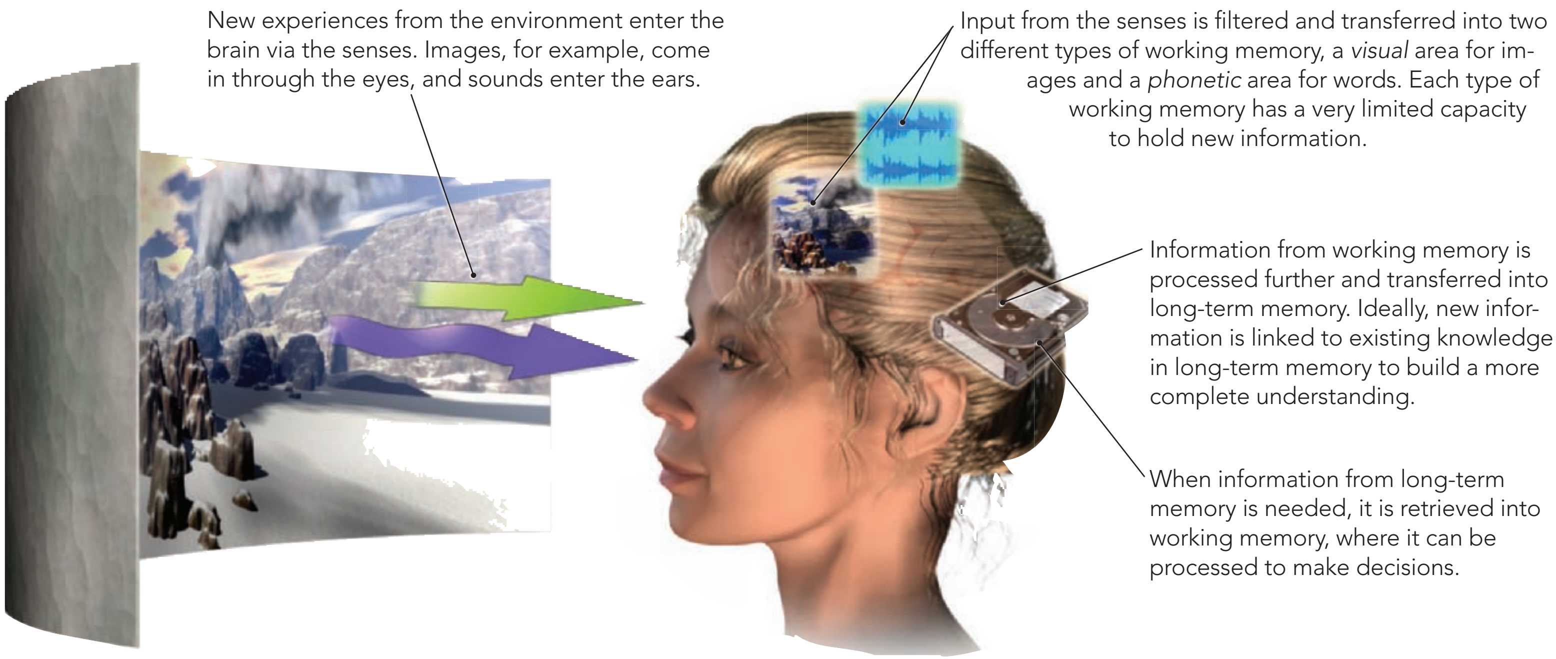
How Is This Textbook Different Than Other Physical Geology Textbooks?

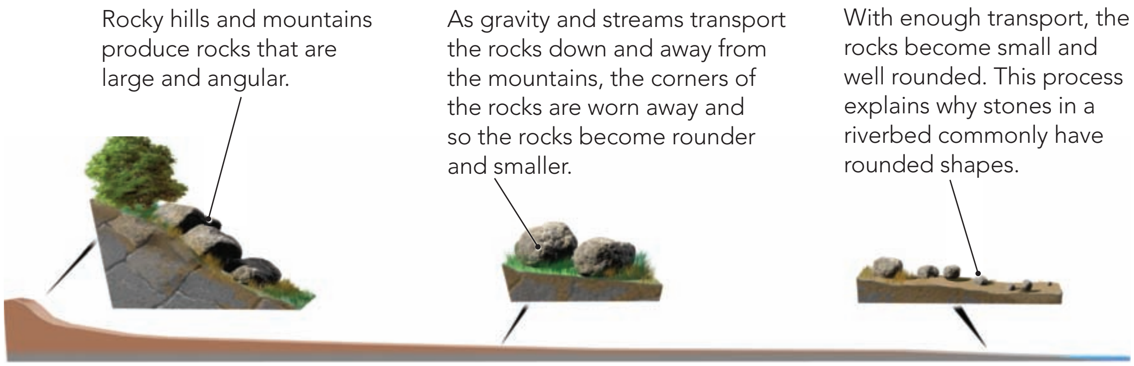
AS YOU EXAMINE *EXPLORING GEOLOGY* you will notice that it is different from other textbooks. You might ask: Why do most pages have few large blocks of text? Why are there over 2,600 illustrations when most introductory geology textbooks have less than 1,000 illustrations? Why do the authors focus on illustrations? In addition to answering these questions, the Preface will explain the text's approach, how a typical chapter is organized, and how you can most efficiently use this textbook for learning geologic concepts and scientific inquiry.

A Why Is the Book Designed Around Figures?

How do we learn new things? Scientists who study thinking and learning speak about two types of memory, working memory and long-term memory. *Working memory*, also called *short-term memory*, holds information that our minds are actively processing, whereas *long-term memory* is like a storehouse in which we file information until we need it. The amount of knowledge we retain depends on transferring information from *working memory* to *long-term memory* and on linking the new information with our existing mental framework.



To utilize both types of working memory and to help link together visual and text information, most information in this book is presented as central figures that are tightly integrated with small blocks of text. Examine this figure and the associated text to see how easily your mind makes sense of the information. ▷



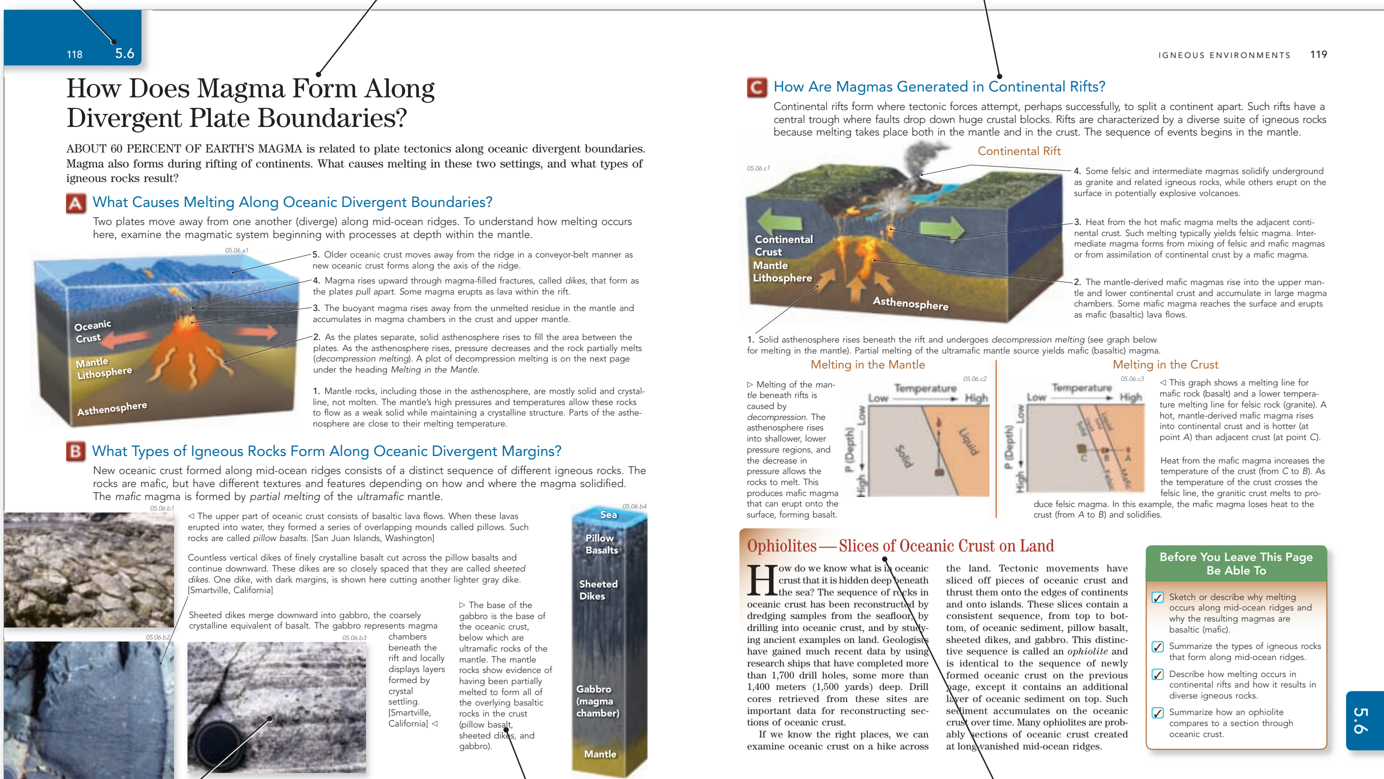
B What Is the Style of the Book?

This book is a new type of textbook intended for an introductory college geology course, such as Physical Geology. The book consists entirely of *two-page spreads* organized in chapters. Each two-page spread, like the one shown below, focuses on one or more important geologic concepts or approaches to geologic problems. These spreads help students learn and organize geologic knowledge in a new and exciting way.

Each two-page spread is a self-contained block of information about a specific topic. Each spread has a unique number, such as 5.6 for the 6th two-page spread in chapter 5.

The title of each spread is a *question* about an important aspect of geology, a way we study geologic problems, or the geology of an interesting place.

Most two-page spreads are subdivided into sections, each of which is a coherent piece of the larger topic. The sections guide students through the pages in an easy-to-follow way and provide a clear break for students to consolidate their knowledge before moving on.



118 5.6

How Does Magma Form Along Divergent Plate Boundaries?

ABOUT 60 PERCENT OF EARTH'S MAGMA is related to plate tectonics along oceanic divergent boundaries. Magma also forms during rifting of continents. What causes melting in these two settings, and what types of igneous rocks result?

A What Causes Melting Along Oceanic Divergent Boundaries?

Two plates move away from one another (diverge) along mid-ocean ridges. To understand how melting occurs here, examine the magmatic system beginning with processes at depth within the mantle.

05.06.a1

Oceanic Crust
Mantle Lithosphere
Asthenosphere

5. Older oceanic crust moves away from the ridge in a conveyor-belt manner as new oceanic crust forms along the axis of the ridge.

4. Magma rises upward through magma-filled fractures, called *dikes*, that form as the plates *pull apart*. Some magma erupts as lava within the rift.

3. The buoyant magma rises away from the unmelted residue in the mantle and accumulates in magma chambers in the crust and upper mantle.

2. As the plates separate, solid asthenosphere rises to fill the area between the plates. As the asthenosphere rises, pressure decreases and the rock partially melts (*decompression melting*). A plot of decompression melting is on the next page under the heading *Melting in the Mantle*.

1. Mantle rocks, including those in the asthenosphere, are mostly solid and crystalline, not molten. The mantle's high pressures and temperatures allow these rocks to flow as a weak solid while maintaining a crystalline structure. Parts of the asthenosphere are close to their melting temperature.

B What Types of Igneous Rocks Form Along Oceanic Divergent Margins?

New oceanic crust formed along mid-ocean ridges consists of a distinct sequence of different igneous rocks. The rocks are mafic, but have different textures and features depending on how and where the magma solidified. The *mafic* magma is formed by *partial melting* of the *ultramafic* mantle.

05.06.b1

◁ The upper part of oceanic crust consists of basaltic lava flows. When these lavas erupted into water, they formed a series of overlapping mounds called pillows. Such rocks are called *pillow basalts*. [San Juan Islands, Washington]

Countless vertical dikes of finely crystalline basalt cut across the pillow basalts and continue downward. These dikes are so closely spaced that they are called *sheeted dikes*. One dike, with dark margins, is shown here cutting another lighter gray dike. [Smartville, California]

05.06.b2

05.06.b3

Sheeted dikes merge downward into gabbro, the coarsely crystalline equivalent of basalt. The gabbro represents magma chambers beneath the rift and locally displays layers formed by crystal settling. [Smartville, California] ◁

▷ The base of the gabbro is the base of the oceanic crust, below which are ultramafic rocks of the mantle. The mantle rocks show evidence of having been partially melted to form all of the overlying basaltic rocks in the crust (pillow basalt, sheeted dikes, and gabbro).

05.06.b4

Sea
Pillow Basalts
Sheeted Dikes
Gabbro (magma chamber)
Mantle

IGNEOUS ENVIRONMENTS 119

C How Are Magmas Generated in Continental Rifts?

Continental rifts form where tectonic forces attempt, perhaps successfully, to split a continent apart. Such rifts have a central trough where faults drop down huge crustal blocks. Rifts are characterized by a diverse suite of igneous rocks because melting takes place both in the mantle and in the crust. The sequence of events begins in the mantle.

Continental Rift

05.06.c1

Continental Crust
Mantle Lithosphere
Asthenosphere

4. Some felsic and intermediate magmas solidify underground as granite and related igneous rocks, while others erupt on the surface in potentially explosive volcanoes.

3. Heat from the hot mafic magma melts the adjacent continental crust. Such melting typically yields felsic magma. Intermediate magma forms from mixing of felsic and mafic magmas or from assimilation of continental crust by a mafic magma.

2. The mantle-derived mafic magmas rise into the upper mantle and lower continental crust and accumulate in large magma chambers. Some mafic magma reaches the surface and erupts as mafic (basaltic) lava flows.

1. Solid asthenosphere rises beneath the rift and undergoes *decompression melting* (see graph below for melting in the mantle). Partial melting of the ultramafic mantle source yields mafic (basaltic) magma.

Melting in the Mantle

▷ Melting of the *mantle* beneath rifts is caused by *decompression*. The asthenosphere rises into shallower, lower pressure regions, and the decrease in pressure allows the rocks to melt. This produces mafic magma that can erupt onto the surface, forming basalt.

05.06.c2

Temperature
Low High
P (Depth)
Low High
Solid
Liquid

Melting in the Crust

05.06.c3

Temperature
Low High
P (Depth)
Low High
C B A
Felsic
Mafic

◁ This graph shows a melting line for mafic rock (basalt) and a lower temperature melting line for felsic rock (granite). A hot, mantle-derived mafic magma rises into continental crust and is hotter (at point *A*) than adjacent crust (at point *C*).

Heat from the mafic magma increases the temperature of the crust (from *C* to *B*). As the temperature of the crust crosses the felsic line, the granitic crust melts to produce felsic magma. In this example, the mafic magma loses heat to the crust (from *A* to *B*) and solidifies.

Ophiolites — Slices of Oceanic Crust on Land

How do we know what is in oceanic crust that it is hidden deep beneath the sea? The sequence of rocks in oceanic crust has been reconstructed by dredging samples from the seafloor, by drilling into oceanic crust, and by studying ancient examples on land. Geologists have gained much recent data by using research ships that have completed more than 1,700 drill holes, some more than 1,400 meters (1,500 yards) deep. Drill cores retrieved from these sites are important data for reconstructing sections of oceanic crust.

If we know the right places, we can examine oceanic crust on a hike across the land. Tectonic movements have sliced off pieces of oceanic crust and thrust them onto the edges of continents and onto islands. These slices contain a consistent sequence, from top to bottom, of oceanic sediment, pillow basalt, sheeted dikes, and gabbro. This distinctive sequence is called an *ophiolite* and is identical to the sequence of newly formed oceanic crust on the previous page, except it contains an additional layer of oceanic sediment on top. Such sediment accumulates on the oceanic crust over time. Many ophiolites are probably sections of oceanic crust created at long-vanished mid-ocean ridges.

Before You Leave This Page Be Able To

- ✓ Sketch or describe why melting occurs along mid-ocean ridges and why the resulting magmas are basaltic (mafic).
- ✓ Summarize the types of igneous rocks that form along mid-ocean ridges.
- ✓ Describe how melting occurs in continental rifts and how it results in diverse igneous rocks.
- ✓ Summarize how an ophiolite compares to a section through oceanic crust.

5.6

The textbook is built around large and small illustrations that convey knowledge in a visual way.

Short blocks of text, which label and explain key features one at a time and in complete sentences, accompany each figure. This approach allows our minds to better integrate the various types of information and to envision how the different parts and processes are related. The figures are designed so that key points are described in a logical order.

Most two-page spreads contain a major block of text at the end of the spread. This text block provides a more in-depth discussion of some important and interesting aspect of the topic.

Our Goals for This Book

Geology may be the only science course students take in college, or it may be one of a number of science classes that they take. Whatever the circumstance, we designed, wrote, and illustrated this book with several clear goals in mind. One major goal is to help students become better at observing the world around them and at understanding how geology controls so much of what they see in landscapes. Another goal is to help students think logically about the natural world and to help them know how to study natural phenomena using a scientific approach. We also want to help students appreciate how geology is relevant to their life, on a local and a global scale, and how a knowledge of geology can help them avoid natural hazards, such as flooding and landslides. Finally, we, like most geologists, love traveling across and studying different parts of our planet. We want to share our excitement for how geology shapes our world and how geologists contribute to modern society.

How Is Each Chapter Organized?

EACH CHAPTER INCLUDES FOUR TYPES of two-page spreads: a chapter *opening* spread, a number of *topical* spreads, a chapter *application* spread, and a chapter-closing *investigation* spread. Each type of spread has its own distinguishing characteristics and was designed to be approached in a specific way.

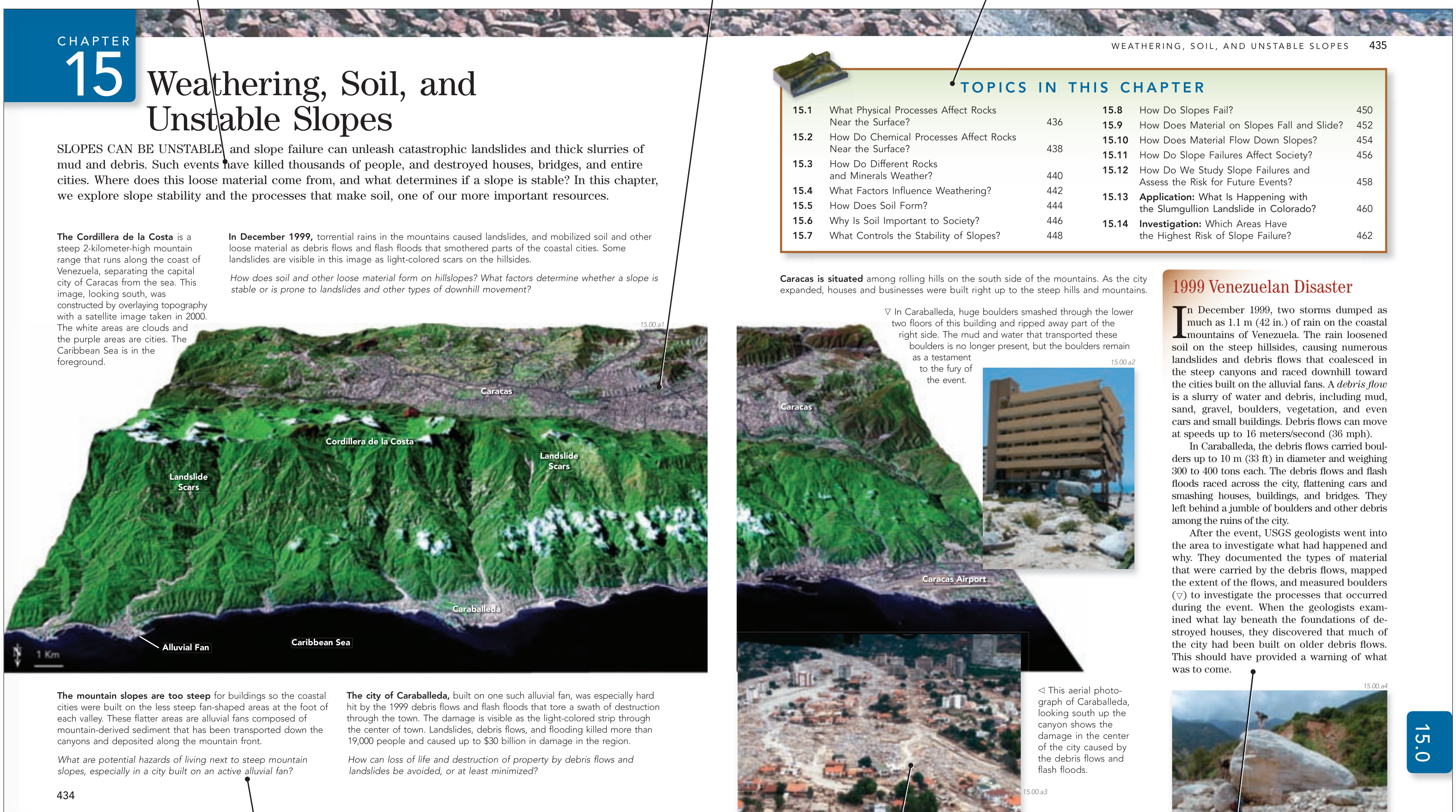
A How Does Each Chapter Begin?

Chapter-*opening* two-page spreads focus on an interesting place that illustrates the main aspects of the chapter and why the information covered is relevant to society.

The opening paragraph introduces some central ideas from the chapter and previews some main issues related to this topic.

Chapter-opening spreads are generally organized around one large figure, such as a map or computer-generated satellite image.

A list of topics helps students navigate the chapter and anticipate which topics will be covered.



CHAPTER 15

Weathering, Soil, and Unstable Slopes

SLOPES CAN BE UNSTABLE, and slope failure can unleash catastrophic landslides and thick slurries of mud and debris. Such events have killed thousands of people, and destroyed houses, bridges, and entire cities. Where does this loose material come from, and what determines if a slope is stable? In this chapter, we explore slope stability and the processes that make soil, one of our more important resources.

The Cordillera de la Costa is a steep 2-kilometer-high mountain range that runs along the coast of Venezuela, separating the capital city of Caracas from the sea. This image, looking south, was constructed by overlaying topography 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.

In December 1999, torrential rains in the mountains caused landslides, and mobilized soil and other loose material as debris flows and flash floods that smothered parts of the coastal cities. Some landslides are visible in this image as light-colored scars on the hillsides.

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?

15.00.a1

The mountain slopes are too steep for buildings so the coastal cities were built 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 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 by the 1999 debris flows and flash floods that tore a swath of destruction through the town. The damage is visible as the light-colored strip through the center of town. Landslides, debris flows, and flooding killed more than 19,000 people and caused up to $30 billion in damage in the region.

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

434

WEATHERING, SOIL, AND UNSTABLE SLOPES 435

TOPICS IN THIS CHAPTER

Caracas is situated among rolling hills on the south side of the mountains. As the city expanded, houses and businesses were built right up to the steep hills and mountains.

▽ In Caraballeda, huge boulders smashed through the lower two floors of this building and ripped away part of the right side. The mud and water that transported these boulders is no longer present, but the boulders remain as a testament to the fury of the event.

15.00.a2

◁ 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.

15.00.a3

1999 Venezuelan Disaster

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 numerous landslides and debris flows that coalesced in the steep canyons and raced downhill toward the cities built on the alluvial fans. A *debris flow* is a slurry of water and debris, including mud, sand, gravel, boulders, vegetation, and even cars and small buildings. Debris flows can move at speeds up to 16 meters/second (36 mph).

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 among the ruins of the city.

After the event, USGS geologists 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 the processes that occurred during the event. When the geologists examined what lay beneath the foundations of destroyed houses, they discovered that much of the city had been built on older debris flows. This should have provided a warning of what was to come.

15.00.a4

15.0

The text blocks highlight important attributes of this locality or of the geologic phenomena featured in the chapter. These text blocks include questions that a student should be able to answer by the end of the chapter.

Smaller photographs and figures address different features or manifestations of the geologic processes that are explored further within the chapter.

A major text block provides a more detailed narrative about some interesting aspect of the region, such as the important geologic events that affected the region, its cities, and its people.

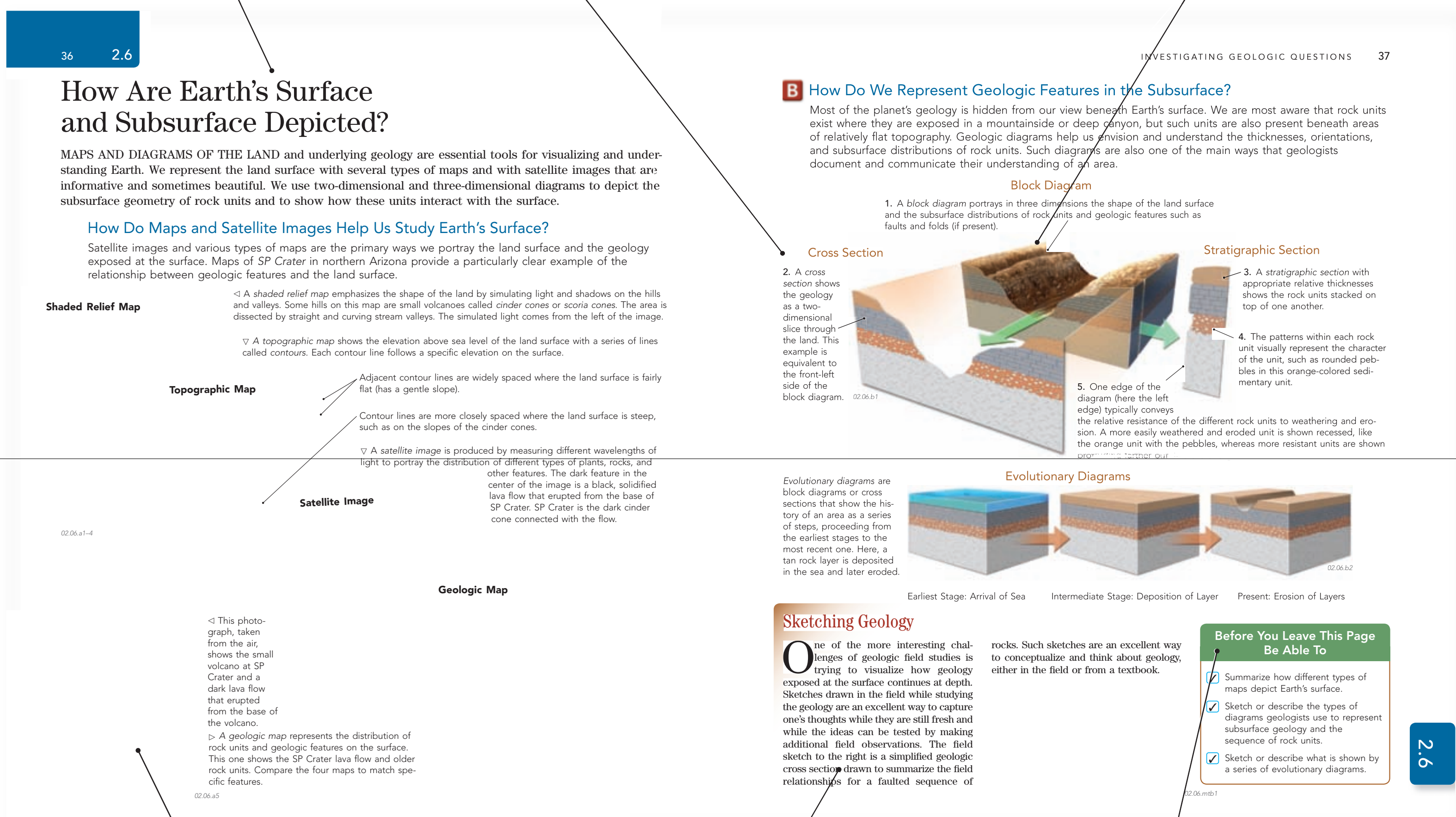
B What Do Topical Two-Page Spreads Include?

Topical two-page spreads are the foundation of the book. Each spread is about one or more closely related topics. Topical spreads convey the geologic content and help organize knowledge. Each chapter contains at least one two-page spread illustrating how geology impacts society and another two-page spread that specifically describes how we study geologic problems.

Topical two-page spreads begin with a question and then explore that question within the rest of the two-page spread.

Information is conveyed by the illustrations, photographs, and associated text blocks. The blocks are numbered if they should be read in a specific order.

This book contains many unique illustrations designed to help convey the content, to explain different types of geologic figures, and to provide a visual representation for calculations.



36 2.6

How Are Earth's Surface and Subsurface Depicted?

MAPS AND DIAGRAMS OF THE LAND and underlying geology are essential tools for visualizing and understanding Earth. We represent the land surface with several types of maps and with satellite images that are informative and sometimes beautiful. We use two-dimensional and three-dimensional diagrams to depict the subsurface geometry of rock units and to show how these units interact with the surface.

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 and the geology exposed at the surface. Maps of *SP Crater* in northern Arizona provide a particularly clear example of the relationship between geologic features and the land surface.

Shaded Relief Map

◁ A *shaded relief map* emphasizes the shape of the land by simulating light and shadows on the hills and valleys. Some hills on this map are small volcanoes called *cinder cones* or *scoria cones*. The area is dissected by straight and curving stream valleys. The simulated light comes from the left of the image.

▽ A *topographic map* shows the elevation above sea level of the land surface with a series of lines called *contours*. Each contour line follows a specific elevation on the surface.

Topographic Map

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

Contour lines are more closely spaced where the land surface is steep, such as on the slopes of the cinder cones.

▽ A *satellite image* is produced by measuring different wavelengths of light to portray the distribution of different types of plants, rocks, and other features. The dark feature in the center of the image is a black, solidified lava flow that erupted from the base of SP Crater. SP Crater is the dark cinder cone connected with the flow.

Satellite Image

02.06.a1–4

Geologic Map

◁ This photograph, taken from the air, shows the small volcano at SP Crater and a dark lava flow that erupted from the base of the volcano.

▷ *A geologic map* represents the distribution of rock units and geologic features on the surface. This one shows the SP Crater lava flow and older rock units. Compare the four maps to match specific features.

02.06.a5

INVESTIGATING GEOLOGIC QUESTIONS 37

B How Do We Represent Geologic Features in the Subsurface?

Most of the planet's geology is hidden from our view beneath Earth's surface. We are most aware that rock units exist where they are exposed in a mountainside or deep canyon, but such units are also present beneath areas of relatively flat topography. Geologic diagrams help us envision and understand the thicknesses, orientations, and subsurface distributions of rock units. Such diagrams are also one of the main ways that geologists 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 and geologic features such as faults and folds (if present).

Cross Section

2. A *cross section* shows the geology as a two-dimensional slice through the land. This example is equivalent to the front-left side of the block diagram. 02.06.b1

Stratigraphic Section

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

4. The patterns within each rock unit visually represent the character of the unit, such as 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 weathered and eroded unit is shown recessed, like the orange unit with the pebbles, whereas more resistant units are shown

Evolutionary Diagrams

Evolutionary diagrams are block diagrams or cross sections that show the history of an area as a series of steps, proceeding from the earliest stages to the most recent one. Here, a tan rock layer is deposited in the sea and later eroded.

02.06.b2

Earliest Stage: Arrival of Sea | Intermediate Stage: Deposition of Layer | Present: Erosion of Layers

Sketching Geology

One of the more interesting challenges of geologic field studies is trying to visualize how geology exposed at the surface continues at depth. Sketches drawn in the field while studying the geology are an excellent way to capture one's thoughts while they are still fresh and while the ideas can be tested by making additional field observations. The field sketch to the right is a simplified geologic cross section drawn to summarize the field relationships for a faulted sequence of rocks. Such sketches are an excellent way to conceptualize and think about geology, either in the field or from a textbook.

Before You Leave This Page Be Able To

- ✓ Summarize how different types of maps depict Earth's surface.
- ✓ Sketch or describe the types of diagrams geologists use to represent subsurface geology and the sequence of rock units.
- ✓ Sketch or describe what is shown by a series of evolutionary diagrams.

02.06.mtb1

2.6

Photographs show examples of the features and processes being examined.

Most topical two-page spreads include a major text block that highlights important details or examples of the geologic processes.

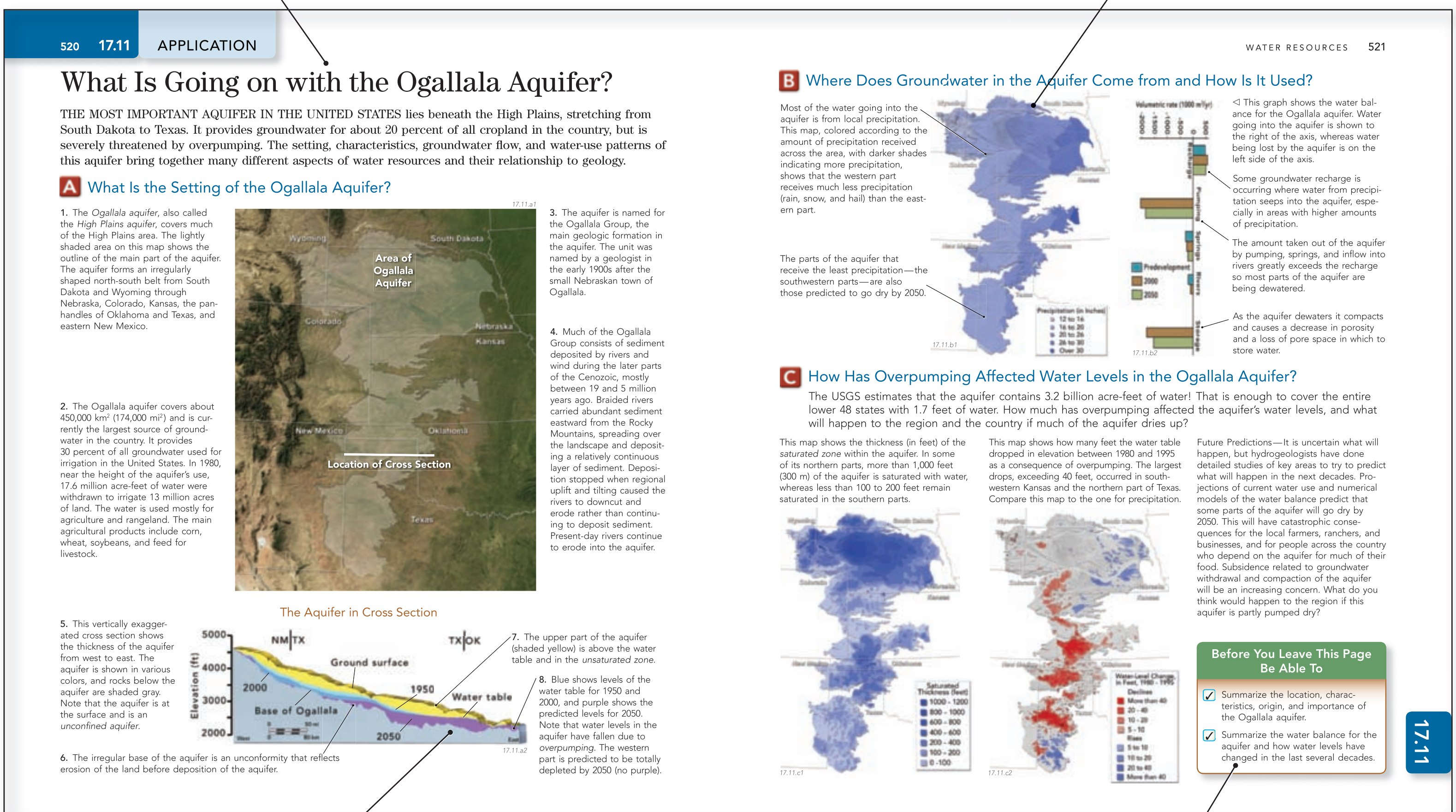
A *Before You Leave This Page* list indicates what is important and what students are expected to understand or be able to do before they move on. This list contains learning objectives for the spread. Test questions are tightly articulated with this list.

C What Is in the Chapter Application Two-Page Spread?

The next-to-last two-page spread in each chapter is an *application spread*, which is designed to help students integrate the various concepts from the chapter and to show how these concepts can be applied to an actual location. The application spread also serves as preparation for the following *investigation* two-page spread.

Application spreads are about real places that nicely illustrate the geologic concepts and features covered in the chapter.

Many application spreads explicitly illustrate how a type of geologic problem is investigated and how geologic processes have relevance to society.



520 17.11 APPLICATION

What Is Going on with the Ogallala Aquifer?

THE MOST IMPORTANT AQUIFER IN THE UNITED STATES lies beneath the High Plains, stretching from South Dakota to Texas. It provides groundwater for about 20 percent of all cropland in the country, but is severely threatened by overpumping. The setting, characteristics, groundwater flow, and water-use patterns of this aquifer bring together many different aspects of water resources and their relationship to geology.

A What Is the Setting of the Ogallala Aquifer?

1. The *Ogallala aquifer*, also called the *High Plains aquifer*, covers much of the High Plains area. The lightly shaded area on this map shows the outline of the main part of the aquifer. The aquifer forms an irregularly shaped north-south belt from South Dakota and Wyoming through Nebraska, Colorado, Kansas, the panhandles of Oklahoma and Texas, and eastern New Mexico.

2. The Ogallala aquifer covers about 450,000 km² (174,000 mi²) and is currently the largest source of groundwater in the country. It provides 30 percent of all groundwater used for irrigation in the United States. In 1980, near the height of the aquifer's use, 17.6 million acre-feet of water were withdrawn to irrigate 13 million acres of land. The water is used mostly for agriculture and rangeland. The main agricultural products include corn, wheat, soybeans, and feed for livestock.

3. The aquifer is named for the Ogallala Group, the main geologic formation in the aquifer. The unit was named by a geologist in the early 1900s after the small Nebraskan town of Ogallala.

4. Much of the Ogallala Group consists of sediment deposited by rivers and wind during the later parts of the Cenozoic, mostly between 19 and 5 million years ago. Braided rivers carried abundant sediment eastward from the Rocky Mountains, spreading over the landscape and depositing a relatively continuous layer of sediment. Deposition stopped when regional uplift and tilting caused the rivers to downcut and erode rather than continuing to deposit sediment. Present-day rivers continue to erode into the aquifer.

Wyoming, South Dakota, Area of Ogallala Aquifer, Colorado, Nebraska, Kansas, New Mexico, Oklahoma, Location of Cross Section, Texas

The Aquifer in Cross Section

5. This vertically exaggerated cross section shows the thickness of the aquifer from west to east. The aquifer is shown in various colors, and rocks below the aquifer are shaded gray. Note that the aquifer is at the surface and is an *unconfined aquifer*.

6. The irregular base of the aquifer is an unconformity that reflects erosion of the land before deposition of the aquifer.

7. The upper part of the aquifer (shaded yellow) is above the water table and in the *unsaturated zone*.

8. Blue shows levels of the water table for 1950 and 2000, and purple shows the predicted levels for 2050. Note that water levels in the aquifer have fallen due to *overpumping*. The western part is predicted to be totally depleted by 2050 (no purple).

Elevation (ft), 5000, 4000, 3000, 2000, NM TX, TX OK, Ground surface, 2000, 1950, Water table, Base of Ogallala, 2050, West, East

WATER RESOURCES 521

B Where Does Groundwater in the Aquifer Come from and How Is It Used?

Most of the water going into the aquifer is from local precipitation. This map, colored according to the amount of precipitation received across the area, with darker shades indicating more precipitation, shows that the western part receives much less precipitation (rain, snow, and hail) than the eastern part.

The parts of the aquifer that receive the least precipitation—the southwestern parts—are also those predicted to go dry by 2050.

This graph shows the water balance for the Ogallala aquifer. Water going into the aquifer is shown to the right of the axis, whereas water being lost by the aquifer is on the left side of the axis.

Some groundwater recharge is occurring where water from precipitation seeps into the aquifer, especially in areas with higher amounts of precipitation.

The amount taken out of the aquifer by pumping, springs, and inflow into rivers greatly exceeds the recharge so most parts of the aquifer are being dewatered.

As the aquifer dewaters it compacts and causes a decrease in porosity and a loss of pore space in which to store water.

Volumetric rate (1000 m³/yr), Recharge, Pumping, Springs, Rivers, Storage, Predevelopment, 2000, 2050, Precipitation (in inches)

C How Has Overpumping Affected Water Levels in the Ogallala Aquifer?

The USGS estimates that the aquifer contains 3.2 billion acre-feet of water! That is enough to cover the entire lower 48 states with 1.7 feet of water. How much has overpumping affected the aquifer's water levels, and what will happen to the region and the country if much of the aquifer dries up?

This map shows the thickness (in feet) of the *saturated zone* within the aquifer. In some of its northern parts, more than 1,000 feet (300 m) of the aquifer is saturated with water, whereas less than 100 to 200 feet remain saturated in the southern parts.

This map shows how many feet the water table dropped in elevation between 1980 and 1995 as a consequence of overpumping. The largest drops, exceeding 40 feet, occurred in southwestern Kansas and the northern part of Texas. Compare this map to the one for precipitation.

Future Predictions—It is uncertain what will happen, but hydrogeologists have done detailed studies of key areas to try to predict what will happen in the next decades. Projections of current water use and numerical models of the water balance predict that some parts of the aquifer will go dry by 2050. This will have catastrophic consequences for the local farmers, ranchers, and businesses, and for people across the country who depend on the aquifer for much of their food. Subsidence related to groundwater withdrawal and compaction of the aquifer will be an increasing concern. What do you think would happen to the region if this aquifer is partly pumped dry?

Saturated Thickness (feet), Water-Level Change in Feet, 1980–1995, Decline, Rises

Before You Leave This Page Be Able To

- Summarize the location, characteristics, origin, and importance of the Ogallala aquifer.
- Summarize the water balance for the aquifer and how water levels have changed in the last several decades.

17.11

The locality is explored from various perspectives, using maps, photographs, and other figures to show how different topics in the chapter relate to one another and to the larger picture.

Some application spreads do not have a major text block, but they do have a *Before You Leave This Page* list, indicating what a student should be able to do before beginning the investigation.

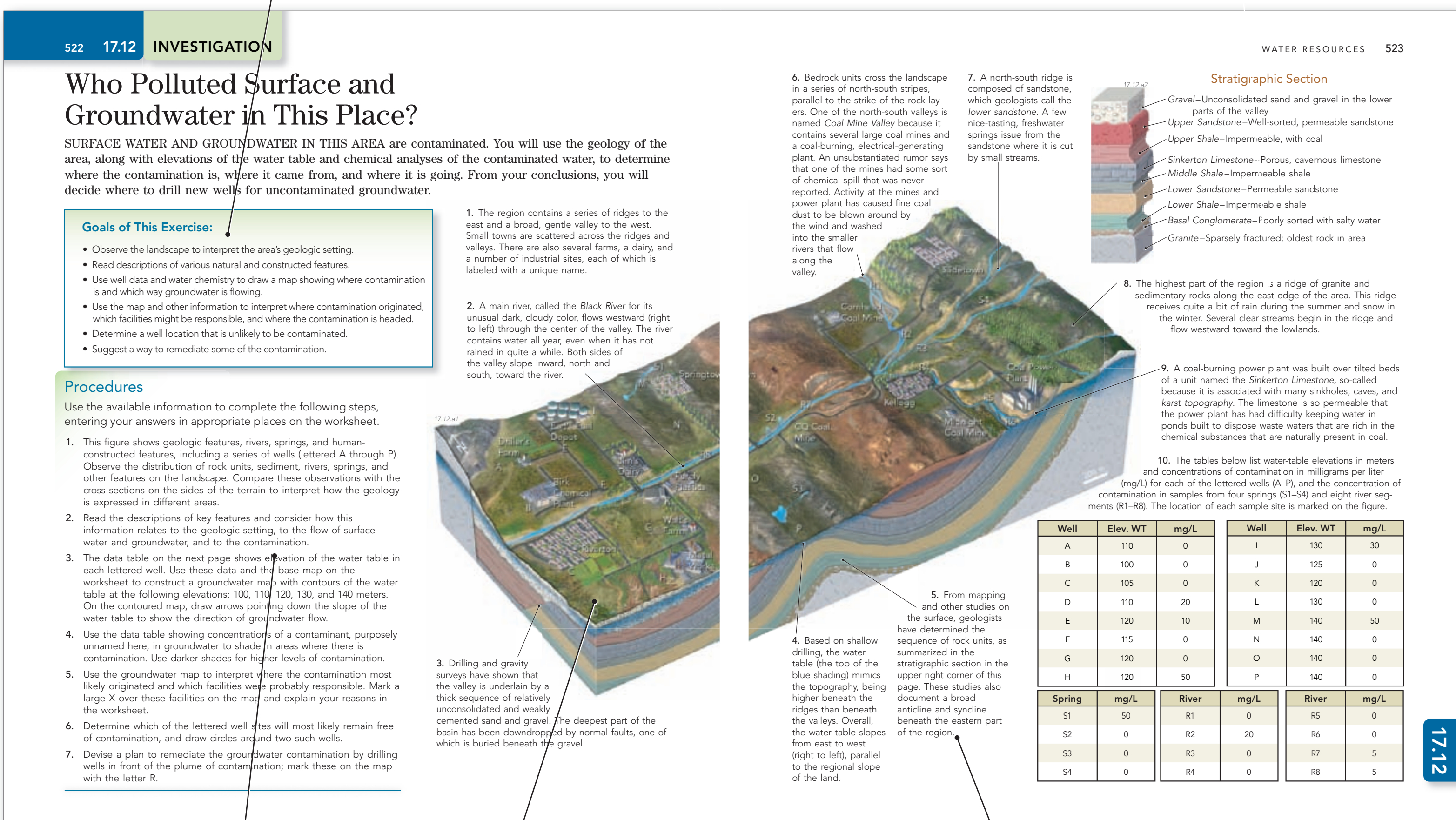
D How Does Each Chapter End?

Each chapter ends with an *investigation* two-page spread that is an exercise in which students apply the knowledge, skills, and approaches learned in the chapter. These exercises commonly involve virtual places that students will explore and investigate to answer a series of geologic questions. They are modeled after the types of problems geologists investigate and use the same kinds of data and illustrations encountered in the chapter.

A list of goals for the exercise indicates what students will need to do to complete the investigation exercise. The exercise assumes that students have mastered the content and approaches described in previous parts of the chapter.

An instructor might do the investigation as an in-class exercise, use it to assess what students have learned, assign it as homework, or integrate it into the laboratory.

Many investigation exercises involve (a) making observations from photographs, data, or rock samples, (b) completing well-explained calculations, or (c) constructing graphs, maps, or cross sections.


522 17.12 INVESTIGATION

Who Polluted Surface and Groundwater in This Place?

SURFACE WATER AND GROUNDWATER IN THIS AREA are contaminated. You will use the geology of the area, along with elevations of the water table and chemical analyses of the contaminated water, to determine where the contamination is, where it came from, and where it is going. From your conclusions, you will decide where to drill new wells for uncontaminated groundwater.

Goals of This Exercise:

- Observe the landscape to interpret the area's geologic setting.
- Read descriptions of various natural and constructed features.
- Use well data and water chemistry to draw a map showing where contamination is and which way groundwater is flowing.
- Use the map and other information to interpret where contamination originated, which facilities might be responsible, and where the contamination is headed.
- Determine a well location that is unlikely to be contaminated.
- Suggest a way to remediate some of the contamination.

Procedures

Use the available information to complete the following steps, entering your answers in appropriate places on the worksheet.

1. This figure shows geologic features, rivers, springs, and human-constructed features, including a series of wells (lettered A through P). Observe the distribution of rock units, sediment, rivers, springs, and other features on the landscape. Compare these observations with the cross sections on the sides of the terrain to interpret how the geology is expressed in different areas.
2. Read the descriptions of key features and consider how this information relates to the geologic setting, to the flow of surface water and groundwater, and to the contamination.
3. The data table on the next page shows elevation of the water table in each lettered well. Use these data and the base map on the worksheet to construct a groundwater map with contours of the water table at the following elevations: 100, 110, 120, 130, and 140 meters. On the contoured map, draw arrows pointing down the slope of the water table to show the direction of groundwater flow.
4. Use the data table showing concentrations of a contaminant, purposely unnamed here, in groundwater to shade in areas where there is contamination. Use darker shades for higher levels of contamination.
5. Use the groundwater map to interpret where the contamination most likely originated and which facilities were probably responsible. Mark a large X over these facilities on the map and explain your reasons in the worksheet.
6. Determine which of the lettered well sites will most likely remain free of contamination, and draw circles around two such wells.
7. Devise a plan to remediate the groundwater contamination by drilling wells in front of the plume of contamination; mark these on the map with the letter R.

1. The region contains a series of ridges to the east and a broad, gentle valley to the west. Small towns are scattered across the ridges and valleys. There are also several farms, a dairy, and a number of industrial sites, each of which is labeled with a unique name.

2. A main river, called the *Black River* for its unusual dark, cloudy color, flows westward (right to left) through the center of the valley. The river contains water all year, even when it has not rained in quite a while. Both sides of the valley slope inward, north and south, toward the river.

17.12.a1

3. Drilling and gravity surveys have shown that the valley is underlain by a thick sequence of relatively unconsolidated and weakly cemented sand and gravel. The deepest part of the basin has been downdropped by normal faults, one of which is buried beneath the gravel.

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6. Bedrock units cross the landscape in a series of north-south stripes, parallel to the strike of the rock layers. One of the north-south valleys is named *Coal Mine Valley* because it contains several large coal mines and a coal-burning, electrical-generating plant. An unsubstantiated rumor says that one of the mines had some sort of chemical spill that was never reported. Activity at the mines and power plant has caused fine coal dust to be blown around by the wind and washed into the smaller rivers that flow along the valley.

7. A north-south ridge is composed of sandstone, which geologists call the *lower sandstone*. A few nice-tasting, freshwater springs issue from the sandstone where it is cut by small streams.

17.12.a2

Stratigraphic Section

Gravel–Unconsolidated sand and gravel in the lower parts of the valley
Upper Sandstone–Well-sorted, permeable sandstone
Upper Shale–Impermeable, with coal
Sinkerton Limestone–Porous, cavernous limestone
Middle Shale–Impermeable shale
Lower Sandstone–Permeable sandstone
Lower Shale–Impermeable shale
Basal Conglomerate–Poorly sorted with salty water
Granite–Sparsely fractured; oldest rock in area

8. The highest part of the region is a ridge of granite and sedimentary rocks along the east edge of the area. This ridge receives quite a bit of rain during the summer and snow in the winter. Several clear streams begin in the ridge and flow westward toward the lowlands.

9. A coal-burning power plant was built over tilted beds of a unit named the *Sinkerton Limestone*, so-called because it is associated with many sinkholes, caves, and *karst topography*. The limestone is so permeable that the power plant has had difficulty keeping water in ponds built to dispose waste waters that are rich in the chemical substances that are naturally present in coal.

4. Based on shallow drilling, the water table (the top of the blue shading) mimics the topography, being higher beneath the ridges than beneath the valleys. Overall, the water table slopes from east to west (right to left), parallel to the regional slope of the land.

5. From mapping and other studies on the surface, geologists have determined the sequence of rock units, as summarized in the stratigraphic section in the upper right corner of this page. These studies also document a broad anticline and syncline beneath the eastern part of the region.

10. The tables below list water-table elevations in meters and concentrations of contamination in milligrams per liter (mg/L) for each of the lettered wells (A–P), and the concentration of contamination in samples from four springs (S1–S4) and eight river segments (R1–R8). The location of each sample site is marked on the figure.

Well	Elev. WT	mg/L
A	110	0
B	100	0
C	105	0
D	110	20
E	120	10
F	115	0
G	120	0
H	120	50

Well	Elev. WT	mg/L
I	130	30
J	125	0
K	120	0
L	130	0
M	140	50
N	140	0
O	140	0
P	140	0

Spring	mg/L
S1	50
S2	0
S3	0
S4	0

River	mg/L
R1	0
R2	20
R3	0
R4	0

River	mg/L
R5	0
R6	0
R7	5
R8	5

17.12

Step-by-step instructions guide students while they record observations, calculations, and results.

Most investigation exercises are built around three-dimensional perspectives of a place that provides the context for the problems. These places are chosen to have realistic and challenging, but solvable, issues.

The figure is accompanied by a series of small text blocks that provide descriptions of different geologic features that you could observe if you were actually traversing across the region. These text blocks provide clues to help investigate various alternatives, answer the geologic questions, or determine the best course of action.

How Should Students Use This Book?

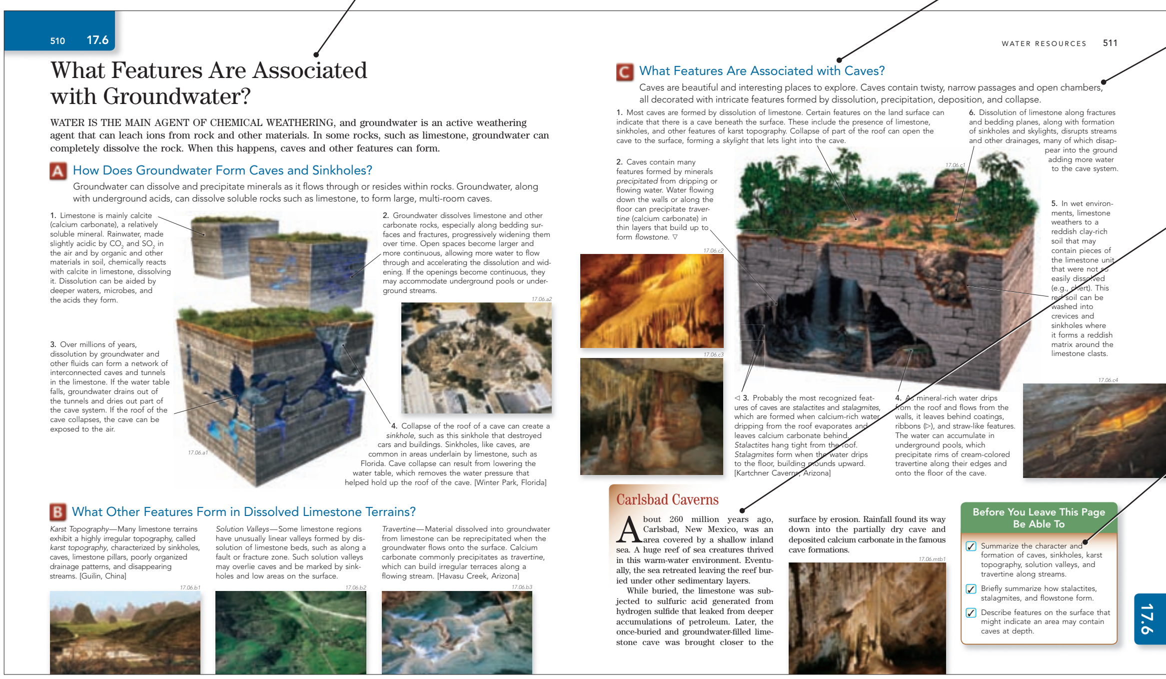
THE DESIGN OF THIS BOOK aims to make reading and studying as efficient and enjoyable as possible. In normal textbooks, two major challenges are trying to decide *what is most important* and *how the text relates to the figures*. This book simplifies that process because the text and figures are tightly integrated. The book also showcases the key concepts and ideas of geology because less important aspects are deliberately excluded. The authors think that everything in this book is important!

A How Do We Recommend You Read and Study This Book?

This book poses questions at all levels, from titles of each two-page spread to questions embedded within text blocks and lists. You should be able to answer any question posed in the opening two-page spread, in the title of a two-page spread, in a section heading, and especially in the *Before You Leave This Page* list. Finally, know how to complete the investigation at the end of the chapter.

Read the title of a two-page spread first, and then think about the question. This should activate *prior knowledge* and help link new information into an existing mental framework, making the new information easier to learn, retain, and use.

For each section, read and think about its question. Begin the section by closely observing the main figure. After mentally absorbing the whole scene, read each small text block associated with the figure and integrate the text and visual images into memory.


510 17.6

What Features Are Associated with Groundwater?

WATER IS THE MAIN AGENT OF CHEMICAL WEATHERING, and groundwater is an active weathering agent that can leach ions from rock and other materials. In some rocks, such as limestone, groundwater can completely dissolve the rock. When this happens, caves and other features can form.

A How Does Groundwater Form Caves and Sinkholes?

Groundwater can dissolve and precipitate minerals as it flows through or resides within rocks. Groundwater, along with underground acids, can dissolve soluble rocks such as limestone, to form large, multi-room caves.

1. Limestone is mainly calcite (calcium carbonate), a relatively soluble mineral. Rainwater, made slightly acidic by CO_2 and SO_2 in the air and by organic and other materials in soil, chemically reacts with calcite in limestone, dissolving it. Dissolution can be aided by deeper waters, microbes, and the acids they form.

2. Groundwater dissolves limestone and other carbonate rocks, especially along bedding surfaces and fractures, 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. Over millions of years, dissolution by groundwater and other fluids 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. If the roof of the cave collapses, the cave can be exposed to the air.

4. Collapse of the roof of a cave can create a *sinkhole*, such as this sinkhole that destroyed cars and buildings. Sinkholes, like caves, are common in areas underlain by limestone, such as Florida. Cave collapse can result from lowering the water table, which removes the water pressure that helped hold up the roof of the cave. [Winter Park, Florida]

B What Other Features Form in Dissolved Limestone Terrains?

Karst Topography—Many limestone terrains exhibit a highly irregular topography, called *karst topography*, characterized by sinkholes, caves, limestone pillars, poorly organized drainage patterns, and disappearing streams. [Guilin, China]

Solution Valleys—Some limestone regions have unusually linear valleys formed by dissolution of limestone beds, such as along a fault or fracture zone. Such solution valleys may overlie caves and be marked by sinkholes and low areas on the surface.

Travertine—Material dissolved into groundwater from limestone can be reprecipitated when the groundwater flows onto the surface. Calcium carbonate commonly precipitates as *travertine*, which can build irregular terraces along a flowing stream. [Havasu Creek, Arizona]

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C What Features Are Associated with Caves?

Caves are beautiful and interesting places to explore. Caves contain twisty, narrow passages and open chambers, all decorated with intricate features formed by dissolution, precipitation, deposition, and collapse.

1. Most caves are formed by dissolution of limestone. Certain features on the land surface can indicate that there is a cave beneath the surface. 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* (calcium carbonate) in thin layers that build up to form *flowstone*. ▽

◁ 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 the water drips to the floor, building mounds upward. [Kartchner Caverns, Arizona]

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

5. In wet environments, limestone weathers to a reddish clay-rich soil that may contain pieces of the limestone unit that were not so easily dissolved (e.g., chert). This red soil can be washed into crevices and sinkholes where it forms a reddish matrix around the limestone clasts.

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

Carlsbad Caverns

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

While buried, the limestone was subjected to sulfuric acid generated from hydrogen sulfide that leaked from deeper accumulations of petroleum. Later, the once-buried and groundwater-filled limestone cave was brought closer to the surface by erosion. Rainfall found its way down into the partially dry cave and deposited calcium carbonate in the famous cave formations.

Before You Leave This Page Be Able To

- Summarize the character and formation of caves, sinkholes, karst topography, solution valleys, and travertine along streams.
- Briefly summarize how stalactites, stalagmites, and flowstone form.
- Describe features on the surface that might indicate an area may contain caves at depth.

17.6

Before moving to the next section, take a moment to reflect on what you just learned in order to transfer this knowledge into long-term memory.

Read the major text block after completing everything else on the two-page spread. This text will help consolidate the ideas presented and provide an example of how the geologic concepts apply to a real place or a societal issue.

Lastly, read the *Before You Leave This Page* list and make sure you can answer all the questions. Record answers in your notes to solidify the knowledge while it is still fresh and to save time when studying later. Writing or sketching thoughts is a great way to help retain the main points because it makes us examine and clarify our ideas and, thus, transfer them into long-term memory.

B How Are Geologic Terms Introduced in This Book?

This book includes only those terms that we consider to be essential to thinking, writing, and talking about geology. We generally have readers observe a feature or process before providing its name, as shown below.

▷ Examine this photograph from the American Southwest. What do you observe, and what are the characteristics of the main feature shown?


00.03.b1

This feature is called a *mesa*, which is a flat-topped hill or mountain bounded by cliffs or steep slopes on at least one side. Key terms in this book are in *italics*.

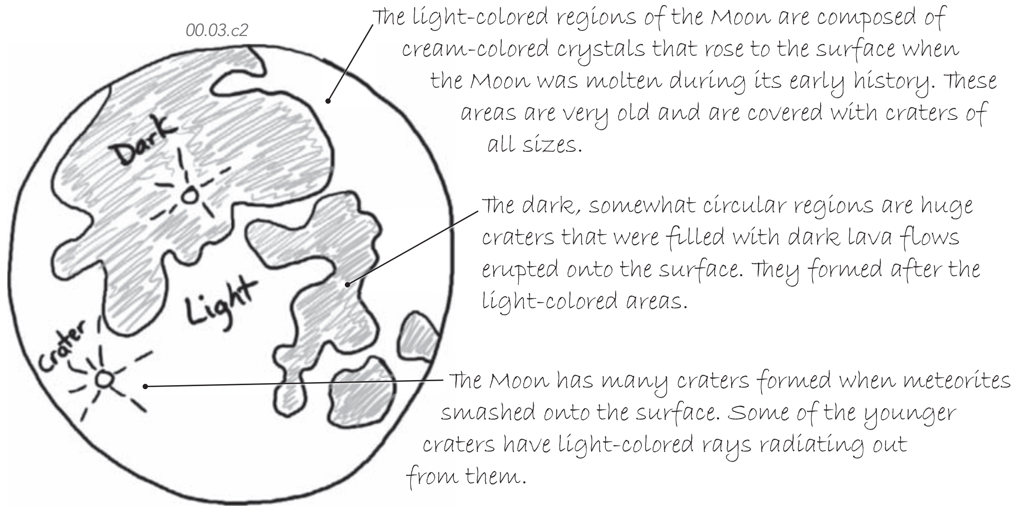
Observing a feature before learning its name makes it easier to remember what the term means. Then, this compact word can be used to refer to these kind of features.

C How Can Annotated Sketches Help Students Learn Geology?

The following illustrations demonstrate a way that text and figures can be integrated to produce a coherent understanding of geologic concepts and processes. To begin to understand this approach, observe the photograph of the Moon and identify some of its main features. Then examine the accompanying sketch and the words that summarize what we know about these features.

00.03.c1

00.03.c2



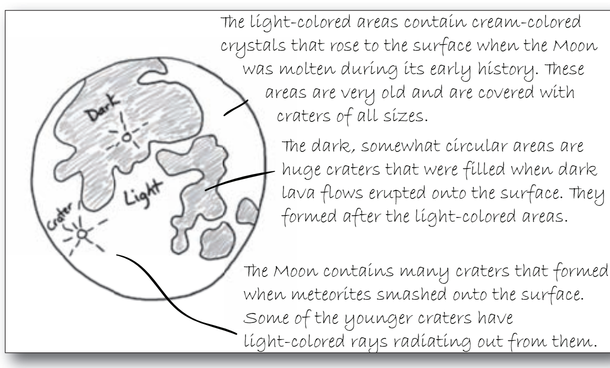
D How Do You Construct a Concept Sketch?

The annotated sketch of the Moon is an example of what we call a *concept sketch*. Here's how to make one.

Begin by observing a natural phenomenon, landscape, animation, photograph, or textbook illustration. Make a list of the main features or processes that you think should be depicted.

Draw a sketch that is simple but clearly shows the essential information.

Annotate your sketch with complete sentences to identify features, describe how they form, and summarize the main geologic processes.



Draw lines connecting your text to the appropriate features on the sketch.

You can increase your understanding by explaining the concept sketch to yourself and to a classmate, describing the features and processes shown.

If you can draw, label, and accurately explain a concept sketch, you probably understand that concept well. Such understanding will help with whatever types of questions you are asked to answer.

Learning with Concept Sketches

We have used concept sketches in our own classes for years, and we regard them as one of the best ways to learn and teach geology. They are an excellent way to construct knowledge from readings, lectures, and observations of landscapes and other rock exposures. Constructing a concept sketch enables students to visualize the different parts of a geologic system in their proper spatial context. They require students to identify the important aspects of the system and to de-emphasize the less important complexities present in all natural systems. You will note that this book consists largely of illustrations that resemble concept sketches.

We recommend that for each section you construct your own concept sketches from our more detailed illustrations and text. In essence, you are striving to put these illustrations and descriptions, and the processes and concepts they represent, into your own words and mind. This book is ideally suited for learning with concept sketches, if you choose to do so.

Making concept sketches also links students with the way geologists approach geologic questions. Geology has a long heritage of using pictures to convey observations and interpretations. Geologists draw sketches in the field or any time they are trying to share ideas with others. Drawing sketches is a natural way to conceptualize hidden places and distant times.

For more information about concept sketches, see Johnson, J.K., and Reynolds, S.J., 2005, *Journal of Geoscience Education*, v. 53, pp. 85–95.

What Resources Support This Textbook?

McGraw-Hill offers various tools and technology products to support *Exploring Geology*. Instructors can obtain teaching aids by calling the Customer Service Department at 800-338-3987 or contacting their local McGraw-Hill sales representative.

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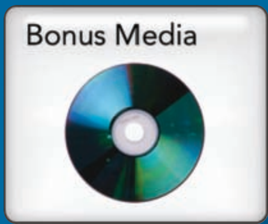
Author Resources

Instructor's Testing and Resource CD-ROM

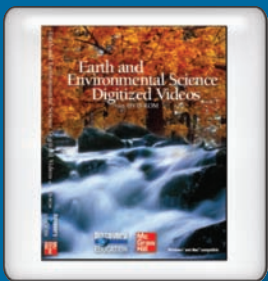
This cross-platform CD, prepared by the authors, provides a wealth of resources for the instructor. Among the supplements featured on this CD is a computerized test bank that uses testing software to quickly create customized exams. The user-friendly program allows instructors to search for questions by topic, format, or difficulty level; edit existing questions or add new ones; and scramble questions for multiple versions of the same test. Word files of the test bank questions are provided for those instructors who prefer to work outside the test-generator software.

The Instructor's Guide is also included on the Instructor's Testing and Resource CD. This manual contains valuable information on how to teach using *Exploring Geology*. A quick guide to teaching each chapter is provided. Chapter sections include suggestions for using PowerPoint presentations and interactive media in the classroom. Suggestions are also given for using concept sketches for assessment and classroom presentation. The Instructor's Guide is keyed to the PowerPoint presentations.



Media DVD for Instructors

This DVD, prepared by the authors, will bring the geology experience right into the classroom! It provides lecture PowerPoint files with key points built around the spectacular art from the book. Certain slides in the presentations contain built-in links to launch media files, most of which consist of interactive versions of figures from the book. The media includes images that can be rotated; images that can be used with a GeoWall; 3-D maps; and animations.



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This exciting DVD offers 50 short (3–5 minute) videos on topics ranging from conservation to volcanoes. Begin your class with a quick peek at science in action.

Classroom Performance System and Questions

McGraw-Hill has partnered with eInstruction to provide the revolutionary Classroom Performance System (CPS) and to bring interactivity into the classroom. CPS is a wireless response system that gives the instructor and students immediate feedback from the entire class. The wireless response pads are essentially remotes that are easy to use and engage students. CPS allows you to motivate student preparation, interactivity, and active learning so you can receive immediate feedback and know what students understand. A text-specific set of questions, formatted for both CPS and PowerPoint, is available via download from the Instructor area of *Exploring Geology* ARIS site.

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Acknowledgments

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This book contains over 2,600 figures, two to three times more than a typical introductory geology textbook. This massive art program required great effort and artistic abilities by the artists who turned our vision and sketches into what truly are pieces of art. In addition to our coauthor Chuck Carter, we greatly appreciate the dedication and artistic touches of illustrators Susie Gillatt, Cindy Shaw, Daniel Miller, David Fierstein, Karen Carter, and Ren Olsen. We also benefited from interactions with designers Chris Willis and David Hash, who helped translate our ideas about pedagogy into a workable and aesthetically sound design. Many people went out of their way to provide us with photographs, illustrations, and advice, in some cases going out into the field to take the photographs we needed. These helpful people included Vince Matthews, Ron Blakey, Michael Collier, Matthew Larsen, Allen Glazner, Karen Carr, Ed Garnero, Ramón Arrowsmith, Don Burt, Phil Christianson, Tom Sharp, Steve Semken, Doug Bartlett, Spencer Lucas, Michael Ort, Nancy Riggs, Peg Owens, Tom McGuire, and Barbara Tewksbury.

We used a number of data sources to create many illustrations. Reto Stöckli of the Department of Environmental Sciences at ETH Zürich and NASA Goddard produced the Blue Marble and Blue Marble Next Generation global satellite composites. We used data from the ZULU server at of the NASA Earth Science Enterprise Scientific Data Purchase Program for hundreds of figures in this book. Brian Davis of the USGS EROS Data Center was quick to find elusive data, and Collin Bode of the National Center for Earth-surface Dynamics was indispensable in helping us process GIS data. Debbie Leedy provided mineralogy and chemistry 3D files, and Melanie Busch and Joshua Coyan provided other 3D files.

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Michael Taber *University of Northern Colorado*
Jan Tullis *Brown University*
Lensyl Urbano *University of Memphis*
Stacey Verardo *George Mason University*
Mari Vice *University of Wisconsin, Platteville*
Adil M. Wadia *The University of Akron, Wayne College*
Stephen Wareham *California State University, Fullerton*
Richard Warner *Clemson University*
Barry Weaver *University of Oklahoma*
John Weber *Grand Valley State University*
David A. Williams *Arizona State University*
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2006 Geology Survey Participants

We would also like to thank those who participated in our geology survey. Your feedback will continue to be used by McGraw-Hill to expand our geology resources:

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Art Review Team

We extend a special thanks to the Art Review Team whose members provided constructive criticism to the art work as it was rendered by our author team. The team members included:

Mark D. Feigenson *Rutgers University*
G. Michael Grammer *Western Michigan University*
Scott R. Linneman *Western Washington University*
Brian E. Lock *University of Louisiana at Lafayette*
Stephen Wareham *California State University, Fullerton*

Sales Champions

Thank you also goes to our sales champions. This team of McGraw-Hill sales representatives has provided valuable feedback throughout the development of *Exploring Geology*. They have supported *Exploring Geology* from its early stages in development and are now ready to promote this text to the market.

Nicole Prevanas
Catherine Riley
Scott Rubin
Oliver Tillman
Kathyrn Ziesel

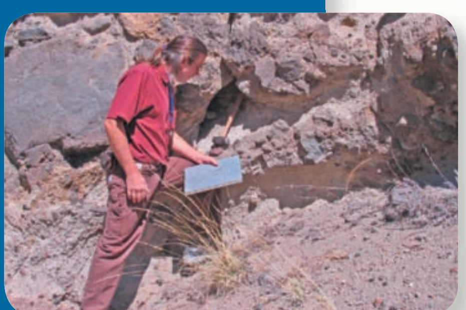
About the Authors

Stephen Reynolds

Stephen Reynolds received an undergraduate geology degree from University of Texas at El Paso, and M.S. and Ph.D. degrees in structure/tectonics and regional geology from the University of Arizona. He then spent ten years directing the geologic framework and mapping program of the Arizona Geological Survey, where he completed the 1988 Geologic map of Arizona. Steve currently is a professor in the School of Earth and Space Exploration at Arizona State University, where he has taught Physical Geology, Structural Geology, Field Geology, Orogenic Systems, Cordilleran Regional Geology, Teaching Methods in the Geosciences, and others. He helped establish the ASU Center for Research on Education in Science, Mathematics, Engineering, and Technology (CRESMET), and was President of the Arizona Geological Society. He has authored or edited nearly 200 geologic maps, articles, and reports, including the 866-page *Geologic Evolution of Arizona*. He also coauthored *Structural Geology of Rocks and Regions*, the most widely used Structural Geology textbook, and *Observing and Interpreting Geology*, a laboratory manual for Physical Geology. For the last ten years, he has done science-education research on student learning in college geology courses, especially the role of visualization. Steve is known for innovative teaching methods, has received numerous teaching awards, and has an award-winning website. As a National Association of Geoscience Teachers (NAGT) distinguished speaker, he traveled across the country presenting talks and workshops on how to infuse active learning and inquiry into large introductory geology classes. He also 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.

Julia K. Johnson

Julia K. Johnson received B.S. and M.S. degrees from the Department of Geological Sciences at Arizona State University, and she currently is a full-time faculty member in the School of Earth and Space Exploration at ASU. Her M.S. and Ph.D. research involved structural geology and geoscience education research. The main focus of her geoscience education research is on student- and instructor-generated sketches for learning, teaching, and assessment in college geology classes. Prior to coming to ASU, she did groundwater studies of copper deposits and then taught full time in the Maricopa County Community College District, teaching Physical Geology, Environmental Geology, and their labs. At ASU, she teaches Introduction to Geology to nearly 1,000 students per year and supervises the associated introductory geology labs. She also coordinates the introductory geology teaching efforts of the School of Earth and Space Exploration, helping other instructors incorporate active learning and inquiry into large lecture classes. Julia is recognized as one of the best science teachers at ASU and has received student-nominated teaching awards and very high teaching evaluations in spite of her challenging classes. In recognition of her teaching, she was a Featured Faculty of the Month on ASU's website in 2005. She has authored publications on geology and science-education research, including an article in the *Journal of Geoscience Education* on concept sketches. She coauthored *Observing and Interpreting Geology* and also developed a number of websites used by geology students around the world, such as the *Visualizing Topography* and *Biosphere 3D* website.



Michael Kelly

Michael Kelly received an undergraduate geology degreee from the University of California, Santa Cruz and an M.S. degree in geology from Northern Arizona University. His graduate research defined ductile structures and strain in Mojave Desert mountain ranges. As a USGS geologist, he mapped in the western U.S., coauthoring several geologic maps and performing paleomagnetic research and laboratory studies on Columbia River Basalts. As Senior Geologist at EMCON Associates, he led environmental investigations into geologically complex groundwater industrial contamination sites across the Pacific Northwest. He returned to the southwest as the director of the Center for Research and Evaluation of Advanced Technologies in Education (CREATE) at NAU and was adjunct faculty in Environmental Sciences. Here, Kelly's research activities centered around the use of virtual reality to enhance undergraduate science education. He was Co-Investigator on numerous NSF science education projects and is author or coauthor on numerous publications resulting from the CREATE's efforts. Kelly is lead author on a virtual reality geology laboratory curriculum that has been in use by undergraduates since 1999. Today, Kelly designs and assesses media-enhanced science curriculum. His recent research focuses on spatial learning, particularly how landscapes and terrain are interpreted and how they can be used as frameworks for understanding connected science domains. Kelly recently designed virtual reality exhibits installed in two national parks, and his 3-D terrain software *ROMA* is used nationally for geoscience education in secondary and undergraduate institutions. He recently published in the *Journal of Geoscience Education* a study on the effectiveness of the GeoWall in undergraduate geology.

Paul Morin

Paul Morin specializes in earth-science visualization at the University of Minnesota, Department of Geology and Geophysics and the National Center of Earth Surface Dynamics. His interests have to do with the effect of artistic technique and technology on the efficacy of visualizations in the hands of students. Paul co-founded the GeoWall Consortium, a group of over 200 teaching institutions using visualization and stereo projection in the classroom. Currently, over 25% of all students taking introductory Physical Geology Lab in the U.S. have access to a GeoWall. Over the past five years, Paul has been instrumental in bringing earth science visualization to science museums around the world. He is currently co-investigator and co-developer of *Water Planet*, a 5,000 to 10,000 square foot traveling exhibit about water's role in shaping Earth. He was a major contributor of interactive visualizations to the NAGT-sponsored laboratory manual for Physical Geology. For several years, he has been an NAGT distinguished speaker, visiting universities and colleges to present talks on the role of visualization in geology courses. He is regarded by many people as one of the top visualization developers in the geosciences. Paul's current research has been on the replacement of standard geologic and topographic maps in the classroom with GeoWall and anaglyph versions. Other professional interests include the visualization of data sources that are traditionally viewed as being too complex for students to understand, such as three-dimensional spherical convection, seismic tomography, and paleontology.

Chuck Carter

Chuck Carter has been working in the artistic end of the science and entertainment industries for more than 20 years. His illustration and animation work has been used extensively by *National Geographic*, and his illustrations and layouts are featured in books published by *National Geographic* to feature the best of their artwork. He was the first freelance artist hired by *National Geographic* to create a 3-page digital illustration (on dinosaur evolution) and in 1994 was instrumental in helping launch *National Geographic Online*. He also has worked with Harcourt Education, McGraw-Hill Higher Education, *Knight-Ridder News in Motion*, and other clients for more than 18 years. He has produced illustrations and animations for the U.S. Navy, U.S. Department of Defense, and various defense contractors. His entertainment projects include being lead illustrator on the computer game *Myst* and he has worked on more than 20 other video games, including the popular *Command and Conquer* series, as a digital artist, animator, writer, art director, and computer-graphics supervisor. While working with Threshold Entertainment, he worked as a digital matte painter for shows like *Babylon 5*. He is lead illustrator and a coauthor of this book