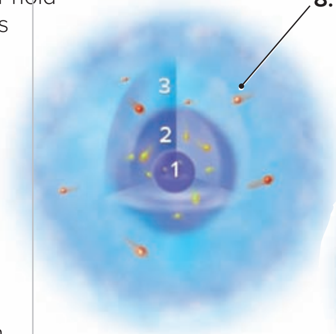
4. Negatively charged (–) electrons, shown in red, surround and can be thought of as orbiting the nucleus. To be electrically neutral, an atom must have the same number of electrons (–) and protons (+). The proton's positive charges attract the atom's electrons, keeping them associated with the nucleus. The area where the electrons travel is called the *electron cloud*, but it really is not a cloud. It is simply a way of showing the area in which the electrons can reside. The outer edge of the cloud defines the size of an atom, but nearly all of the atom is empty space.

Electron Shells

5. Groups of electrons orbit the nucleus at different distances, called *electron shells*. Each shell has a different level of energy, increasing away from the nucleus. The atom below has three shells, numbered 1, 2, and 3.

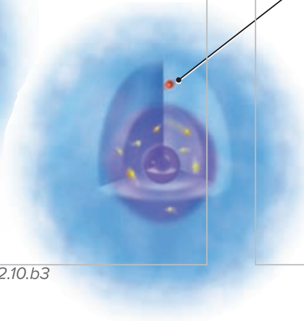
6. The inner shell (1), closest to the nucleus, can hold two electrons. Moving outward, successive shells can hold 8, 18, and 32 electrons. Electrons fill inner shells before they fill outer shells, so the inner shells are full but the outermost shell may only be partially full.

7. Atoms are most stable when their outermost shell is full, so atoms with only a few electrons in an unfilled outer shell may donate electrons to another atom in order to become more stable. Alternatively, atoms with a nearly full outer shell may borrow electrons from another atom to get a full shell and become stable.



02.10.b2

8. This chlorine atom has seven electrons in its outer shell and so can accommodate one more. It would try to gain an electron to fill its outer shell (3).



02.10.b3

9. This atom (sodium) has only one electron in its outer shell and so has a tendency to lose or loan this electron, perhaps donating it to an atom such as the chlorine atom on the left.

10. If an atom *gains* an electron, it acquires an overall *negative* charge. If it *loses* an electron, it acquires a *positive* charge. Charged atoms are called *ions*.

C How Does the Periodic Table Organize the Characteristics of Elements?

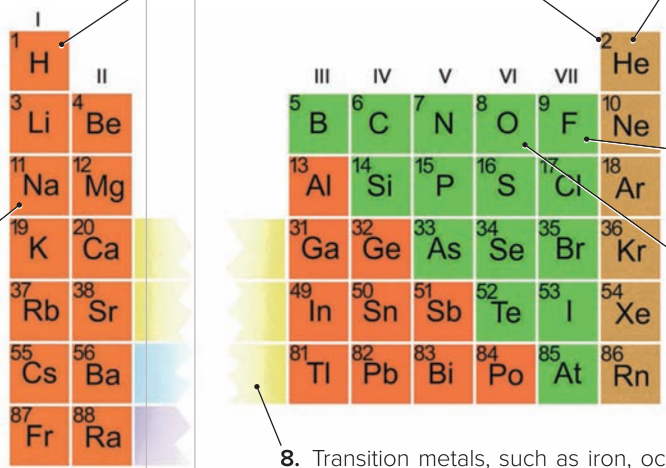
Chemists use the Periodic Table to organize the elements according to the elements' *atomic number* and *electron shells*. The table begins with the lightest element (hydrogen) and advances to the heaviest elements. Below we consider the two left-hand columns and the six right-hand columns because these are the most straightforward.

1. The columns are numbered from I to VII with Roman numerals to indicate the *number of electrons* in the outermost shell.

2. The rows correspond to the *number of electron shells*. Elements in the top row have one shell, those in the second row have two shells, and so forth.

3. Elements in the first column have only one electron in their outer shell. Hydrogen (H) only has one shell (it is in row one), whereas sodium (Na) is in the third row and so has three shells. Recall that the number of outer electrons influences whether an atom loses or gains electrons.

4. The first shell can hold only two electrons, which is why a large gap exists between the right and left sides of the first row.



02.10.c1

5. The last column is reserved for noble gases, which do not easily gain or lose an electron because they have complete outer shells. This column could be numbered with both II and VIII—helium (He) only has two electrons, enough to fill its outer shell, whereas other noble gases in the column have eight or more electrons filling their outer shell.

6. Fluorine (F), in the second row, has two shells. It has seven electrons in its outer shell and so is in column VII. If it could borrow another electron, its outer shell would be full.

7. Oxygen (O) has two shells and six electrons in its outer shell; it needs two more electrons to fill this shell. Two oxygen atoms can fill their outer shells by bonding with a silicon atom, which has four electrons in its outer shell.

8. Transition metals, such as iron, occupy columns in the central part of the table (not shown). They lose and gain electrons from several shells, not just the outermost shell.

Some Practice with the Periodic Table

We can use the Periodic Table to predict how many shells each element has and how many electrons are in its outer shell. Try this for lithium, magnesium, nitrogen, and potassium. After you are done, check your answers in the table to the right. We try this out with chlorine, to show how it works.

Chlorine (Cl): Chlorine is in the third row, so it has three shells. It is in the seventh column (VII), so has seven electrons in its outer shell. It seeks one more electron to complete its outer shell, and this can be accomplished by borrowing an electron from sodium (Na), as in halite (NaCl).

Lithium (Li)—2 shells, 1 electron in outer shell
Magnesium (Mg)—3 shells, 2 electrons in outer shell
Nitrogen (N)—2 shells, 5 electrons in outer shell
Potassium (K)—4 shells, 1 electron in outer shell

Portraying the Atom

Atoms are tiny, but they can be detected by high-powered electron microscopes. We cannot *look* down an optical microscope and see an atom with its nucleus and electrons. Our view of an atom is a *model*—a human-generated representation, or approximation, of what we think is there. Many tests have confirmed that the basic model is valid, but there are limitations. In particular, drawing an atom presents unavoidable problems.

The first problem is one of scale. The nucleus is so tiny compared to the size of the atom that you cannot show an accurately scaled nucleus and still fit the atom on a page. A hydrogen atom, for example, is nearly 150,000 times larger than its nucleus. The electrons, too, are extremely small when compared to an entire atom and so cannot be plotted to scale.

A second problem is how to show the electrons. They are in motion but do not travel around the nucleus in a regular manner. It is tempting to draw electron orbitals the same way we draw planets orbiting our Sun. In reality, an electron can be nearly anywhere within the cloud of electrons, although at any instant it is most likely to be somewhere near the center of its shell. Electron shells represent different *energy levels* more than they represent specific distances away from the nucleus.

Finally, atoms are not hard spheres with well-defined edges. Atoms are more empty space than matter, and their edges are defined by how far out the outermost electrons travel away from the nucleus. We often show atoms as hard-edged spheres because it is much easier to see relationships between solid objects than between fuzzy, partially overlapping clouds. Such depictions, however, are incorrect in detail.

Before You Leave This Page

- ✓ Describe the relationship between a mineral and the elements of which it is composed.
- ✓ Explain or sketch the structure of an atom, including its main particles.
- ✓ Sketch the general shape of the Periodic Table and explain the significance of its rows and columns.