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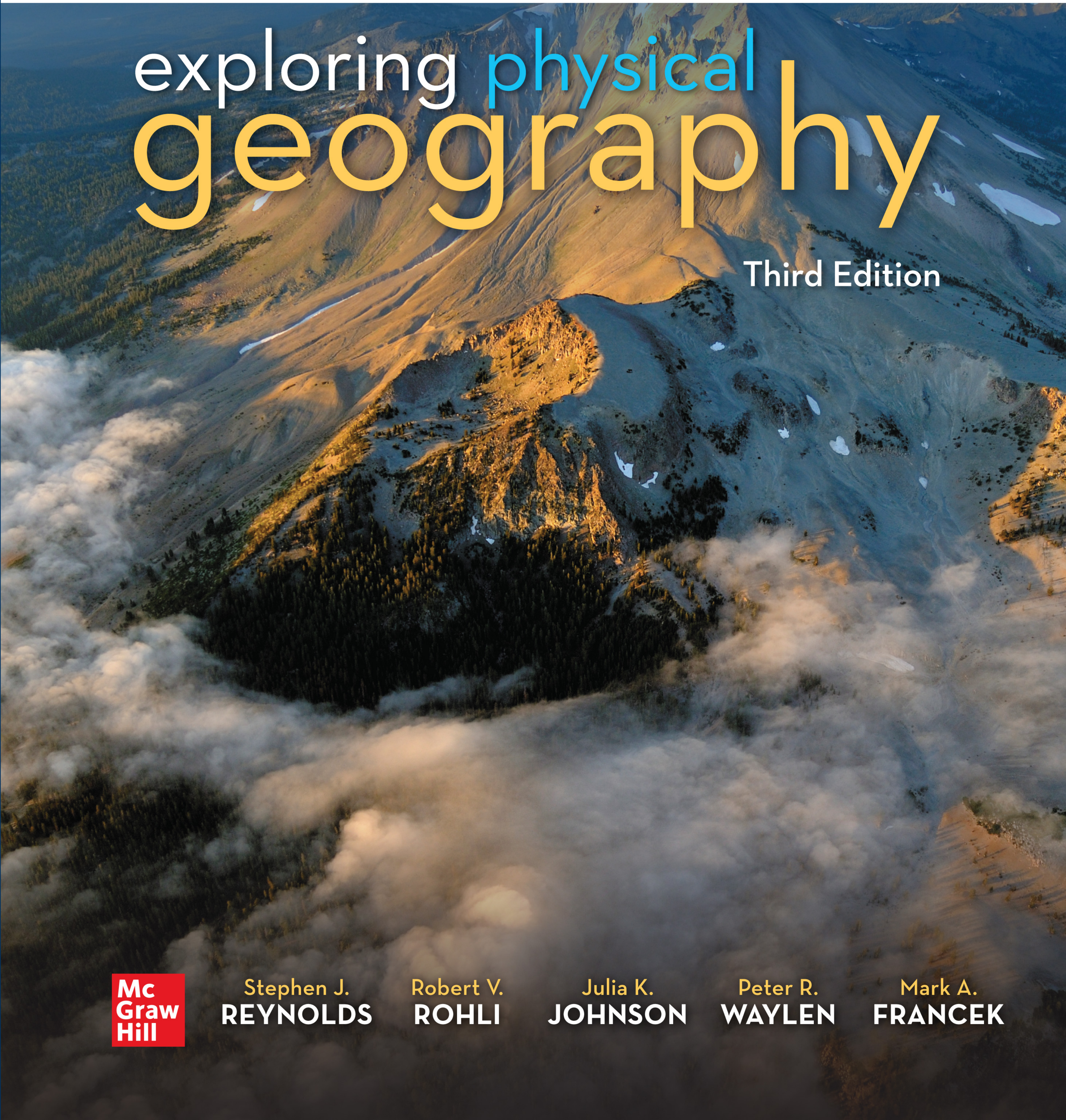

exploring physical geography

Third Edition

Stephen J. REYNOLDS
Robert V. ROHLI
Julia K. JOHNSON
Peter R. WAYLEN
Mark A. FRANCEK

Mc Graw Hill

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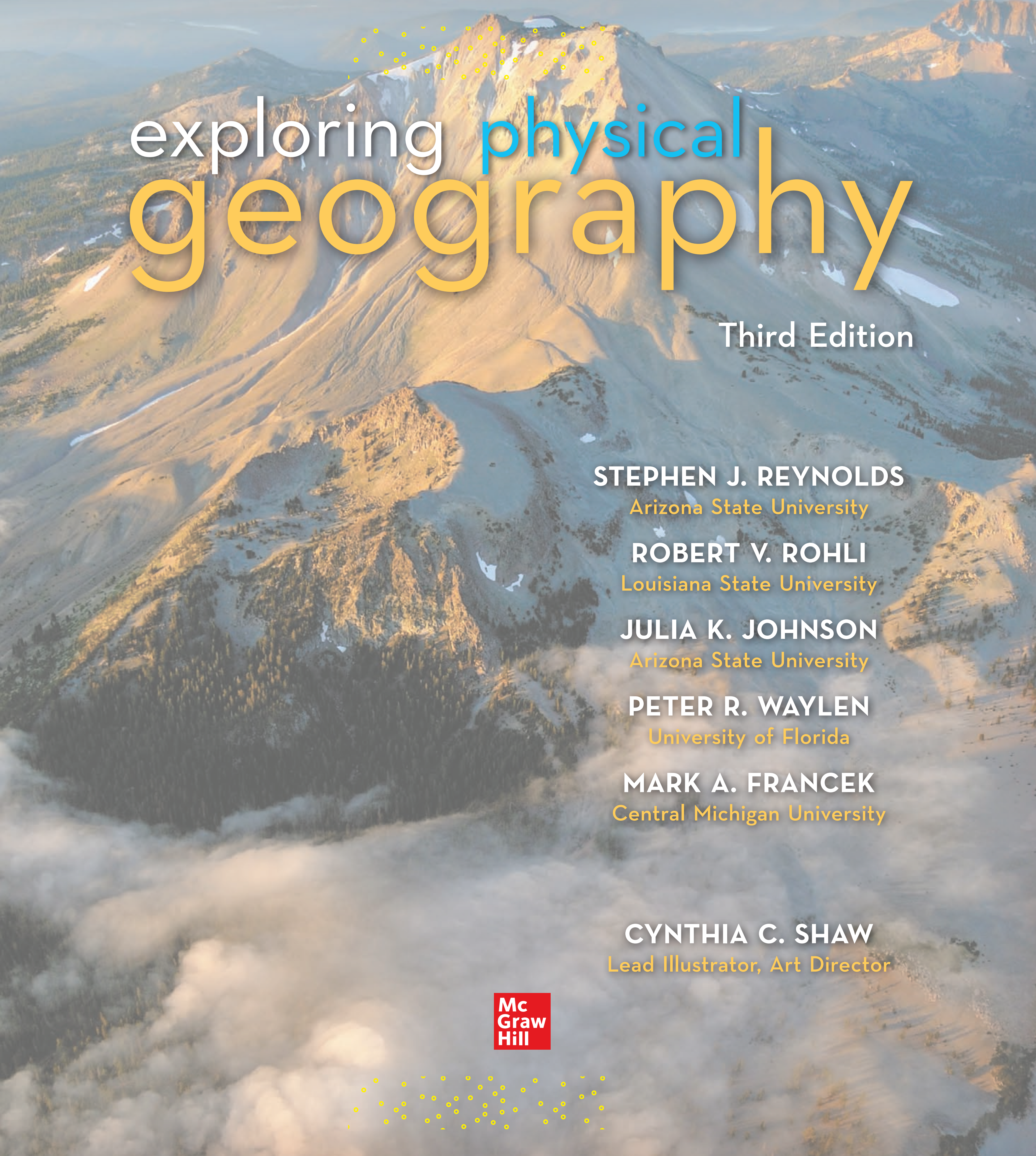
About the Cover

Sunrise highlights the bare northeast face of Lassen Peak, the southernmost active volcano in the Cascade Range. This slope of loose rocks is known as the “Devastated Area” because it was blasted into existence by an eruption on May 22, 1915. Prior to this eruption, Native Americans had already named Lassen the “Mountain Ripped Apart.” The most recent phase of volcanism started in this part of northern California about 3 million years ago, and Lassen first erupted only 27,000 years ago. The entire mountain is a lava dome, one of the largest in the world. The volcanoes of the Cascade Range form where the Juan de Fuca tectonic plate subducts beneath the North American plate.

Lassen Peak stands at an elevation of 3,187 m (10,457 feet) above sea level, towering over the surrounding landscape. Storms from the Pacific Ocean can bring 23 m (75 feet) or more of snow each winter, and large patches remain even into late September, when this picture was taken. Glacial erosion during the last 2 million years played an important role in shaping the peak, but no glaciers are present now.

Even though the most recent eruption was more than a century ago, rocks beneath the surface remain fiercely hot. Moisture on the surface seeps down into the peak. Under the pressure of overlying rock, that water can be heated to 235°C (455°F). As the superheated water rises back to the surface, pressures drop and the water flashes to steam, visible as fumaroles rich in dissolved hydrochloric acid and hydrogen sulfide gas. The acidic water creates toxic pools, but even so, proto-bacteria called *Archaea* can survive here. Forests of hemlock and pine cover the lower slopes, but the upper flanks of Lassen remain bare because plants cannot flourish in the cold conditions and on the dry rock-strewn slope that lacks soil.

Michael Collier received his B.S. in geology at Northern Arizona University, M.S. in structural geology at Stanford, and M.D. from the University of Arizona. He rowed boats commercially in the Grand Canyon in the late 1970s and early 1980s. He now lives in Flagstaff, Arizona, where he practices family medicine. Collier has published books about the geology of Grand Canyon National Park, Death Valley, Denali National Park, and Capitol Reef National Park. He has done books on the Colorado River basin, glaciers of Alaska, and climate change in Alaska. He recently completed a three-book series on American mountains, rivers, and coastlines, designed around his spectacular photographs taken from the air. As a special-projects writer with the USGS, he wrote books about the San Andreas fault, climate change, and downstream effects of dams, with each book featuring his many photographs. Collier has produced an iPad app about seeing landscapes from the air. He received the USGS Shoemaker Communication Award in 1997, the National Park Service Director’s Award in 2000, and the American Geological Institute’s Public Contribution to Geosciences Award in 2005.



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Arizona State University

ROBERT V. ROHLI
Louisiana State University

JULIA K. JOHNSON
Arizona State University

PETER R. WAYLEN
University of Florida

MARK A. FRANCEK
Central Michigan University

CYNTHIA C. SHAW
Lead Illustrator, Art Director

Mc Graw Hill

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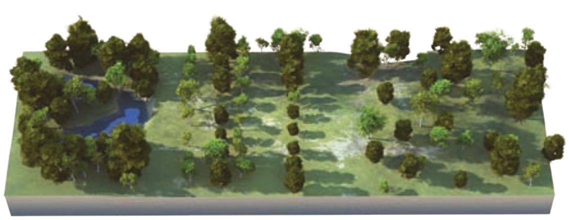

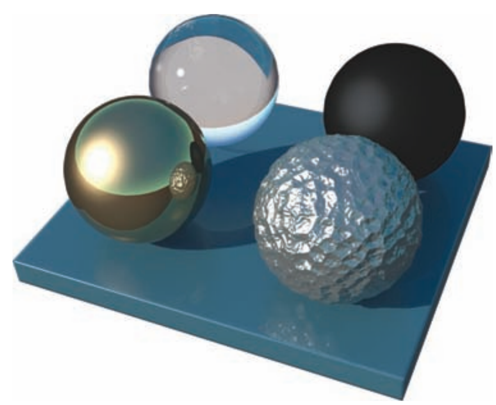

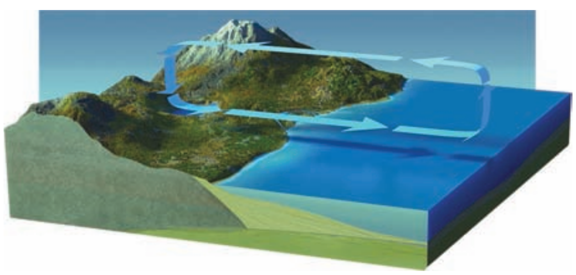

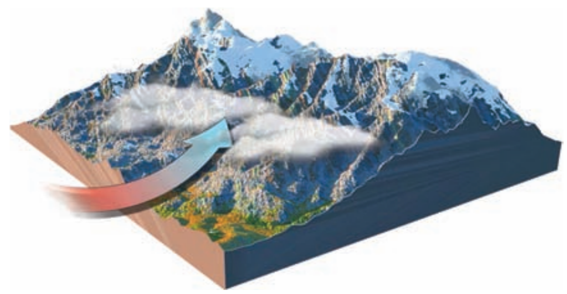

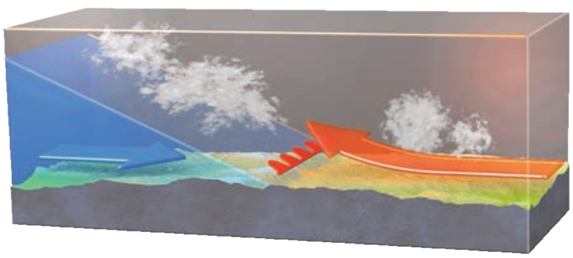

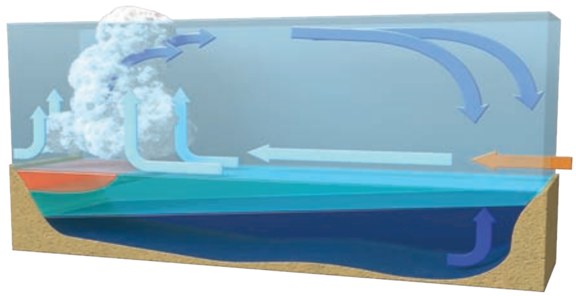

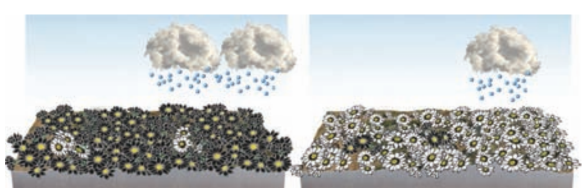

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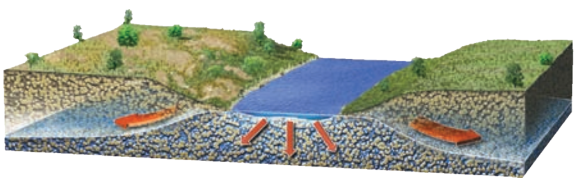

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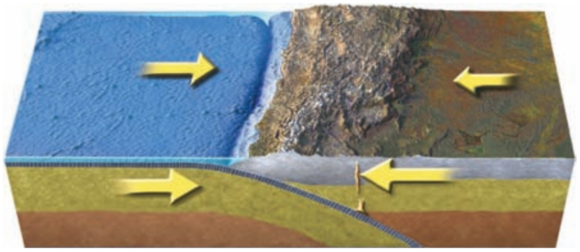

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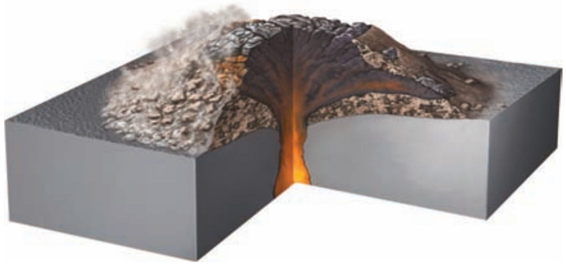

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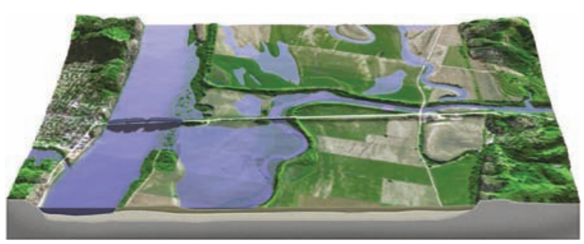

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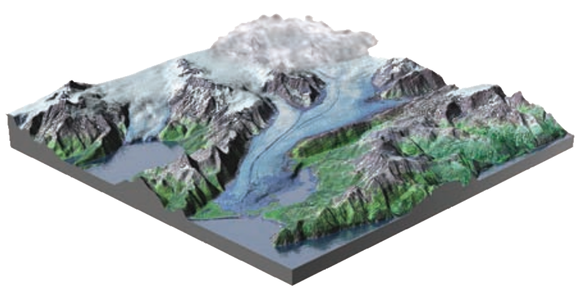

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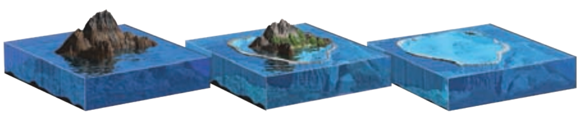

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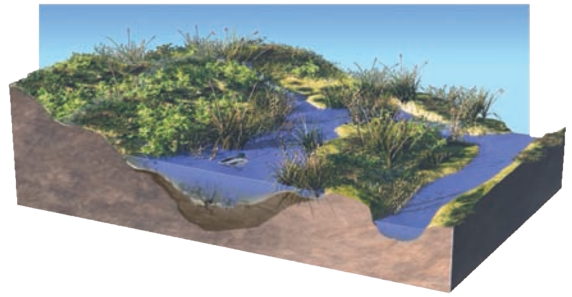


PREFACE

TELLING THE STORY . . .

WE WROTE *EXPLORING PHYSICAL GEOGRAPHY* 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 weather, climate, 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 coauthors 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 geographic concepts and their relevance. Instructors would also be able to spend more class time teaching students to observe and interpret landscapes, atmospheric phenomena, and ecosystems, and to participate in the process of scientific inquiry, which represents the top goal for many instructors.

COGNITIVE AND SCIENCE-EDUCATION RESEARCH

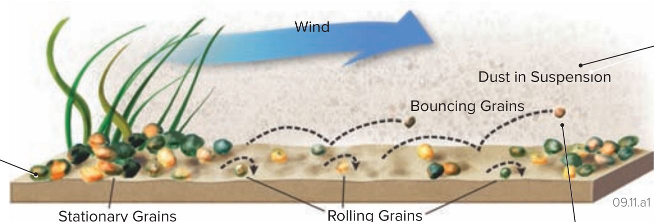
To design a book that supports instructor goals, we delved into cognitive and science-education research, especially research on how our brains process different types of information, what obstacles limit student learning from textbooks, and how students use visuals versus text while studying. We also 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 the evolution of environments. *Exploring Physical Geography* is the result of our literature search and of our own science-education research. As you examine *Exploring Physical Geography*, you will notice that it is stylistically different from most other textbooks, which will likely elicit a few questions.

A How Does Wind Pick Up and Transport Sediment?

Wind is generated by differences in air pressure, and at times it is strong enough to transport material, but only 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 photographs on these two pages.

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

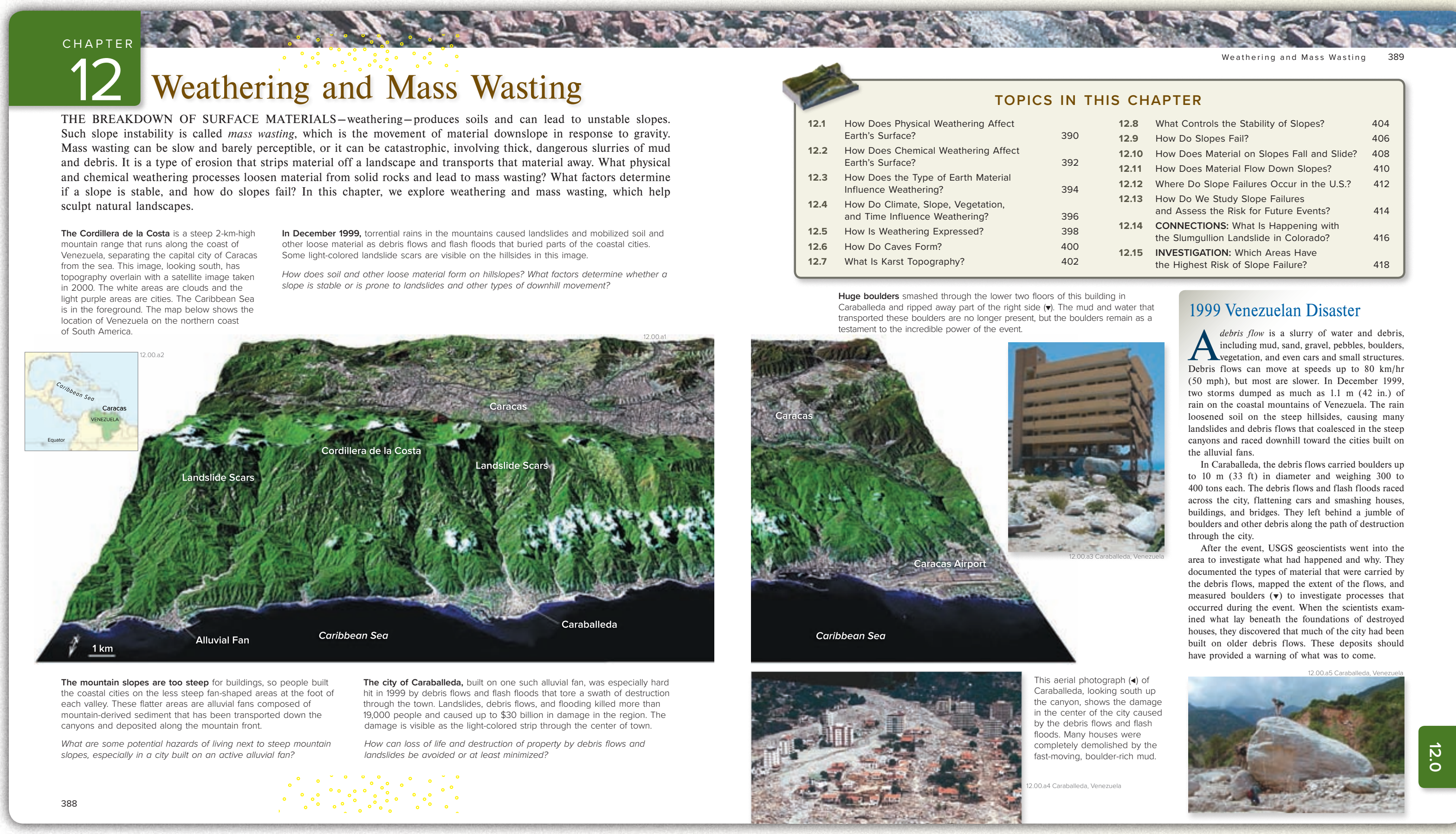


5. Wind can pick up and carry finer material, such as dust, silt, and salt. This mode of transport is called *suspension*. Wind can keep some particles in the air for weeks, transporting them long distances, even across the oceans.

3. Moderately strong winds can roll or slide grains of sand and other loose materials across the ground.

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

HOW DOES THIS BOOK SUPPORT STUDENT CURIOSITY AND INQUIRY?



CHAPTER 12

Weathering and Mass Wasting

THE BREAKDOWN OF SURFACE MATERIALS—weathering—produces soils and can lead to unstable slopes. Such slope instability is called *mass wasting*, which is the movement of material downslope in response to gravity. Mass wasting can be slow and barely perceptible, or it can be catastrophic, involving thick, dangerous slurries of mud and debris. It is a type of erosion that strips material off a landscape and transports that material away. What physical and chemical weathering processes loosen material from solid rocks and lead to mass wasting? What factors determine if a slope is stable, and how do slopes fail? In this chapter, we explore weathering and mass wasting, which help sculpt natural landscapes.

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 light 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 debris flows and 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 incredible power of the event.

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.

12.00.a4 Caraballeda, Venezuela

1999 Venezuelan Disaster

A *debris flow* is a slurry of water and debris, including mud, sand, gravel, pebbles, boulders, vegetation, and even cars and 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.

12.00.a5 Caraballeda, Venezuela

12.0

Exploring Physical Geography 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 geographic terms and the application of knowledge to a new situation. For example, chapter 12 on slope stability, pictured above, begins with a three-dimensional image of northern Venezuela 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 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.

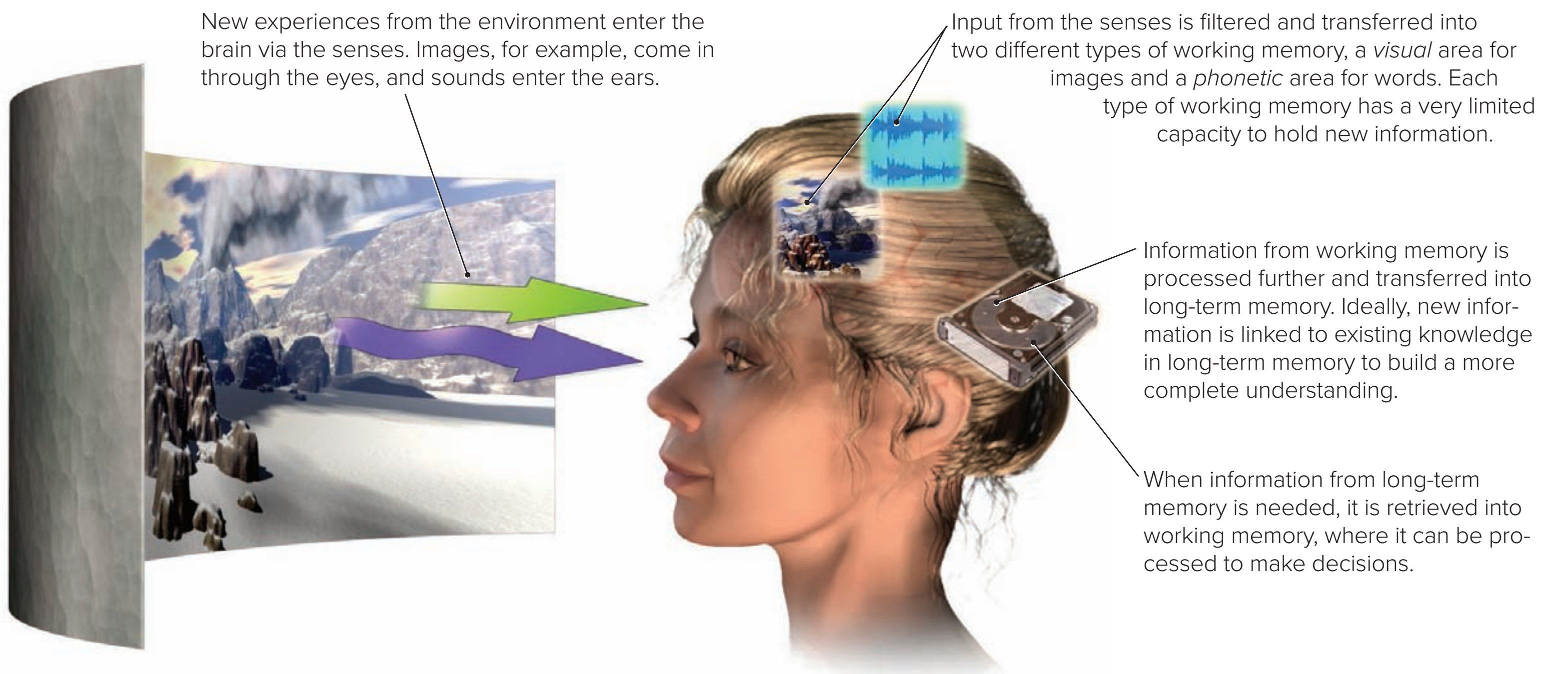
WHY ARE THE PAGES DOMINATED BY ILLUSTRATIONS?

Physical geography is a visual science. Geography 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 biosphere in ways words cannot. In geography, a picture really is worth a thousand words.

Exploring Physical Geography contains a wealth of figures to take advantage of the visual and spatial nature of geography and the efficiency of figures in conveying geographic 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 geographic feature, geographic 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. The short blocks are numbered if they should be read in a specific order.

This approach is especially well suited to covering geographic topics, because it allows the text to have a precise linkage to the geographic location of the aspect being described. A text block discussing the Intertropical Convergence Zone in Costa Rica can have a leader that specifically points to the location of this feature. A cross section of atmospheric circulation 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 Physical Geography* 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). This view of cognition is illustrated in the figure below. Cognitive scientists also speak about two types of memory: *working memory* involves holding and processing information in short-term memory, and *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 two types of information in working memory. For information that has both pictorial and verbal components, as most geographic 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.

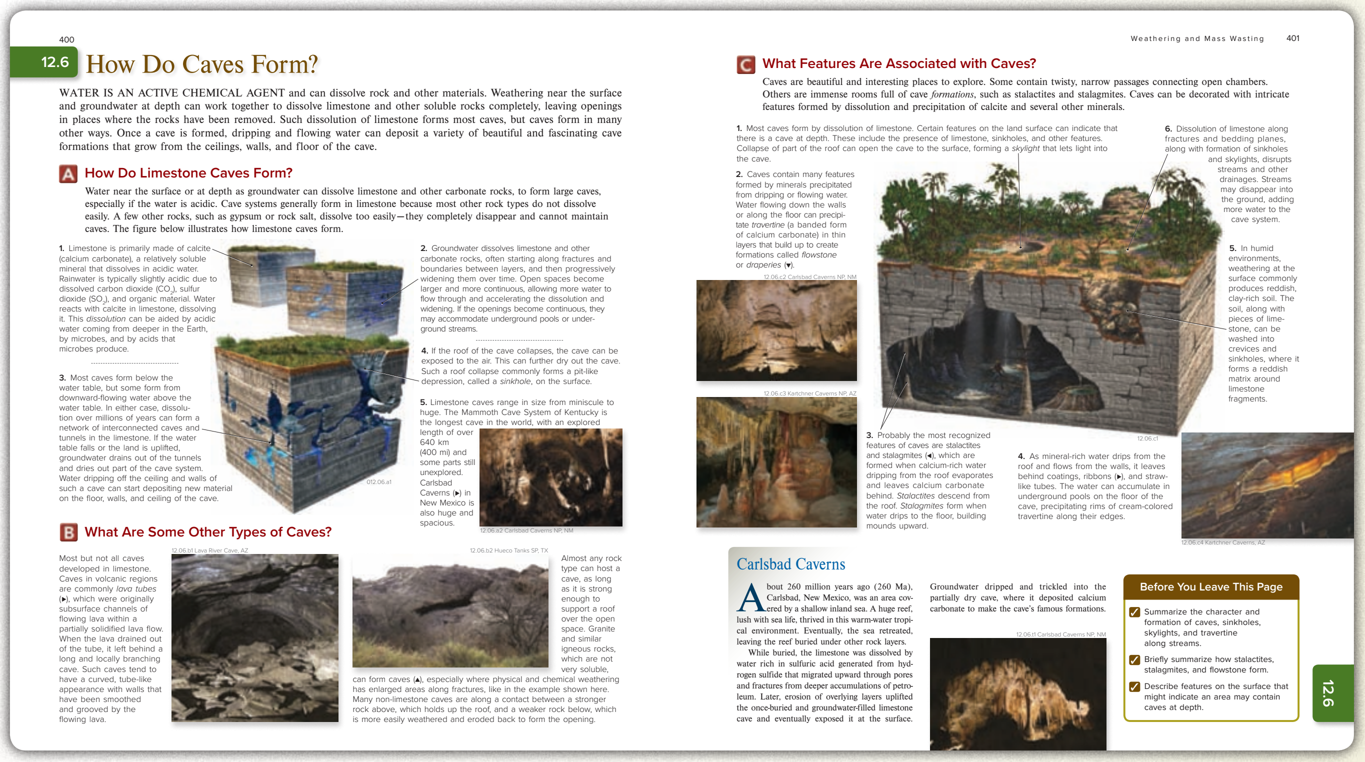


WHY ARE THERE SO MANY FIGURES?

This textbook contains more than 2,600 figures, which is two to three times the number in most introductory geography textbooks. One reason for this is that the book is designed to provide a concrete example of each process, environment, or landscape 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 on this page, conceptualized figures are integrated with photographs and text so that students can build a more coherent view of the environment or process.

Exploring Physical Geography focuses on the most important geographic 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 Physical Geography* 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, weather and climatological data, and aerial photographs. 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 with topography. Research findings by us and other researchers (Roth and Bowen, 1999) indicate that including people and human-related items on 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 geographers study geographic processes and features, (2) illustrate the relevance of the processes on humans, or (3) help students connect and relate to the human dimension of the issue.



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12.6 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 dissolve limestone and other soluble rocks completely, 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 that grow from the ceilings, walls, and floor of the cave.

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 because most other rock types do not dissolve easily. 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, 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 or the land is uplifted, groundwater drains out of the tunnels and dries out part of the cave system. Water dripping off the ceiling and walls of such a cave can start depositing new material on the floor, walls, and ceiling of the cave.

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) and some parts still unexplored. Carlsbad Caverns (▸) in New Mexico is also huge and spacious.

012.06.a1

12.06.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.

12.06.b1 Lava River Cave, AZ

12.06.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, which is more easily weathered and eroded back to form the opening.

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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 rooms full of cave *formations*, such as stalactites and stalagmites. 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. 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* or *draperies* (▾).

12.06.c2 Carlsbad Caverns NP, NM

12.06.c3 Kartchner Caverns NP, 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* descend from the roof. *Stalagmites* form when water drips to the floor, building mounds upward.

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.

12.06.c1

12.06.c4 Kartchner Caverns, AZ

Carlsbad Caverns

About 260 million years ago (260 Ma), 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 migrated upward through pores and fractures 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.

12.06.t1 Carlsbad Caverns NP, NM

Before You Leave This Page

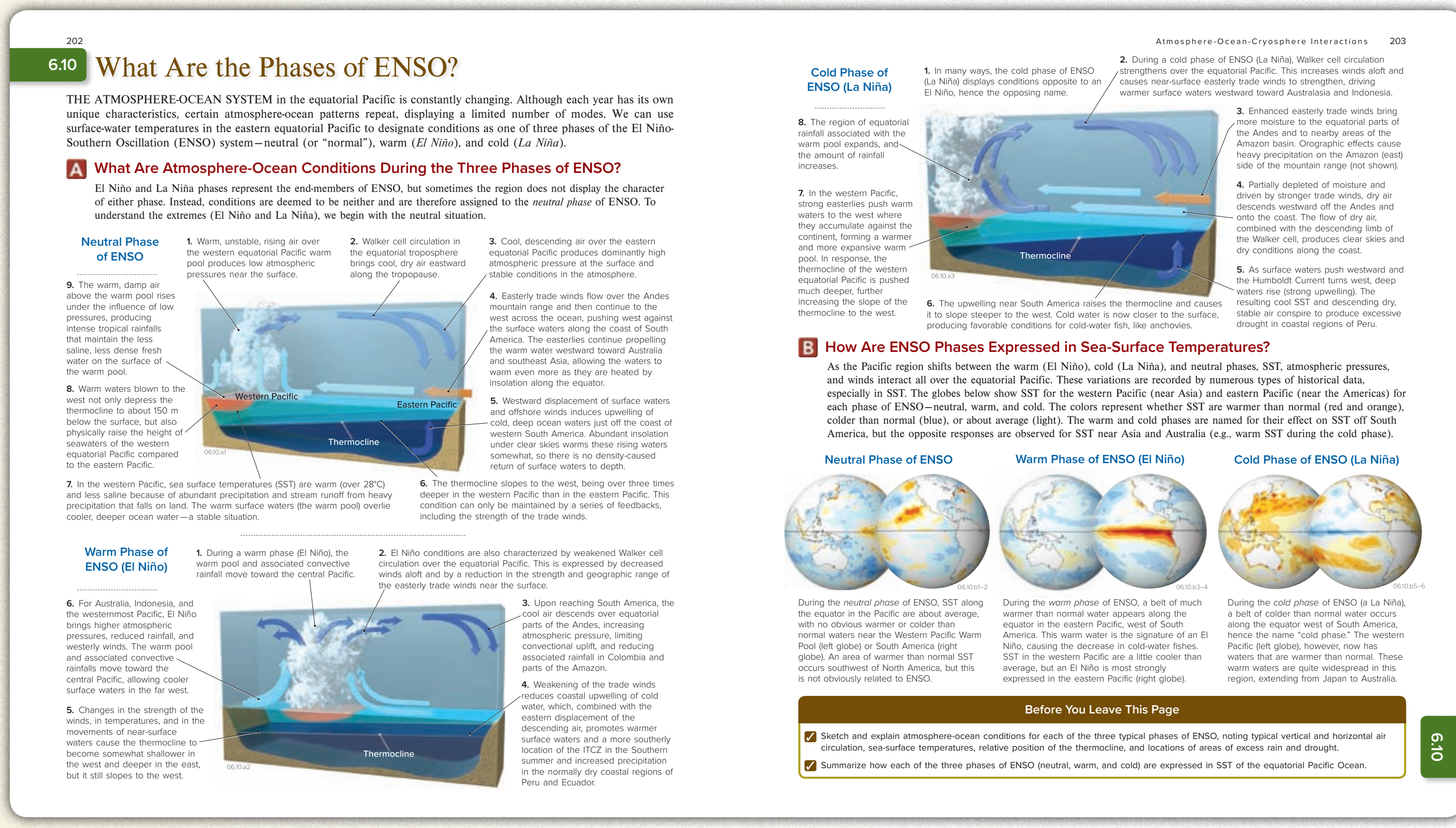
- Summarize the character and formation of caves, sinkholes, skylights, and travertine along streams.
- Briefly summarize how stalactites, stalagmites, and flowstone form.
- Describe features on the surface that might indicate an area may contain caves at depth.

12.6

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 (Jaeger, et al., 2017). 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 6.10 for the tenth topical two-page spread in chapter 6. 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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6.10 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.

Neutral Phase of ENSO

1. Warm, unstable, rising air over the western equatorial Pacific warm pool produces low atmospheric pressures near the surface.

2. Walker cell circulation in the equatorial troposphere brings cool, dry air eastward along the tropopause.

3. Cool, descending air over the eastern equatorial Pacific produces dominantly high atmospheric pressure at the surface and stable conditions in the atmosphere.

4. Easterly trade winds flow over the Andes mountain range and then continue to the west across the ocean, pushing west against the surface waters along the coast of South America. The easterlies continue propelling the warm water westward toward Australia and southeast Asia, allowing the waters to warm even more as they are heated by insolation along the equator.

5. Westward displacement of surface waters and offshore winds induces upwelling of cold, deep ocean waters just off the coast of western South America. Abundant insolation under clear skies warms these rising waters somewhat, so there is no density-caused return of surface waters to depth.

6. The thermocline slopes to the west, being over three times deeper in the western Pacific than in the eastern Pacific. This condition can only be maintained by a series of feedbacks, including the strength of the trade winds.

7. In the western Pacific, sea surface temperatures (SST) are warm (over 28°C) and less saline because of abundant precipitation and stream runoff from heavy precipitation that falls on land. The warm surface waters (the warm pool) overlie cooler, deeper ocean water—a stable situation.

8. Warm waters blown to the west not only depress the thermocline to about 150 m below the surface, but also physically raise the height of seawaters of the western equatorial Pacific compared to the eastern Pacific.

9. The warm, damp air above the warm pool rises under the influence of low pressures, producing intense tropical rainfalls that maintain the less saline, less dense fresh water on the surface of the warm pool.

Western Pacific
Eastern Pacific
Thermocline

Warm Phase of ENSO (El Niño)

1. During a warm phase (El Niño), the warm pool and associated convective rainfall move toward the central Pacific.

2. El Niño conditions are also characterized by weakened Walker cell circulation over the equatorial Pacific. This is expressed by decreased winds aloft and by a reduction in the strength and geographic range of the easterly trade winds near the surface.

3. Upon reaching South America, the cool air descends over equatorial parts of the Andes, increasing atmospheric pressure, limiting convectional uplift, and reducing rainfalls in Colombia and parts of the Amazon.

4. Weakening of the trade winds reduces coastal upwelling of cold water, which, combined with the eastern displacement of the descending air, promotes warmer surface waters and a more southerly location of the ITCZ in the Southern summer and increased precipitation in the normally dry coastal regions of Peru and Ecuador.

5. Changes in the strength of the winds, in temperatures, and in the movements of near-surface waters cause the thermocline to become somewhat shallower in the west and deeper in the east, but it still slopes to the west.

6. For Australia, Indonesia, and the westernmost Pacific, El Niño brings higher atmospheric pressures, reduced rainfall, and westerly winds. The warm pool and associated convective rainfalls move toward the central Pacific, allowing cooler surface waters in the far west.

Thermocline

Atmosphere-Ocean-Cryosphere Interactions 203

Cold Phase of ENSO (La Niña)

1. In many ways, the cold phase of ENSO (La Niña) displays conditions opposite to an El Niño, hence the opposing name.

2. During a cold phase of ENSO (La Niña), Walker cell circulation strengthens over the equatorial Pacific. This increases winds aloft and causes near-surface easterly trade winds to strengthen, driving warmer surface waters westward toward Australasia and Indonesia.

3. Enhanced easterly trade winds bring more moisture to the equatorial parts of the Andes and to nearby areas of the Amazon basin. Orographic effects cause heavy precipitation on the Amazon (east) side of the mountain range (not shown).

4. Partially depleted of moisture and driven by stronger trade winds, dry air descends westward off the Andes and onto the coast. The flow of dry air, combined with the descending limb of the Walker cell, produces clear skies and dry conditions along the coast.

5. As surface waters push westward and the Humboldt Current turns west, deep waters rise (strong upwelling). The resulting cool SST and descending dry, stable air conspire to produce excessive drought in coastal regions of Peru.

6. The upwelling near South America raises the thermocline and causes it to slope steeper to the west. Cold water is now closer to the surface, producing favorable conditions for cold-water fish, like anchovies.

7. In the western Pacific, strong easterlies push warm waters to the west where they accumulate against the continent, forming a warmer and more expansive warm pool. In response, the thermocline of the western equatorial Pacific is pushed much deeper, further increasing the slope of the thermocline to the west.

8. The region of equatorial rainfall associated with the warm pool expands, and the amount of rainfall increases.

Thermocline

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, 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). The warm and cold phases are named for their effect on SST off South America, but the opposite responses are observed for SST near Asia and Australia (e.g., warm SST during the cold phase).

Neutral Phase of ENSO | Warm Phase of ENSO (El Niño) | Cold Phase of ENSO (La Niña)

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.

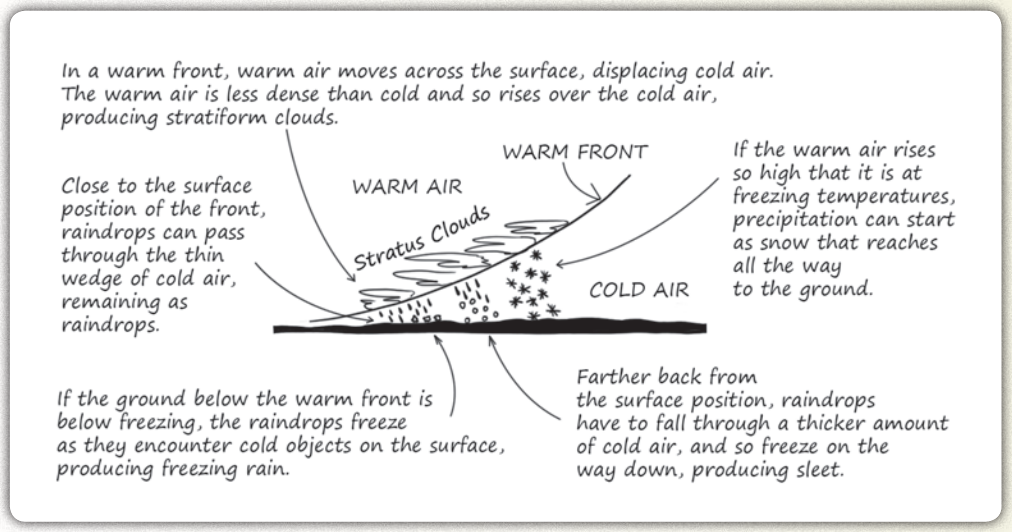
6.10

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 geographic 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 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.

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 geographic features, describe how the features form, characterize the main geographic processes, and summarize histories of landscapes (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 geographic features, processes, and history. Concept sketches are well suited to the visual nature of geography, especially cross sections, maps, and block diagrams. Geographers 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 the evolution of landscapes, circulation in the atmosphere and oceans, motion and precipitation along weather fronts, layers within soils, and biogeochemical cycles. Our research data show that a student who can draw, label, and explain a concept sketch generally has a good understanding of that concept. Based on our incredibly positive experience with concept sketches in introductory and upper-division courses, we decided to include a two-page spread on concept sketches near the end of Chapter 1. This book does not in any way require an instructor to use concept sketches, but we've made it easier if an instructor wants to utilize this approach.

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HOW IS THIS BOOK ORGANIZED?

Two-page spreads are organized into 18 chapters that are arranged into five major groups: (1) introduction to Earth, geography, and energy and matter; (2) atmospheric motion, weather, climate, and water resources; (3) introduction to landscapes, earth materials, sediment transport, plate tectonics, and tectonic processes (e.g., volcanoes and earthquakes); (4) processes, such as stream flow and glaciation, that sculpt and modify landscapes; and (5) soils, biogeography, and biogeochemical cycles. The first chapter provides an overview of geography, including the scientific approach to geography, how we determine and represent location, the tools and techniques used by geographers, and an introduction to *natural systems*—a unifying theme interwoven throughout the rest of the book. Chapter 2 covers energy and matter in the Earth system, providing a foundation for all that follows in the book.

The second group of chapters begins with an introduction to atmospheric motion (chapter 3), another theme revisited throughout the book. 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 3 also covers air pressure, the Coriolis effect, and seasonal and regional winds. This leads naturally into chapter 4, which is a thorough introduction to atmospheric moisture and the consequences of rising and sinking air, including clouds and precipitation. Chapter 5 follows with a visual, map-oriented discussion of weather, including cyclones, tornadoes, and other severe weather. The next chapter (chapter 6), unusual for an introductory geography textbook, is devoted entirely to interactions between the atmosphere, oceans, and cryosphere. It features sections on ocean currents, sea-surface temperatures, ocean salinity, and a thorough treatment of ENSO and other atmosphere-ocean oscillations. This leads into a chapter on climate (chapter 7), which includes controls on climate and a climate classification, featuring a two-page spread on each of the main climate types, illustrated with a rich blend of figures and photographs. These spreads are built around globes that portray a few related climate types, enabling students to concentrate on their spatial distribution and control, rather than trying to extract patterns from a map depicting all the climate types (which the chapter also has). The climate chapter also has a data-oriented presentation of climate change. This second part of the book concludes with chapter 8, which presents the hydrologic cycle and water resources, emphasizing the interaction between surface water and groundwater.

The third part of the book focuses on landscapes and tectonics. It begins with chapter 9, a visually oriented introduction to understanding landscapes, starting with familiar landscapes as an introduction to rocks and minerals. The chapter has a separate two-page spread for each family of rocks and how to recognize each type in the landscape. It presents a brief introduction to weathering, erosion, and transport, aspects that are covered in more detail in later chapters on geomorphology. Wind transport, erosion, and 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. It also covers relative and numeric dating and how we study the ages of landscapes. It is followed by chapter 10 on plate tectonics and regional features. Chapter 10 begins with having students observe large-scale features on land and on 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, evolution of the modern oceans and continents, the origin of high elevations, and the relationship between internal and external processes. The last chapter in this third part (chapter 11) presents the processes, landforms, and hazards associated with volcanoes, deformation, and earthquakes. It also explores the origin of local mountains and basins, another topic unique to this textbook.

The fourth group of chapters concerns the broad field of geomorphology—the form and evolution of landscapes. It begins with chapter 12, a more in-depth treatment of weathering, mass wasting, and slope stability. This chapter also has two-page spreads on caves and karst topography. Chapter 13 is about streams and flooding, presenting a clear introduction to drainage networks, stream processes, different types of streams and their associated landforms and sediment, and how streams change over time. It ends with sections on floods, calculating stream discharges, some examples of devastating local and regional floods, and the many ways in which streams affect people. Chapter 14 covers glaciers and glacial movement, landforms, and deposits. It also discusses the causes of glaciation and the possible consequences of melting of ice sheets and glaciers. Chapter 15 covers the related topic of coasts and changing sea levels. It introduces the processes, landforms, and hazards of coastlines. It also covers the consequences of changing sea level on landforms and humans.

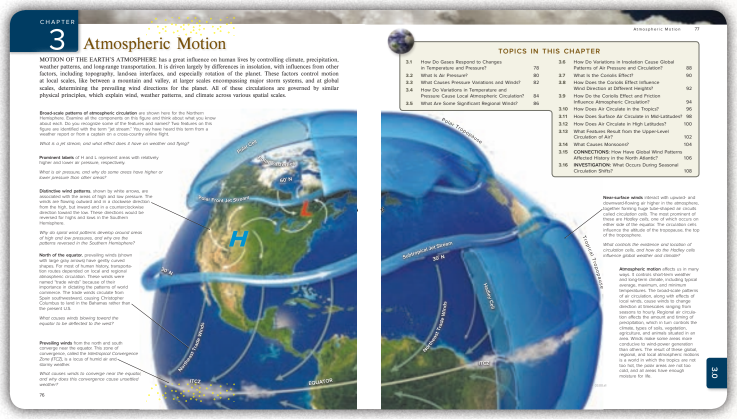
The fifth and final group of chapters focuses on the biosphere and begins with chapter 16, which explores the properties, processes, and importance of soil. This chapter covers soil characterization and classification, including globes showing the spatial distribution of each main type of soil. It ends with a discussion of soil erosion and how soil impacts the way we use land. Chapter 17 provides a visual introduction to ecosystems and biogeochemical cycles. It addresses interactions between organisms and resources within ecosystems, population growth and decline, biodiversity, productivity, and ecosystem disturbance. The last part of chapter 17 covers the carbon, nitrogen, phosphorus, and sulfur cycles, the role of oxygen in aquatic ecosystems, and invasive species. The final chapter in the book, chapter 18, is a synthesis chapter on biomes. It discusses factors that influence biomes and contains at least one two-page spread on each major biome, with maps, globes, photographs, and other types of figures to convey where and why each biome exists. It includes a section on sustainability and ends with a synthesis that portrays biomes in the context of many topics presented in the book, including energy balances, atmospheric moisture and circulation, climate types, and soils.

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.

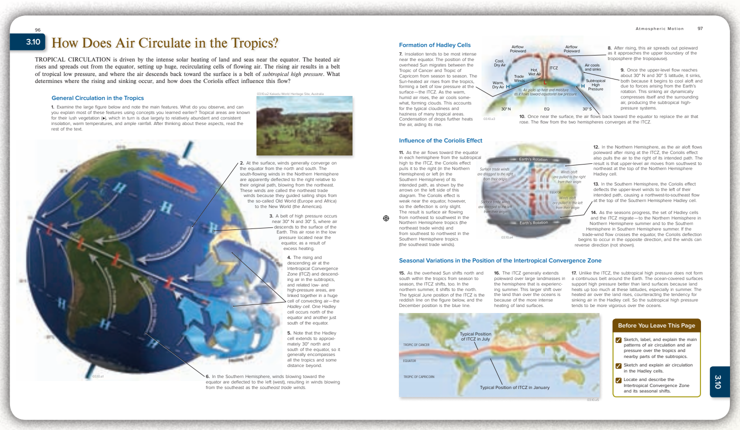
Opening Two-Page Spread

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



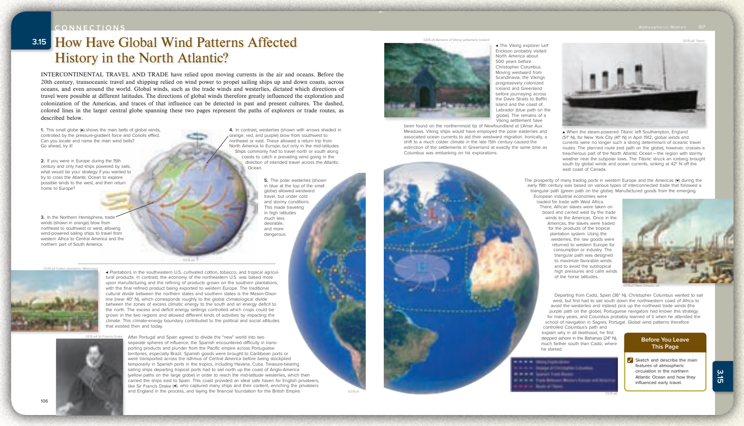
Topical Two-Page Spread

Topical spreads comprise most of the book. They convey the geographic 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. Each chapter has at least one two-page spread illustrating how geography impacts society and commonly another two-page spread that specifically describes how geographers study typical problems.



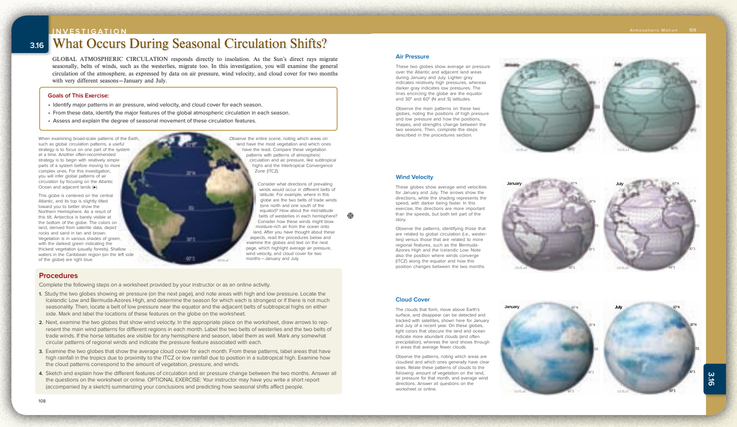
Connections Two-Page Spread

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 geographic concepts and features covered in the chapter, often explicitly illustrating how we investigate a geographic problem and how geographic 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 geographic questions. Investigations are modeled after the types of problems geographers 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 worksheet-based homework, or as online activities.



NEW IN THE THIRD EDITION

By any measure, the third edition of *Exploring Physical Geography* represents a major revision. The style, approach, and sequence of chapters are unchanged, but every chapter received new photographs, revised figures, major to minor editing of text blocks and, in a number of cases, major to minor reorganization. We revised text blocks to improve clarity and conciseness and to present recent discoveries and events. Most chapters contain the same number of two-page spreads, but several chapters gained new spreads containing new figures and text. All text and figures were scrutinized by all five authors, and the resulting improvements and clarifications were countless. The content on every two-page spread was modified in some way, from a few text changes to wholesale reorganization within a spread or among spreads. Nearly all changes were made in response to comments by reviewers, students, and instructors who are using the materials. The most important revisions are listed below.

- This edition includes an important new feature—entirely new one- and two-page spreads in an Appendix designed to improve the quantitative skills of students. These quantitative skills pages are referenced within the main chapters and extend the information within that chapter to include more equations, more quantitative material, and more data from specific sites. The mathematics are described in a step-by-step manner, so that every student can understand how to get to the final result and know how to perform such calculations in the future. There is a two-page spread on fundamental units of matter, energy, and motion, and how to convert from one unit to another. There are one- or two-page spreads on Wien's Law, what Earth's temperature would be if we lacked an atmosphere, how to determine flood probabilities, how to locate an earthquake, how to contour data on maps, and other topics. The Appendix also includes globes suitable for students to copy so that they can mark and color these as different topics are covered in class. Positioning all these materials in the Appendix allows students to follow the overall flow of material within the chapter, uninterrupted, but to have a resource for exploring how we approach a topic in a more quantitative way. The position of these materials in the Appendix allows an instructor to skip any material that they feel is too difficult or time consuming to cover.

- This edition contains 250 new and revised illustrations. Figures from the previous edition were replaced with new versions to update information, to improve student understanding of certain complex topics, and for improved appearance. A number of graphs were enlarged and edited to account for the larger size.

- This edition contains 230 new photographs, with a deliberate intention to represent a wider geographic diversity, striving to provide students with local examples from their region. Some existing photographs from the previous edition were reprocessed from the original image to improve clarity and provide more detail. In some sections, existing photographs were enlarged on the page, requiring reprocessing of the original source. All of these changes to the photographs make the book even more vibrant and engaging.

- For every new or replaced photograph, our photography specialist on the team corrected the color, contrast, and fidelity of each image individually, and created files sized for the larger-than-normal images we provide to instructors. We also edited the text describing the photograph and updated the location label that is part of the figure number in the textbook. Most of the new photographs are the authors' or were contributed by the artists that worked on this book.

- We modified some font styles, including the small tags that contain the figure number and the location. These changes make the figure numbers and location information slightly more readable, but still keeps them subtle, as we prefer, to not overly distract a student's attention.

CHAPTER 1: The opening chapter is heavily revised, with the addition of a new spread on using concept sketches and a timely new Connections spread on the relationship between drought, wildfires, and debris flows. Between the two new spreads, there are nine new photographs and four new figures. There were minor revisions to several other illustrations. As in all chapters, many text blocks were edited.

CHAPTER 2: The second chapter was retitled to be more consistent with the following chapters, and several two-page spreads also received new titles. We revised or rebuilt 26 illustrations, including new versions of seven graphs. We replaced nine photographs, including three in the opening two-page spread.

CHAPTER 3: This chapter received 22 revised illustrations, including updating some to include more recent information. We swapped the positions of spreads on mid-latitude and high-latitude circulation, so that coverage moves from the tropics to the poles, rather than our previous order, where the high-latitude spread preceded the mid-latitude one in order to set the stage for covering upper-level circulation in the mid-latitudes.

CHAPTER 4: Six photographs were replaced in this chapter, mostly of clouds and fog. Six illustrations were revised, including some that had to be rebuilt, such as updating a drought map so that it showed current data. Many text blocks were edited, some extensively.

CHAPTER 5: For this chapter, we replaced four photos, including ones on haboobs and dust devils, phenomena that were specifically sought out by the authors, in storm-chaser mode. We also revised 20 illustrations. The two-page spread on weather fronts was reorganized, incorporating the symbol for each type of front in the heading for that section, among other things.

CHAPTER 6: Chapter 6 contains 22 revised figures, including rebuilt versions of some important figures, such as updated graphs for ocean oscillations. The two-page spread on the phases of ENSO continues to be one of our favorite examples of why an integrated-text-and-figure approach to curricular materials is an obvious advantage over traditional textbooks, where text is in columns without tight linkage to figures.

CHAPTER 7: This chapter on climate was heavily revised, especially the section on climate change. The first two spreads in the four-spread sequence on climate change were largely redone to emphasize recent climate change first, with updated graphs for global temperatures, SST, and satellite data. This is followed by a completely new discussion of the types of proxy data we use to investigate past climate change. To match this recent-first approach, the discussion of greenhouse gases was moved to the start of the spread on the causes of climate change. Due in part to these changes, the chapter received 10 revised or rebuilt illustrations. Revised figures included new globes that include the Republic of South Sudan. There are also 12 new or replaced photographs, including six new photographs illustrating climate proxies. The previous Connections spread on Daisy World was moved to the quantitative skills Appendix, which will allow instructors to consider supplementing this spread with the Daisy World computer simulations that are available. The existing two-page spread on modeling climate change became the new Connections spread and was edited to reflect this new role.

CHAPTER 8: This chapter on water resources gained a new two-page spread on global, regional, and local water issues, a topic of interest to many students. This new spread features 11 new photographs from various cultures and parts of the world, and also includes a new graph on global population growth and accompanying discussion. In addition to these new photographs, nine other photographs were replaced with author versions from geographically diverse regions. These photographs feature water contamination, ecosystems, springs, and power plants. Six illustrations were also revised.

CHAPTER 9: This chapter on landscapes also received a major revision and reorganization. The previous coverage on wind and wind-related features was dramatically increased, with three major new illustrations, including a large, new figure on types of dunes. The wind section now includes 20 photographs, nearly all of them new. The section also contains expanded coverage of the formation of desert pavement, accompanied by a new three-part figure showing its formation. There is also a new illustration and discussion of the variation of wind speed with height. This expanded coverage meshes nicely with detailed material about the cause of deserts in the climate chapter, where it belongs, and material on desert biomes in the biomes chapters. There are a total of 28 new or replaced photographs, including new or improved photographs of rocks. In addition to these extensive changes, we made minor revisions to three figures.

CHAPTER 10: Chapter 10 on plate tectonics received relatively minor revision, but contains nine slightly to moderately revised figures. The section on isostasy became a main lettered section, featuring a revised figure surrounded by text with leaders, whereas in the previous edition it was a short column-based narrative. A number of sections were edited, with slightly adjusted layouts, and one section title was changed.

CHAPTER 11: This chapter experienced a moderate revision, with 21 new photographs of volcanoes, magmatic conduits, and geologic structures. In particular, the photographs of structures were chosen to broaden the geographic coverage represented in the book, including new photos from the Valley and Ridge Province. Several existing photographs were re-cropped to better portray the full extent of a feature, with resulting changes in layout. Ten illustrations received mostly minor revisions.

CHAPTER 12: This chapter on weathering and mass wasting has 24 new photographs, reflecting new events, like the Oso landslide, and the authors seeking out better examples of features of slopes and weathering. The positions of two spreads on weathering were swapped to consolidate coverage. There were minor revisions to four illustrations.

CHAPTER 13: The chapter on streams mostly received minor revisions, except the two-page spread on how streams change over time was reorganized and revised. This revision utilized most of the existing figures, but the layout is new and the sequence in which aspects are discussed is changed. A short section describing the geologic history of the Mississippi River was eliminated. This spread is now more open and inviting. Overall, there are eight new photographs and 18 revised figures.

CHAPTER 14: Chapter 14 has ten new photographs from Antarctica, Washington, Colorado, Wyoming, California, and elsewhere. Text was revised in conjunction with the new photographs. Arrows showing the direction of glacial flow were added to topographic maps that show glacial features. In addition, eight illustrations were slightly revised. Like every chapter, text was extensively edited on most pages.

CHAPTER 15: The coasts chapter was reorganized by rearranging four spreads on sea level change and coastal hazards, shifting the hazard coverage farther back in the chapter, so that it came after discussion of changes in sea level that accompany climate change. The chapter also features 16 new photographs, including a number from the Outer Banks of North Carolina. Six illustrations were lightly revised.

CHAPTER 16: The soils chapter received 10 new photographs and 11 revised illustrations. Accompanying some of the photo replacements are new discussions of the importance of soil to society and soil erosion.

CHAPTER 17: Chapter 17 was extensively revised, expanding by four pages. Two existing two-page spreads on individuals and populations in ecosystems were expanded to three two-page spreads, with a complete rearrangement of sections and much new material. Students will get a more detailed introduction to the types of organisms, how those organisms interact, and how populations change. A spread on biodiversity was expanded to include an additional two-page spread, with a new discussion on the threats to biodiversity. Overall, this chapter has 34 new photographs and 12 revised or new illustrations. Many graphs were enlarged compared to the previous edition of the book.

CHAPTER 18: We replaced 17 photographs featuring plants, animals, and landforms, each representing geographically diverse locations from Africa to California. There were nine revised figures, including globes.

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This book contains over 2,600 figures, several times more than a typical introductory geography 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 a diverse group of authors. 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 the authors' layouts, standardized illustrations, and prepared the final figures for printing. 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 of places, plants, and creatures 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. We also used visually unique artwork by Daniel Miller, David Fierstein, and Susie Gillatt. Suzanne Rohli performed magic with GIS files, did the initial work on the glossary, and helped in many other ways. We were ably assisted in data compilation and other tasks by geography students Emma Harrison, Abeer Hamden, Peng Jia, and Javier Vázquez, and by Cody and Shane Reynolds. Terra Chroma, Inc., of Tucson, Arizona, supported many aspects in the development of this book, including funding parts of the extensive art program and maintenance of the ExploringPhysicalGeography.com website.

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REVIEWERS

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Weber State University, Eric C. Ewert
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PHYSICAL GEOGRAPHY FOCUS GROUP AND SYMPOSIUM PARTICIPANTS

Ball State University, Petra Zimmermann
Blinn College, Rhonda Reagan
California State University-Los Angeles, Steve LaDochy
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University of North Carolina–Greensboro, Michael Lewis
University of Oklahoma, Scott Greene
University of Wisconsin-Oshkosh, Stefan Becker

ABOUT THE AUTHORS

STEPHEN J. REYNOLDS

Stephen J. Reynolds received an undergraduate degree from the University of Texas at El Paso, and M.S. and Ph.D. degrees in geosciences from the University of Arizona. He then spent ten years directing the geologic framework and mapping program of the Arizona Geological Survey, completing a new Geologic Map of Arizona. Steve is in the School of Earth and Space Exploration at Arizona State University, where he is a President's Professor, ASU's highest honor for teaching and scholarship of learning. He was president of the Arizona Geological Society and has authored or edited over 200 maps, articles, and reports on the evolution of Western North America. He also coauthored several widely used textbooks, including the award-winning *Exploring Geology* and *Exploring Earth Science*. His current science research focuses on regional geology, landscape evolution, and resources of the Southwest. He has done science-education research on student learning in college science courses, especially the role of cognition and visualization. He was the first geoscientist with his own eye-tracking laboratory, where he and his students have researched student learning, including the role of textbooks and other educational materials. Steve is known for innovative teaching methods, has received numerous teaching awards, and has an award-winning website. Each year, he travels across the country presenting talks and workshops on how to infuse active learning, inquiry, and cognition-guided teaching into introductory geoscience classes. He has given as many as 20 such talks and workshops in a year, in support of his goal of improving how introductory geoscience is taught. This goal drove the writing of this textbook. He is commonly an invited speaker to national workshops and symposia on active learning, cognition, visualization, and teaching.

ROBERT V. ROHLI

Robert Rohli (B.A., Geography, University of New Orleans; M.S., Atmospheric Sciences, The Ohio State University; Ph.D., Geography from Louisiana State University (LSU)) is a professor in the Department of Oceanography & Coastal Sciences in the College of the Coast & Environment at LSU. Previously, he served as faculty director of the LSU Residential Colleges Program, coordinator of Louisiana Geographic Education Alliance, assistant professor of geography at Kent State University, and regional climatologist at the Southern Regional Climate Center. His teaching and research interests within physical geography include coastal processes, synoptic meteorology/climatology, atmospheric circulation variability, and hydrometeorology. He has taught Physical Geography, Coastal Meteorology, Surface-Atmosphere Interactions, Meteorology, Climatology, Applied Meteorology, Methods in Synoptic Climatology, World Climates, Analysis of Spatial Data, Water Resources Geography, and other courses. His courses emphasize the systems approach to science, student collaboration in group research projects, and development of applied problem-solving skills. He has been an active supporter of undergraduate education initiatives, including living-learning communities, LSU's Communication across the Curriculum program, improved teaching assessment methods, and outreach activities that promote geography and environmental sciences. He has published more than 65 refereed research articles and book chapters, and over 20 other manuscripts, encyclopedia articles, proceedings papers, and technical reports. He has also coauthored *Climatology*, a widely-used textbook, and *Louisiana Weather and Climate*, *Weather and Climate of Florida*, and co-edited *Selected Readings in Applied Climatology*.

JULIA K. JOHNSON

Julia K. Johnson is currently a full-time faculty member in the School of Earth and Space Exploration at Arizona State University. Her M.S. and Ph.D. research involved structural geology and geoscience education research. She teaches introductory geoscience to more than 2,500 students per year, both online and in person, and supervises the associated in-person and online labs. She also coordinates the introductory geoscience teaching efforts of the School of Earth and Space Exploration, helping other instructors incorporate active learning and inquiry into large lecture classes. Julia coordinated an innovative project focused on redesigning introductory geology classes so that they incorporated more online content and asynchronous learning. This project was very successful in improving student performance, mostly due to the widespread implementation of concept sketches and partly due to Julia's approach of decoupling multiple-choice questions and concept-sketch questions during exams and other assessments. 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. Her efforts have dramatically increased enrollments. She coauthored the widely used *Exploring Geology* and *Exploring Earth Science* textbooks and other publications on geology and science-education research, including an article in the *Journal of Geoscience Education* on concept sketches. She is the lead author of *Observing and Interpreting Geology*, an innovative laboratory manual in which all learning is built around a virtual world. She also developed a number of websites used by students around the world, including the *Visualizing Topography* and *Biosphere 3D* websites.

PETER R. WAYLEN

Peter Waylen is Professor of Geography at the University of Florida. He holds a B.Sc. in geography from the London School of Economics, England, and a Ph.D. from McMaster University, Canada. He has also served as assistant professor at the University of Saskatchewan, Canada, visiting associate professor at the University of Waterloo, Canada, Hartley Visiting Research Fellow at the University of Southampton, England, and visiting scholar in the Department of Engineering Hydrology, University College Galway, Ireland. He has served in various administrative positions, including Associate Dean. His teaching and research interests are in the fields of hydrology and climatology, particularly the temporal and spatial variability of risks of such hazards as floods, droughts, freezes, and heat waves, and the way in which these vary in the long run, driven by global-scale phenomena like ENSO (El Niño Southern Oscillation). He has worked throughout Anglo- and Latin America, and several parts of Africa. He teaches Introductory Physical Geography, Principles of Geographic Hydrology, and Models in Hydrology. Peter was recognized as University of Florida Teacher of the Year. His research is principally interdisciplinary and collaborative with colleagues and students. It has been supported variously by the Natural Research Council of Canada, NSF, NOAA, NASA, and the Inter-American Institute for Global Change Research. Results appear in over 100 geography, hydrology, and climatology refereed outlets and book chapters.

MARK A. FRANCEK

Mark Francek is a geography professor at Central Michigan University (CMU). He earned his doctorate in geography from the University of Wisconsin-Milwaukee, his master's in geography from the University of South Carolina, and his bachelor's degree in geography and psychology from the State University College at Geneseo, New York. He has teaching and research interests in earth-science education, physical geography, and soil science. Mark has pedaled three times across America and teaches biking geography field classes in and around the Great Lakes region and the Appalachian Mountains. He has authored and coauthored more than 30 scholarly papers, funded in part by the NSF and the State of Michigan, and has presented his research at national and state conferences. At CMU, Francek has served as acting department chair, director of the Environmental Studies Program, and director of the Science and Technology Residential College. He has received state and national teaching awards, including the CMU Teaching Excellence Award, the Carnegie Foundation for the Advancement of Teaching Michigan Professor of the Year, the Presidents Council State Universities of Michigan Distinguished Professor of the Year, the National Council for Geographic Education Distinguished Teaching Award, and Michigan Science Teachers Association College Teacher of the Year. His "Earth Science Sites of the Week" Listserv, which highlights the best earth-science websites and animations, reaches thousands of K–16 educators from around the world.

Illustrators and Artists

CYNTHIA SHAW

Cynthia Shaw 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 a real impact on shaping kids' attitudes toward fisheries conservation. Currently landlocked in Richland, Washington, Cynthia escapes whenever possible to travel, hike, and dive the reefs to field-sketch and do reference photography for her projects, especially ones that involve warm, tropical waters.

CHUCK CARTER

Chuck Carter has worked in the artistic end of the science and entertainment industries for more than 30 years. In 1993, he helped create the popular computer game *Myst*. Chuck has worked on more than two dozen video games as an artist, art director, computer graphics supervisor, and group manager. He has a decades-long relationship with *National Geographic* as an illustrator and helping launch *National Geographic Online*. Carter worked as a digital matte painter for science fiction shows like *Babylon 5*, *Crusade*, and *Mortal Kombat*, as well as art and animation for motion rides, such as Disney's Mission to Mars and Paramount's Star Trek: the Experience. His illustration clients include *Wired* magazine, *Scientific American*, and numerous book publishers. He is founder of Eagre Games Inc. based in Ellsworth, Maine.

SUSIE GILLATT

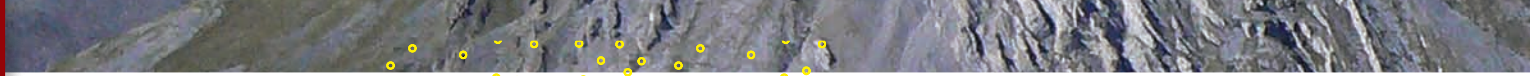
Susie Gillatt grew up in Tucson, Arizona, where she received a Bachelor of Arts degree from the University of Arizona. She has worked as a photographer and in different capacities in the field of video production. She is president of Terra Chroma, Inc., a multimedia studio. Initially specializing in the production of educational videos, she now focuses on scientific illustration and photo preparation for academic books and journals. Many of the photographs in this textbook were contributed by Susie from her travels to different landscapes, ecosystems, and cultures around the world. For her own art, she especially enjoys combining photography with digital and traditional painting mediums, as well as exploring the world of abstract natural patterns. Her award-winning art has been displayed in galleries in Arizona, Colorado, New Mexico and Texas.

exploring physical geography

CHAPTER

1

The Nature of Physical Geography



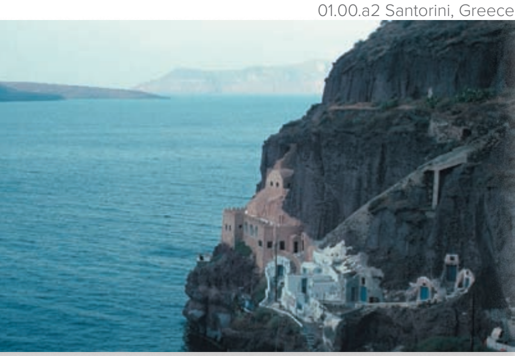
THE EARTH HAS A WEALTH of intriguing features, from dramatic mountains to intricate coastlines and deep ocean trenches, from lush, beautiful valleys to huge areas of sparsely vegetated sand dunes. Above the surface is an active, ever-changing atmosphere with clouds, storms, and variable winds. Occupying all these environments is life. In this chapter and book, we examine the main concepts of physical geography, along with the tools and methods that physical geographers use to study the landscapes, oceans, climate, weather, and ecology of Earth.

The large globe spanning these two pages is a computer-generated representation of Earth, using data collected by several satellites. On land, brown colors depict areas of rock, sand, and soil, whereas green areas have a more dense covering of trees, bushes, grasses, and other vegetation. Oceans and lakes are colored blue, with greenish blue showing places where the water is shallow or where it contains mud derived from the land. Superimposed on Earth's surface are light-colored clouds observed by a different satellite, one designed to observe weather systems.

What are all the things you can observe from this portrait of our planet? What questions arise from your observations?

Most questions that arise from observing this globe are within the domain of *physical geography*. Physical geography deals with the landforms and processes on Earth's surface, the character and processes in oceans and other bodies of water, atmospheric processes that cause weather and climate, and how these various aspects affect life, and much more.

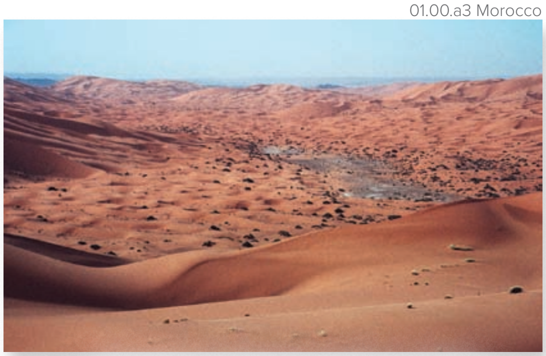
01.00.a2 Santorini, Greece



Natural hazards, including volcanic eruptions and earthquakes, are a major concern in many parts of the world. In the Greek Island of Santorini (◀), people live on the remains of a large volcano that was mostly destroyed in a huge eruption 3,600 years ago, an eruption that probably gave rise to the story of Atlantis.

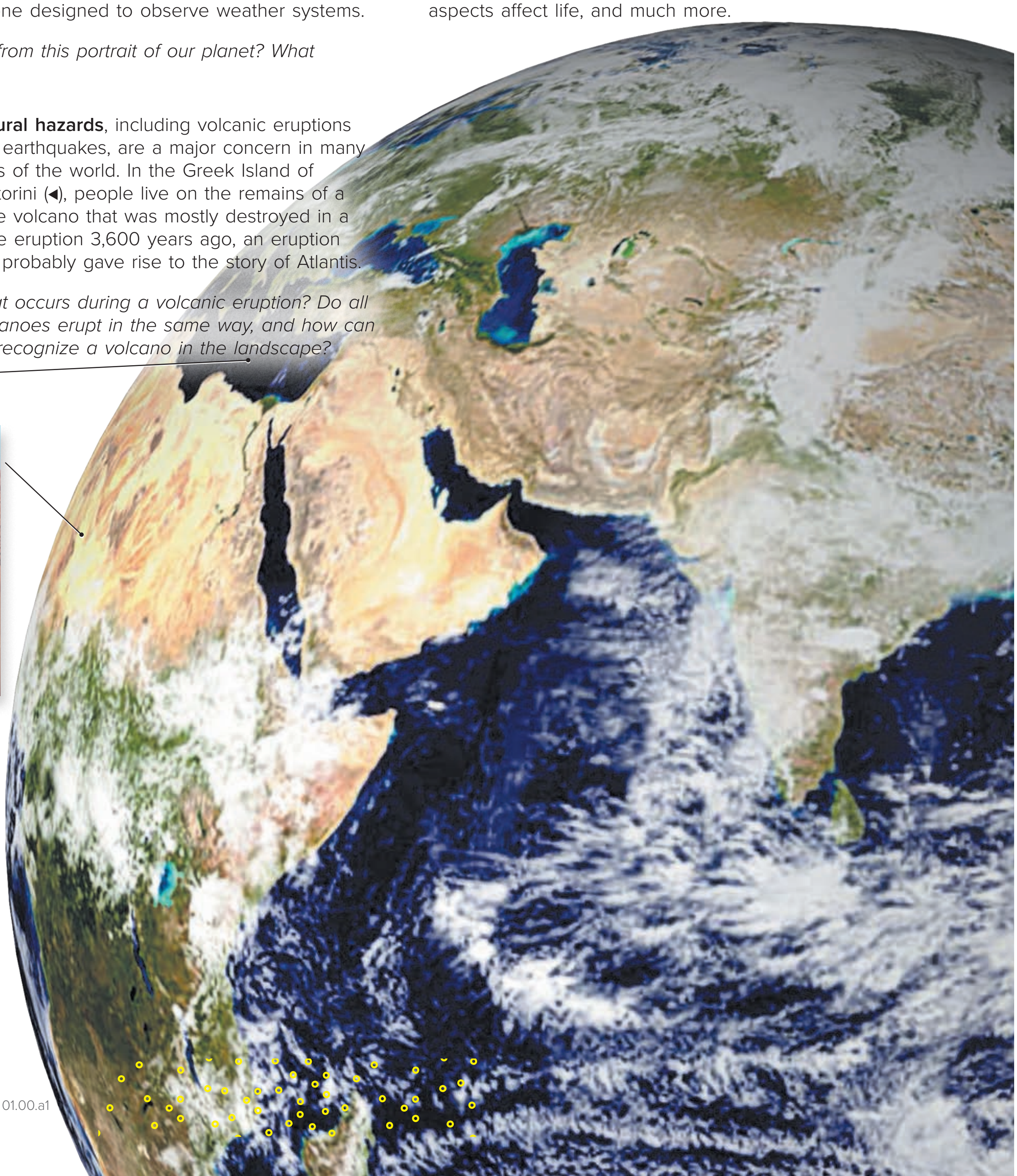
What occurs during a volcanic eruption? Do all volcanoes erupt in the same way, and how can we recognize a volcano in the landscape?

01.00.a3 Morocco



The Sahara Desert, on the opposite side of the Mediterranean Sea from Greece, has a different climate. Here is a dry environment, resulting in huge areas covered by sand dunes (▲) with sparse vegetation.

What causes different regions to have different climates, some that are hot and dry, and others that are cold and wet? Is the climate of the Sahara somehow related to the relative lack of clouds over this area, as shown on the globe? What do the features of the landscape—the landforms—tell us about the surface processes that are forming and affecting the scenery?



01.00.a1

TOPICS IN THIS CHAPTER

01.00.a4 Tibet

Water is the most important resource on the planet, and Earth's temperatures allow water to occur in three states of matter — solid, liquid, and vapor. Examine this photograph (◀) and identify all the ways in which water is expressed on the surface and in the atmosphere. Is some water likely present but not visible? Geographers are concerned with where resources are, what causes resources to be where they are, and how to reconcile the inevitable economic, environmental, and cultural trade-offs involved in using resources.

How does water occur in the atmosphere, what is its role in severe weather, and how does it move on Earth's surface?

01.00.a5 Indonesia

Oceans cover about 70% of Earth's surface. Ocean temperatures, currents, and salinity all play a major role in global weather, climate, and the habitability of places, even for those far from the coast. The oceans and nearby lands (▲) represent important habitats for plants and animals.

How do satellites help us measure surface temperatures of the oceans, and how do changes in temperature affect plants and animals that live in or near the sea?

The Ancient and Modern Discipline of Geography

Geographers seek to understand the Earth. They do this by formulating important and testable questions about the Earth, employing principles from both the natural and social sciences. Geographers use these principles to portray features of the Earth using maps and technologically intensive tools and techniques that are distinctly geographical. Geographers synthesize the diverse information revealed by these tools to investigate the interface between the natural and human environments. The study of the spatial distribution of natural features and processes occurring near Earth's surface, especially as they affect and are affected by humans, is physical geography.

The ancient discipline of geography is especially relevant in our modern world, partly because of the increasing recognition that many problems confronting society involve complex interactions between natural and human dimensions. Such problems include the spatial distribution and depletion of natural resources; contamination of air, water, and soils; susceptibility of areas to landslides, flooding, and other natural disasters; formation of and damage caused by hurricanes, tornadoes, and other severe weather; the current and future challenges of global environmental change; and the environmental implications of globalization. The topics and questions introduced on these pages provide a small sample of the aspects investigated by physical geographers and are discussed more fully in the rest of the book. We hope you enjoy the journey learning about the fascinating planet we call home.

1.1 What Is Physical Geography?

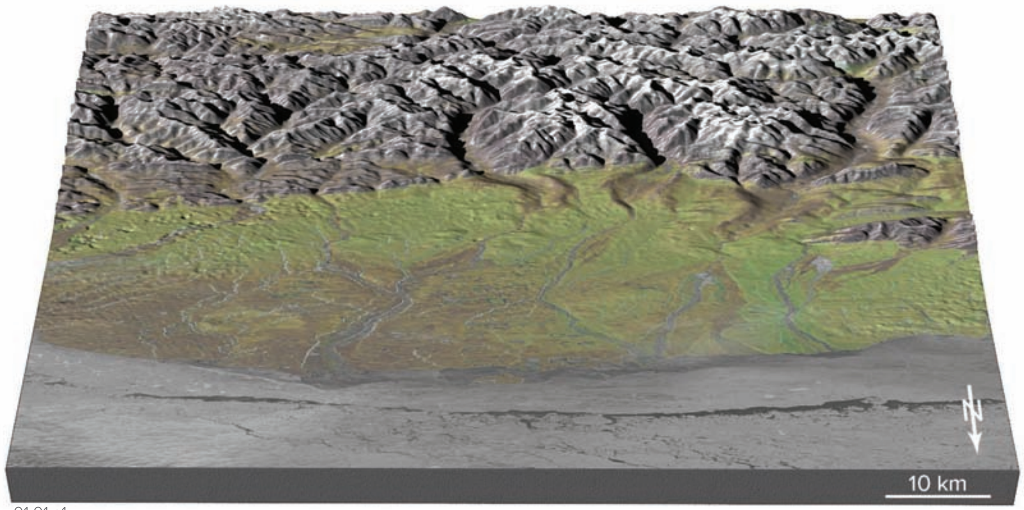
PHYSICAL GEOGRAPHY IS THE STUDY of spatial distributions of phenomena across the landscape, processes that form and change those distributions, and implications for those distributions on people, animals, and plants. Geography is both a natural and a social science. Geographers think broadly, emphasizing interconnections and complex issues, solving complicated problems such as resource management, environmental impact assessment, spread of disease, and urban sprawl. Although many such occupations do not have the title of *geographer*, they require the geographic perspective. Let's have a closer look at what the geographic perspective entails.

A What Approach Do Geographers Use to Investigate Important Issues?

Geographers approach problems from different perspectives than other natural and social scientists. Specifically, geographers think *spatially*, meaning they emphasize the setting, such as location, in addressing problems, and *holistically*, integrating ideas from a wide variety of the natural and social sciences. In many ways, it is not *what* is studied that makes it geography, but instead *how* it is studied. The decision of whether to drill for oil in Alaska's Arctic National Wildlife Refuge (ANWR) is a complicated issue that can be understood best using the geographic approach.

1. This three-dimensional perspective of the central part of ANWR is looking south with the ice-covered Arctic Ocean in the foreground (▶). ANWR is known for its abundant caribou and other animals. Before reading on, examine this scene and think about all the information you would need if you wanted to understand how drilling for oil and gas might impact the caribou.

2. To understand this issue, we might ask a series of questions. Where do the caribou live? Where are they at different times of the year? What do they eat, where are these foods most abundant, and what factors control these abundances? Where is water available, and how much rain and snow do different parts of the region receive? Is the precipitation consistent from year to year? When is the mating season, and where do the mothers raise their young?



01.01.a1

3. We could also ask questions about the subsurface oil reserves. Where is the oil located, and what types of facilities will be required to extract and transport the oil? How much land will be disturbed by such activities, and how will this affect the caribou?

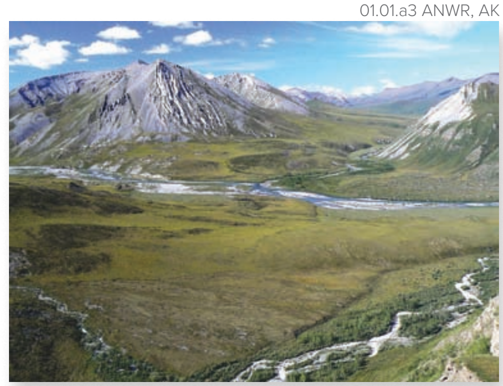
4. The issues of ANWR nicely illustrate why we would use a geographic approach. Most of the questions we asked here have a *spatial component*, as indicated by the word "where," and could be best answered with some type of map. The questions also have an explicit or implicit societal component, such as how development could affect the traditional way of life of the native people of the region.

01.01.a2

5. The *spatial perspective* allows us to compare the locations of the physical, environmental, economic, political, and cultural attributes of the issue. ANWR (◀) is the large area outlined in orange. Its size is deceptive since Alaska is huge (by far the largest state in the U.S.). ANWR is only slightly smaller than the state of South Carolina.

6. To the west of ANWR is the Prudhoe Bay oil field, the largest oil field in North America. Not all of ANWR is likely to contain oil, and an assessment of the oil resources by the U.S. Geological Survey (USGS) identified the most favorable area as being near the coast. To consider the question about oil drilling, we would want to know where this favorable area is, how much land will be disturbed by drilling and associated activities, when these disturbances will occur, and how these compare with the location of caribou at different times of the year, especially where they feed, mate, and deliver their young.

01.01.a3 ANWR, AK



7. The *holistic perspective* allows us to examine the interplay between the environment and other aspects, such as the economic and cultural attributes of the problem. Most of ANWR is a beautiful wilderness area (▲), as well as being home to caribou, native people, and various plants and animals.

B How Does Geography Influence Our Lives?

Observe this photograph, which shows a number of features, including clouds, snowy mountains, slopes, and a grassy field with horses and cows (the small, dark spots). For each feature, think about what is there, what its distribution is, and what processes might be occurring. Then, think about how these factors influence the life of the animals and how they would influence you if this were your home.

01.01.b1 Henry Mtns., UT

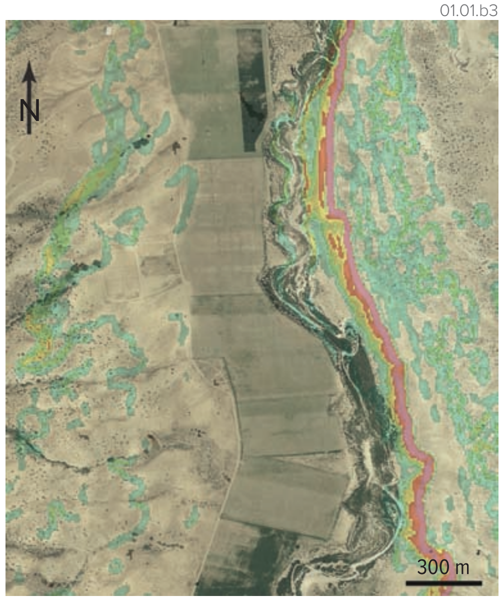
1. The snow-clad mountains, partially covered with clouds, indicate the presence of water, an essential ingredient for life. The mountains have a major influence on water in this scene. Melted snow flows downhill toward the lowlands, to the horses and cows. The elevation and shape of the land influence the spatial distribution and type of precipitation (rain, snow, and hail) and the pattern of streams that develop to drain water off the land.

2. 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 results from loose sand and other materials that were laid down during flooding along a desert stream. The distribution of vegetation is controlled by steepness of slopes, types of soils and other material, water content of the soil, air temperatures, and many other factors, all of which are part of physical geography. The combined effect of such factors in turn affect, and are affected by, the human settlements in the area to make every place, including this one, distinctive and unique.

01.01.b2

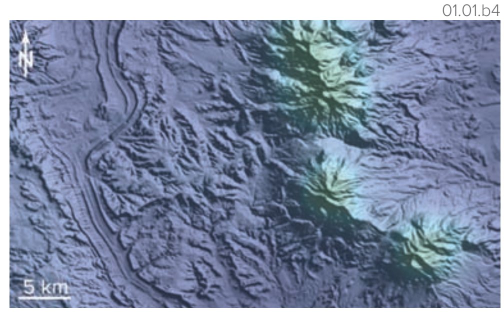
3. This aerial photograph (a photograph taken from the air, like from a plane or drone) gives a better view of the spatial distribution of the green pasture. It reveals the shape of the pasture, and we could measure its length, width, and area. Such measurements would help us decide how many horses and cows the land could support.

01.01.b3



4. Geographers measure various features of the landscape, like the steepness of slopes, and then overlay this information on the original map or image. In the figure above, red shading shows the steepest slopes, along and below the pinkish cliff. Yellow and green indicate gentler slopes, and relatively flat areas are unshaded. Such a map would help us decide which areas could be new pastures.

01.01.b4



5. This image shows the shape of the land across the region, including the mountains (the pasture is on the left). Colors indicate the average amount of precipitation, with green showing the highest amounts. The mountains, on average, receive the most rain and snow.

Before You Leave This Page

- ✓ Describe the geographic approach.
- ✓ List some examples of information used by physical geographers and how these types of information could influence our lives.

1.2 How Do We Investigate Geographic Questions?

PHYSICAL GEOGRAPHERS STUDY DIVERSE TOPICS, ranging from weather systems and climate change to ocean currents and landscape evolution. The types of data required to investigate each of these topics are equally diverse, but most geographers try to approach the topic in a similar, objective way, guided by spatial information and relying on various geographic tools. Geography utilizes approaches from the natural and social sciences, blending them together in a geographic approach. Like other scientists, geographers pose questions about natural phenomena and their implications, propose a possible explanation (hypothesis) that can be tested, make predictions from this hypothesis, and collect data needed to evaluate critically whether the hypothesis passes the tests.

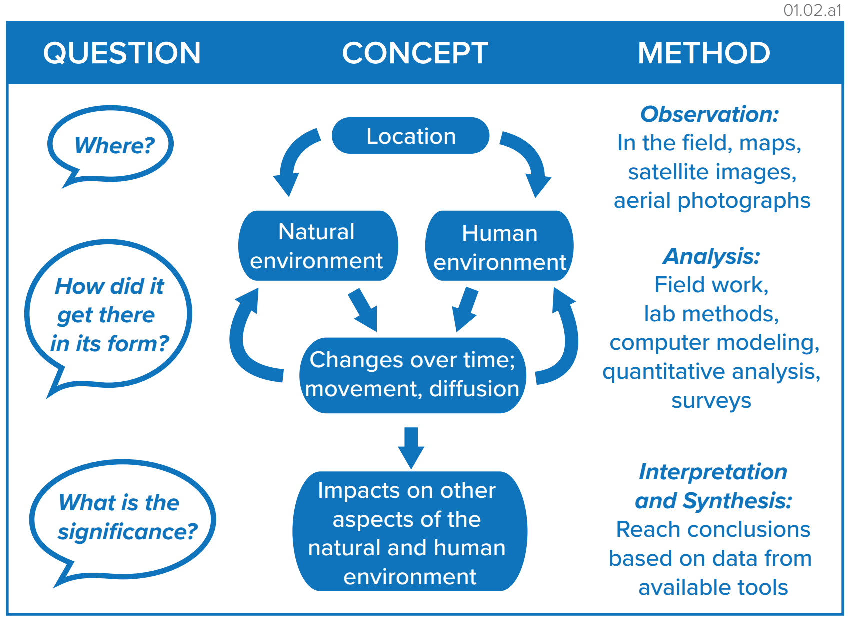
A How Do Geographers Approach Problems?

Examine this figure (▸), which illustrates one way in which geographers approach issues that are important to society. Geographers ask questions like the following:

- Where is it?
- Why is it where it is?
- How did it get where it is?
- Why does it matter where it is?
- How does "where it is" influence where other things are and why they are there?

The conceptual basis of these questions lies in the notion that the *location* of something affects, and is a product of, other features or processes in both the natural and human environment, and of interactions between them. Natural and human phenomena are constantly changing and impacting other features in new ways, influencing aspects like site selection and risk of natural hazards. To address such complex issues, we use a variety of tools and methods, such as maps, computer-simulation models, aerial photographs, satellite imagery, statistical methods, and historical records.

01.02.a1



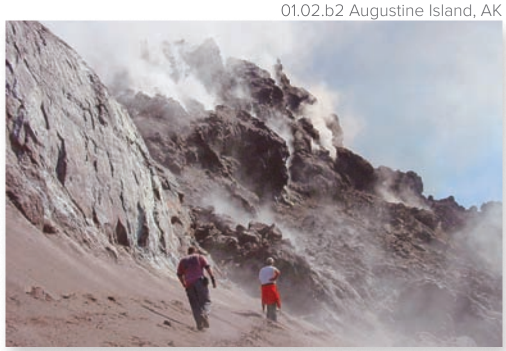
B What Is the Difference Between Qualitative and Quantitative Data?

Some geographical questions can be answered with qualitative data, but others require quantitative data, which are numeric and are typically visualized and analyzed using data tables, calculations, equations, and graphs. A discussion of how we express very large and very small numbers in science is in Appendix 1.2Q.

01.02.b1 Augustine Island, AK

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

01.02.b2 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 slopes seem steep and unstable." Such phrases can convey important information about the site.

01.02.b3 Augustine Island, AK

Quantitative data involve numbers that represent measurements. Most result from scientific instruments, such as this thermal camera that records temperatures on the volcano, or with measuring devices like a compass. We could also collect quantitative measurements about gases released into the air.

C How Do We Test Alternative Explanations?

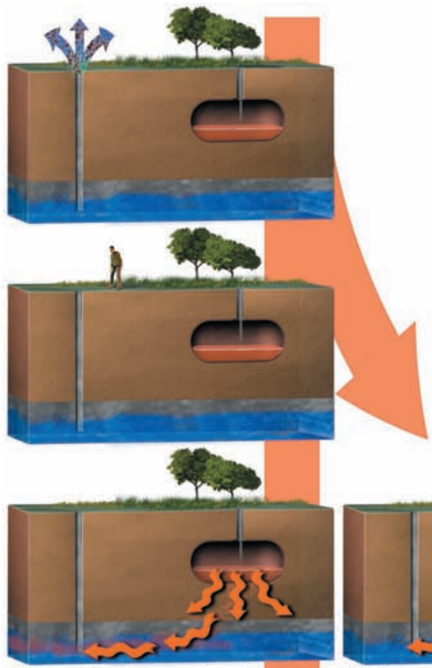
Science proceeds as scientists explore the unknown—making qualitative and quantitative observations and then systematically investigating questions that arise from observations. Often, we try to develop several possible explanations and then devise ways to test each one. The steps in this *scientific method* are illustrated by the example below.

Steps in the Investigation

Observations

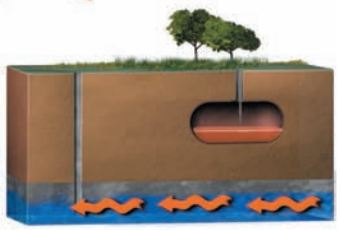
Questions Derived from Observations

Proposed Explanations and Predictions from Each Explanation



1. Someone makes the *observation* that groundwater from a local well near an old buried gasoline tank contains gasoline. 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 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.



3. Scientists often propose several explanations, referred to as *hypotheses*, vetted by initial evidence, 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.

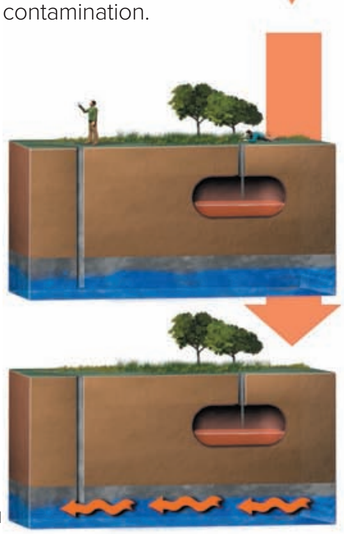
4a. One explanation is that the buried tank is the source of contamination.

4b. 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.

4c. We develop *predictions* for each explanation. A prediction for the explanation in number 4a might be that the tank has some kind of leak and should be surrounded by gasoline. Also, if the explanation in number 4a is true, 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



01.02.c1

5. To study this problem, we must compile and analyze all the necessary data. This might include maps showing the location of water wells, the direction of groundwater flow, and locations of gas stations and other possible sources of gasoline. We compare the results of any investigation with the predictions to determine which possible explanation is most consistent with the new data.

6. Data collected during the investigation support the conclusion that the buried tank is not the source of contamination. There were no holes in the tank or any gasoline in the soil around the tank. Records show that the tank held leaded gasoline, but gasoline in the groundwater is unleaded. Any possible explanation that is inconsistent with data is probably incorrect, so we pursue other explanations. In this example, a nearby underground pipeline may be the source of the gasoline. We can devise ways to evaluate this new hypothesis by investigating the pipeline. We also can revisit the previously rejected hypothesis if we discover a new way in which it might explain the data.

7. The goal is to collect data, assemble information, and draw conclusions without letting our personal bias interfere with conducting good science. We want to reach the explanation that best explains all the data. Few things are ever "proven" in science, some can be "disproven," but generally we are left to weigh the pros and cons of several still-viable explanations. We choose the explanation that, based on the data, is most likely to be correct.

Before You Leave This Page

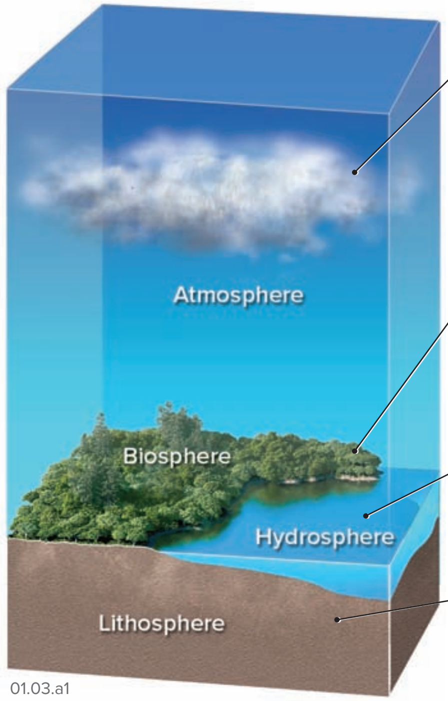
- ✓ Summarize some of the aspects commonly considered using a geographic approach.
- ✓ Explain the difference between qualitative and quantitative data, providing examples.
- ✓ Explain the logical scientific steps taken to evaluate a possible explanation critically.

1.3 How Do Natural Systems Operate?

OUR WORLD HAS A NUMBER OF SYSTEMS—a collection of matter, energy, and processes that are somehow related and interconnected. These involve the structure and motion of the atmosphere, water in all its forms, processes of the solid Earth, and how these three domains (air, water, and Earth) 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 it also 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.



01.03.a1

1. The *atmosphere* is a mixture of mostly nitrogen and oxygen gas that surrounds Earth's surface, gradually diminishing in concentration out to a distance of approximately 100 kilometers. In addition to gas, the atmosphere includes clouds, precipitation, and solid 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 less than 4%.

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 kilometers 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. 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 in which matter and energy are moved or transformed. For example, rainfall on the land can collect into a stream that moves sand and stones in the channel. The energy in this case is mostly provided by gravity, which causes the raindrops to fall and the flowing water to move downhill. There are two main types of systems: *open systems* and *closed systems*.


01.03.b1 Noxubee NWR, MS

1. 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 soil-derived nutrients, extracting carbon dioxide from the air to make the carbon-rich wood and leaves, sometimes shedding those leaves during the winter and expelling oxygen as a by-product of photosynthesis, fueled by externally derived energy from the Sun.

2. 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 and the arrival of occasional meteorites. It is an open system for energy, which is gained via sunlight and can be lost to space.


01.03.b2

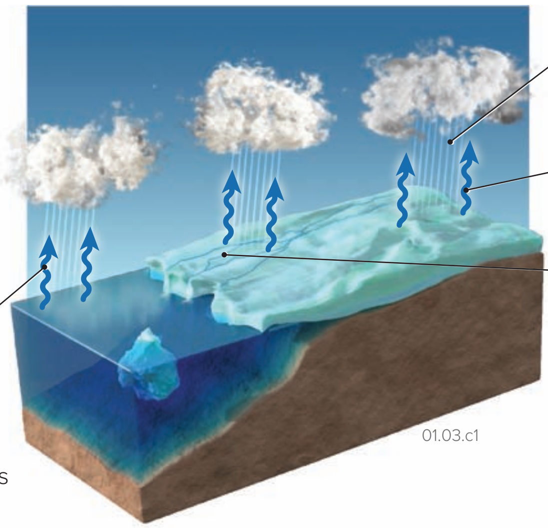
C How Do Earth Systems Operate?

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 the low-level clouds illustrated here.



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,* which are huge, flowing fields of ice.

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.

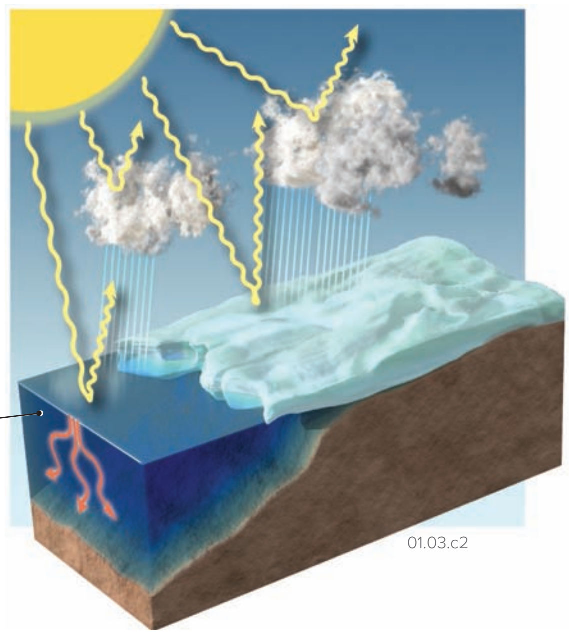
6. The movement of matter and energy carried in the various forms of water is an example of a *dynamic system*—a system in which matter, energy, or both, are constantly changing their position, amounts, or form.

Feedbacks

7. The system can respond to changes in various ways, which can either reinforce the effect, causing the overall changes to be amplified (increased in effect), or partially or completely counteract the effect, causing changes to be dampened (decreased in effect). 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*.



10. Warming of the water results in more energy available for evaporation, moving water from the surface to the atmosphere, which may result in more clouds. Low-level clouds are highly reflective, so as cloud cover increases they intercept and reflect more sunlight, leading to less warming. This type of response does not reinforce the change but dampens it and diminishes its overall effect. This dampening and resultant counteraction is called a *negative feedback*.

11. As this 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 net impact of positive and negative feedbacks can lead to a stable but gradually changing state, a condition called *dynamic equilibrium.* A complex system may continue changing in ways that keep it from stabilizing, thus never attaining anything that resembles 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.

1.3