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exploring physical geography

Third Edition

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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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EXPLORING PHYSICAL GEOGRAPHY, THIRD EDITION

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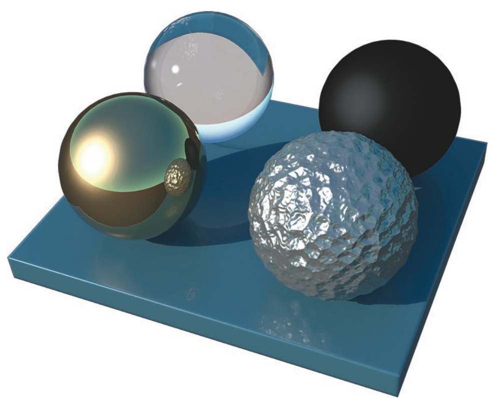

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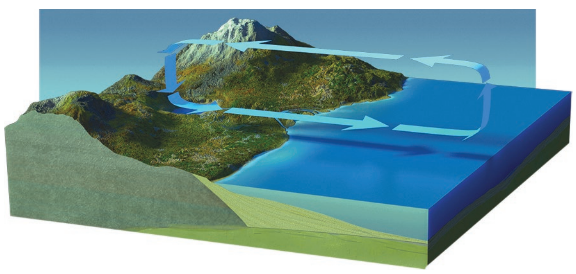

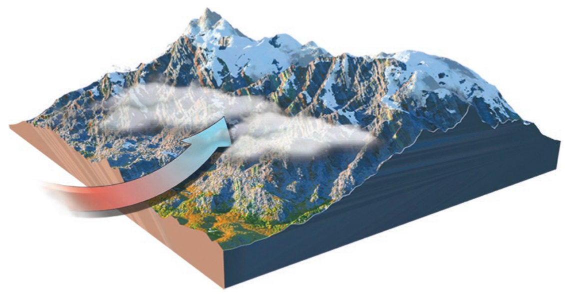

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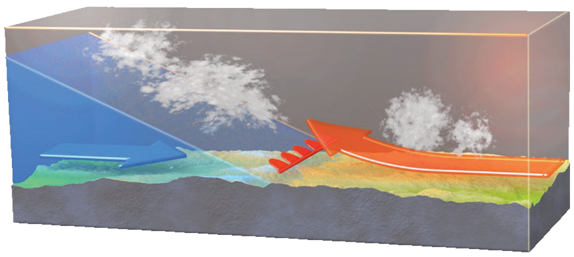

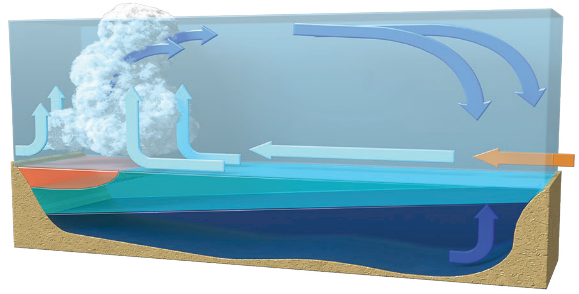

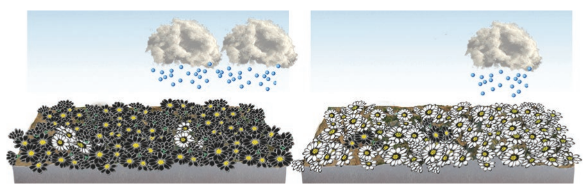

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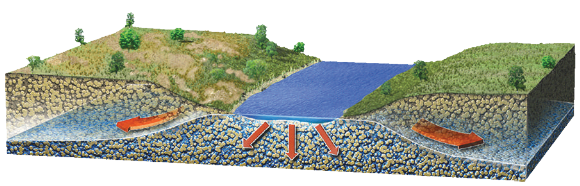

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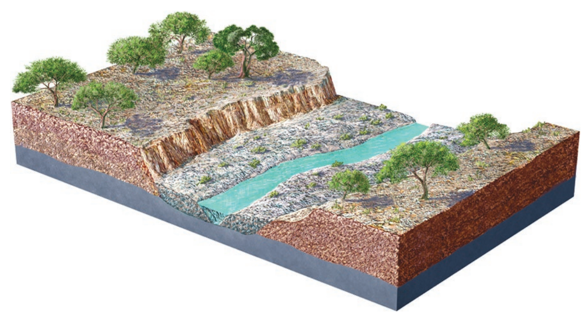

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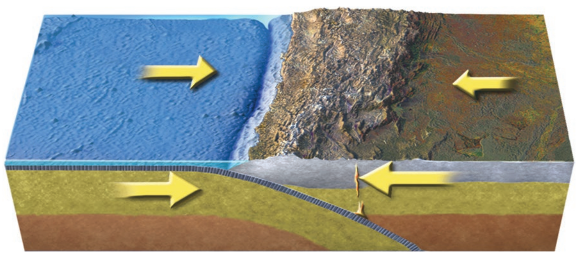

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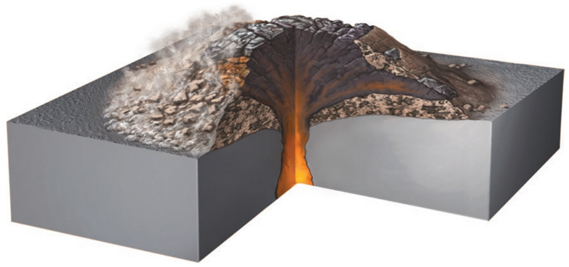

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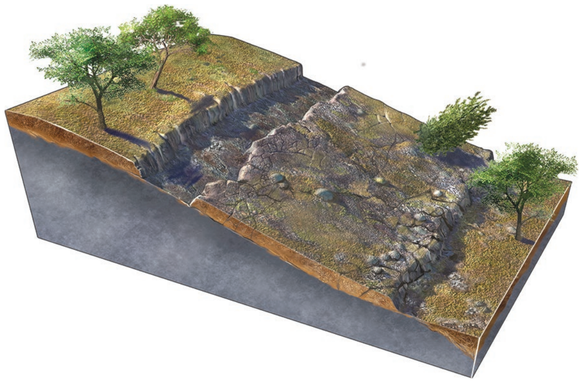

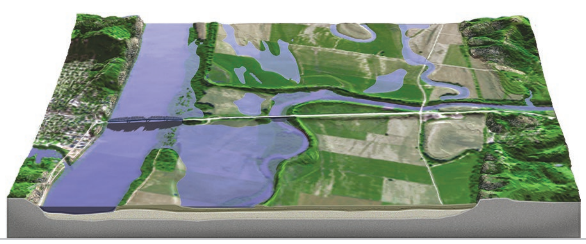

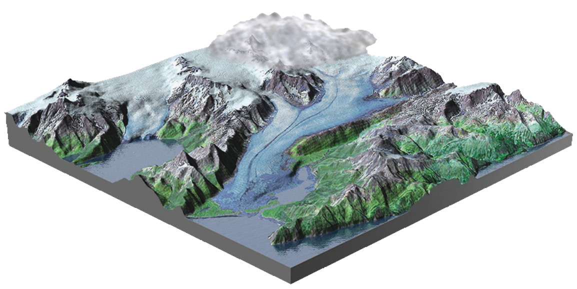

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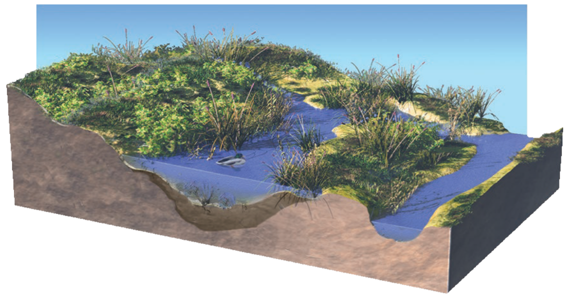

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PREFACE

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

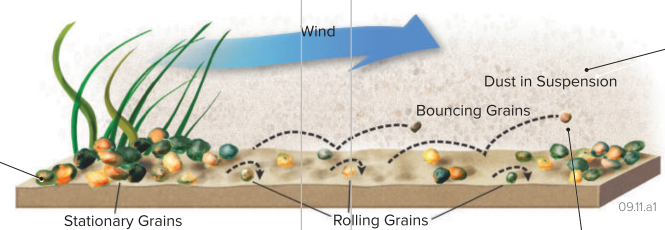
To design a book that supports instructor goals, we delved into cognitive and science-education research, especially research on how our brains process different types of information, what obstacles limit student learning from textbooks, and how students use visuals versus text while studying. We also 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 sed ment 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.

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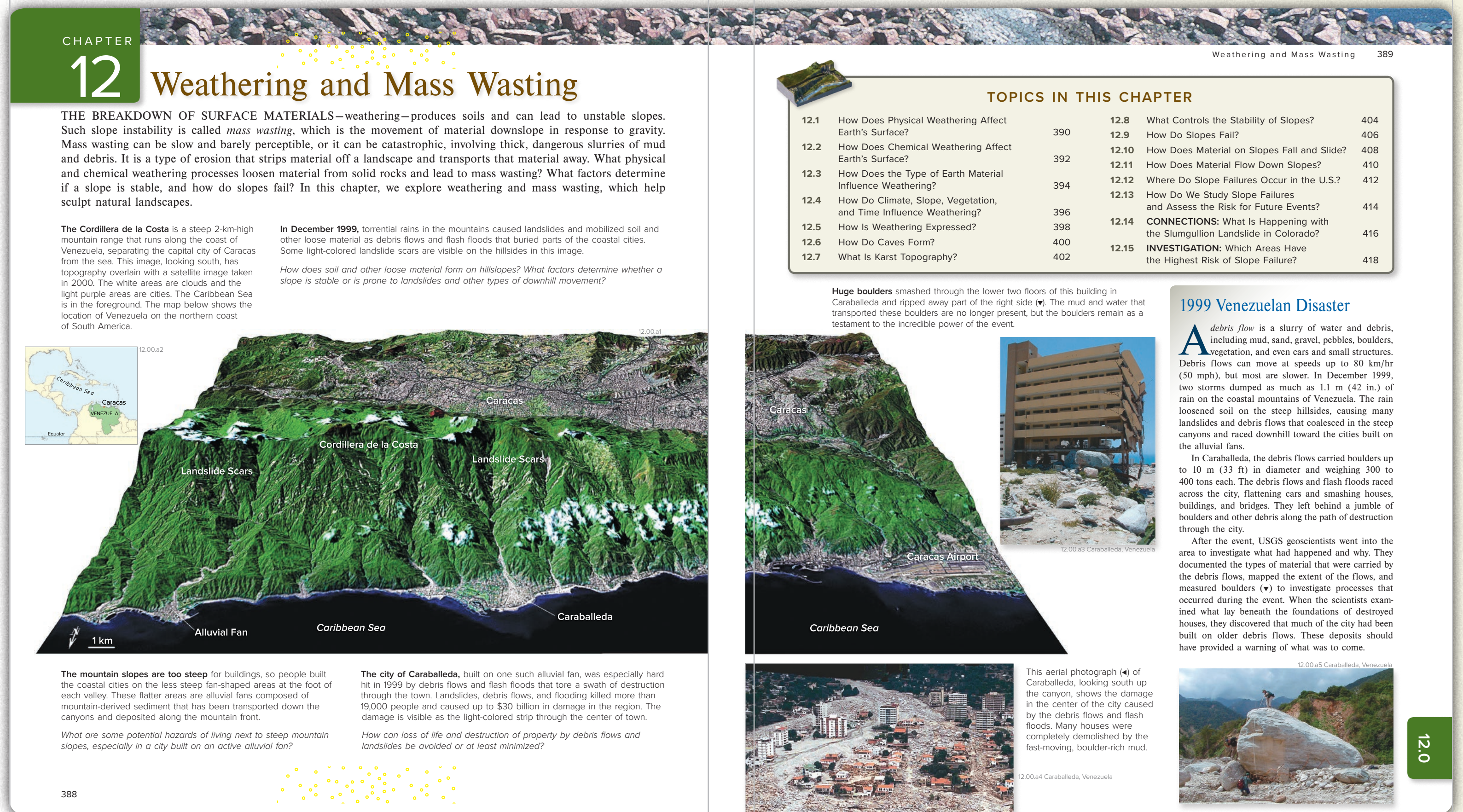
HOW DOES THIS BOOK SUPPORT STUDENT CURIOSITY AND INQUIRY?


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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Weathering and Mass Wasting 389

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.

12.00.a3 Caraballeda, Venezuela

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

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.

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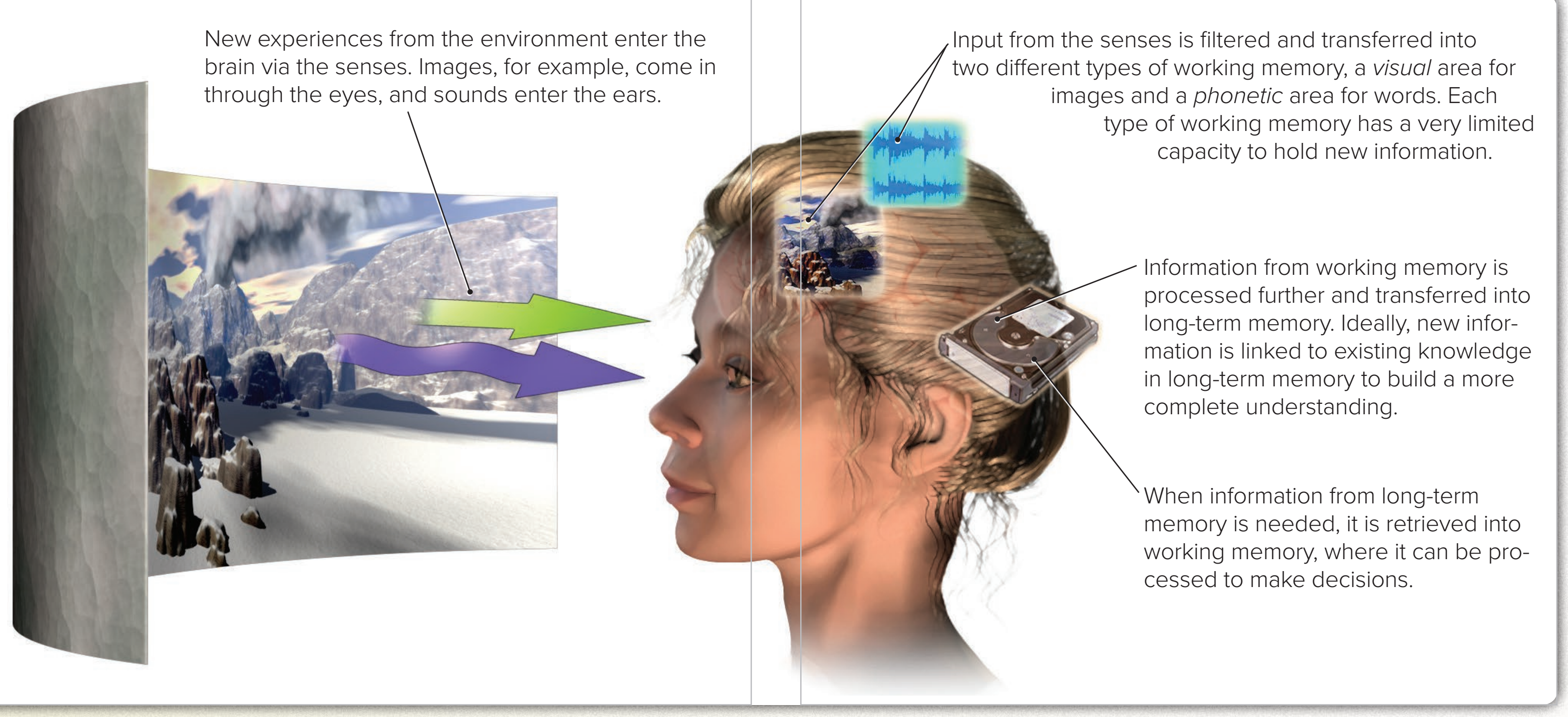
WHY ARE THE PAGES DOMINATED BY ILLUSTRATIONS?

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.



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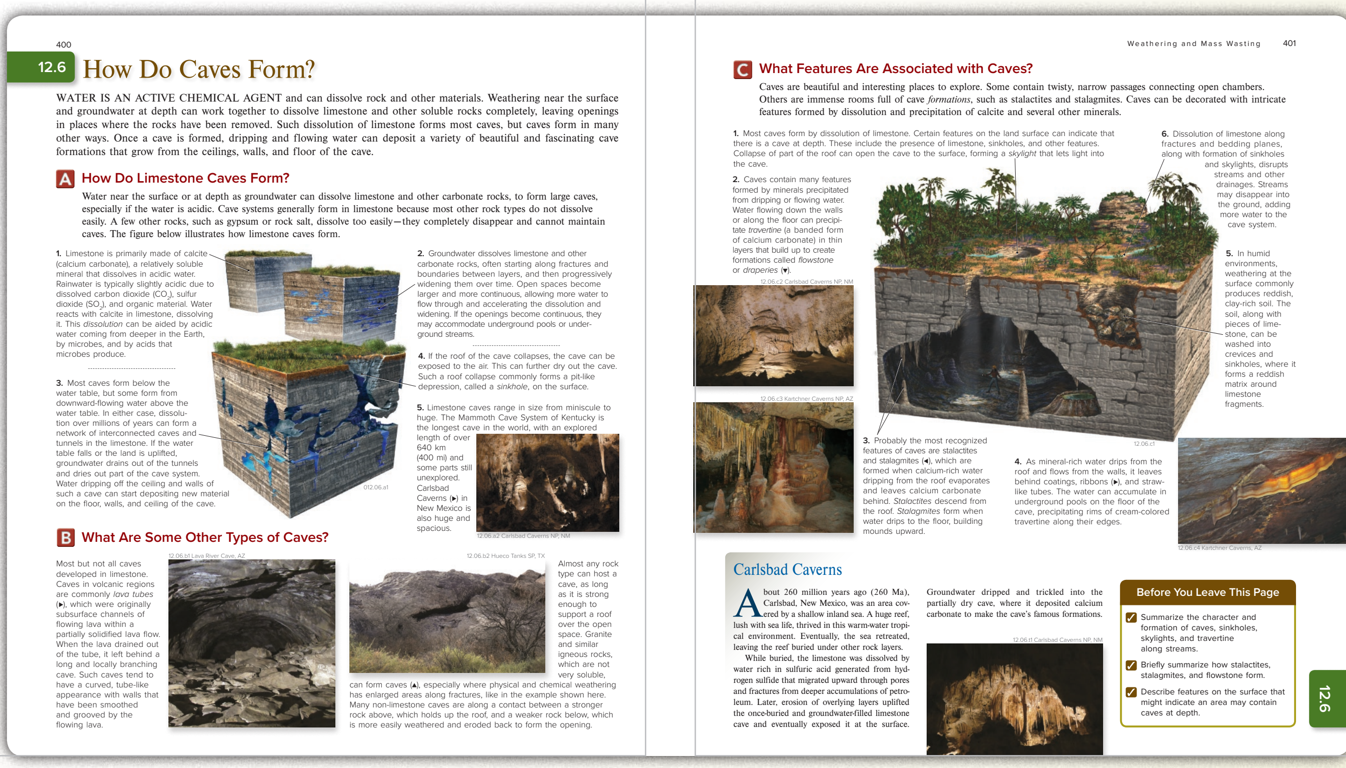
WHY ARE THERE SO MANY FIGURES?

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.

012.06.a1

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.

12.06.a2 Carlsbad Caverns NP, NM

B What Are Some Other Types of Caves?

12.06.b1 Lava River Cave, AZ

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.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.

Weathering and Mass Wasting 401

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

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.

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.

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.

12.06.c1

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.

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

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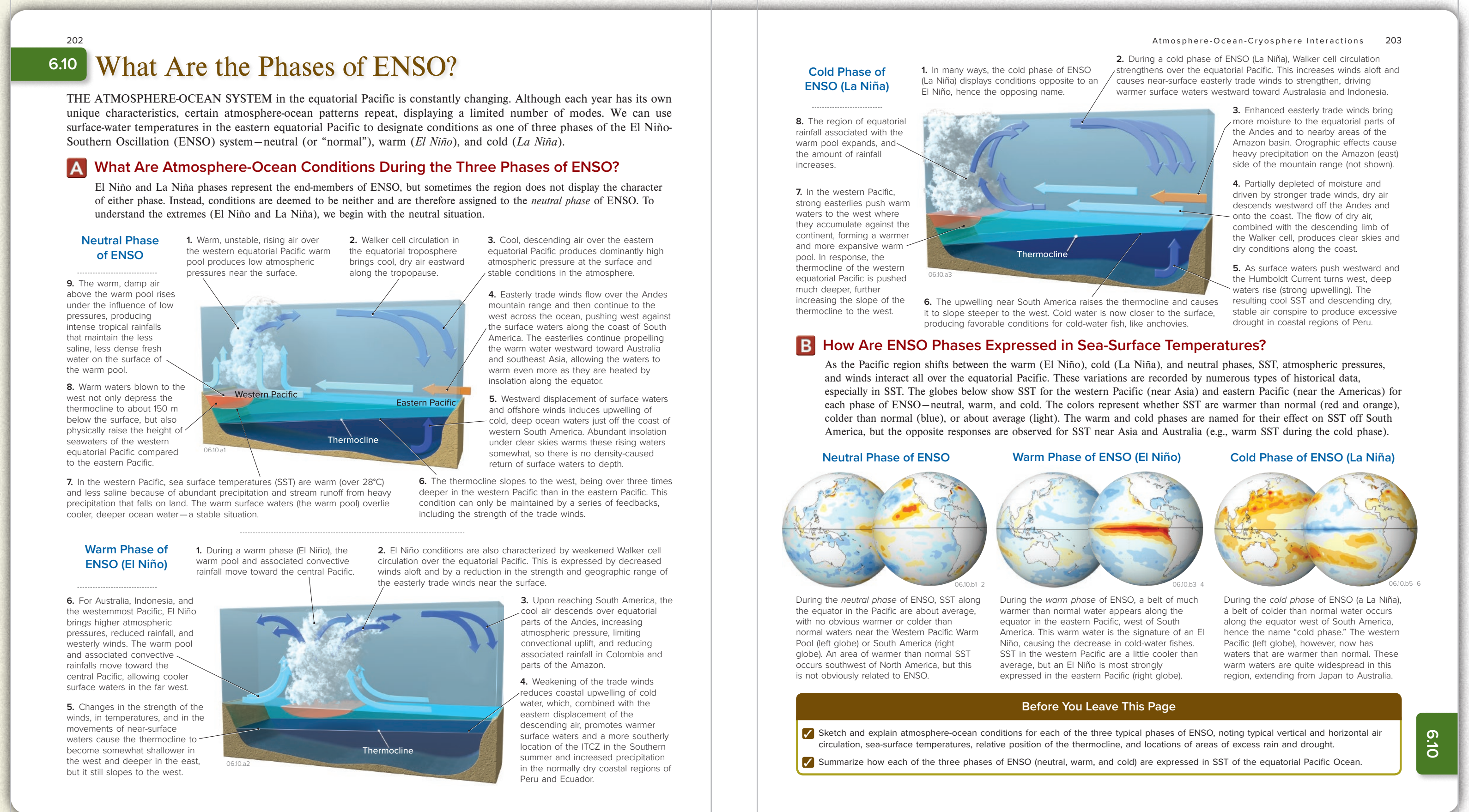
WHY DOES THE BOOK CONSIST OF TWO-PAGE SPREADS?

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.


202

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
06.10.a1

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 associated rainfall 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
06.10.a2

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
06.10.a3

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
06.10.b1–2
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.

Warm Phase of ENSO (El Niño)
06.10.b3–4
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).

Cold Phase of ENSO (La Niña)
06.10.b5–6
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.

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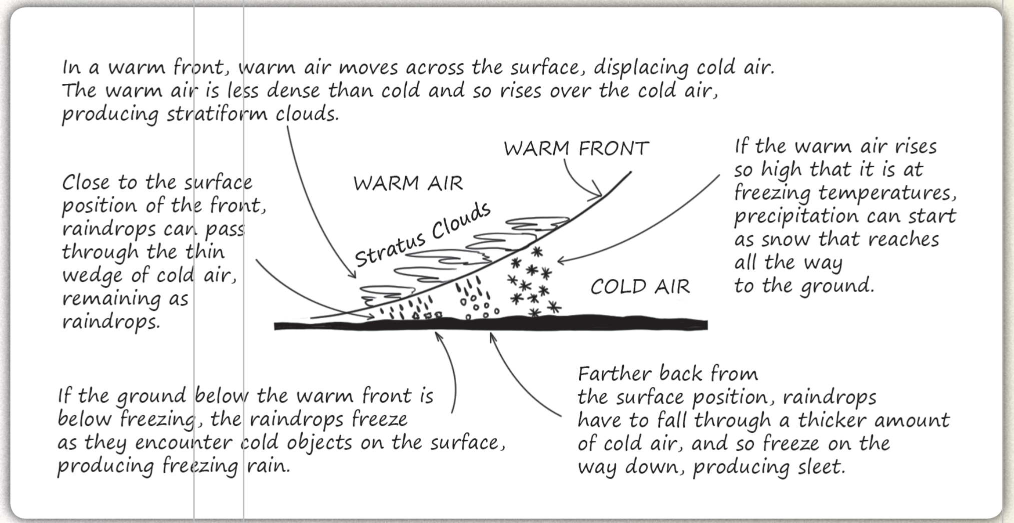
The two-page spread approach also has advantages for the instructor. Before writing this book, the authors wrote most of the items for the *Before You Leave This Page* lists. We then used this list to decide what figures were needed, what topics would be discussed, and in what order. In other words, *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.

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TWO-PAGE SPREADS

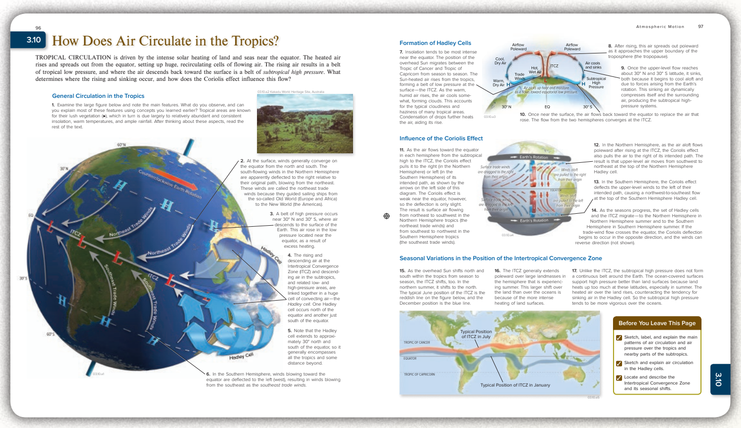
Most of the book consists of *two-page spreads*, each of which is about one or more closely related topics. Each chapter has four main types of two-page spreads: opening, topical, connections, and investigation.

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.

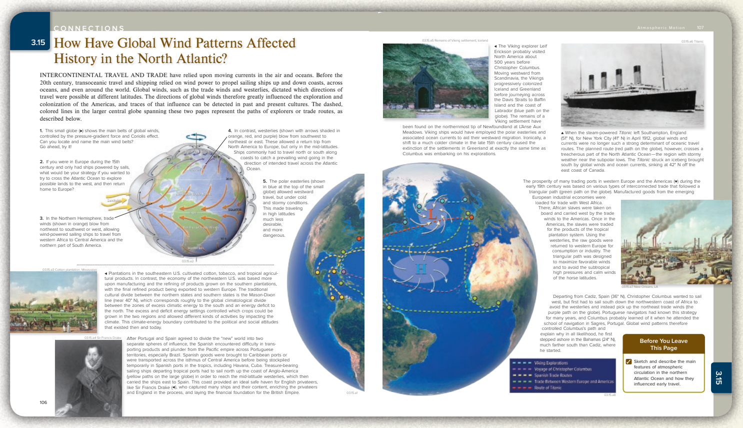
Topical Two-Page Spread

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.



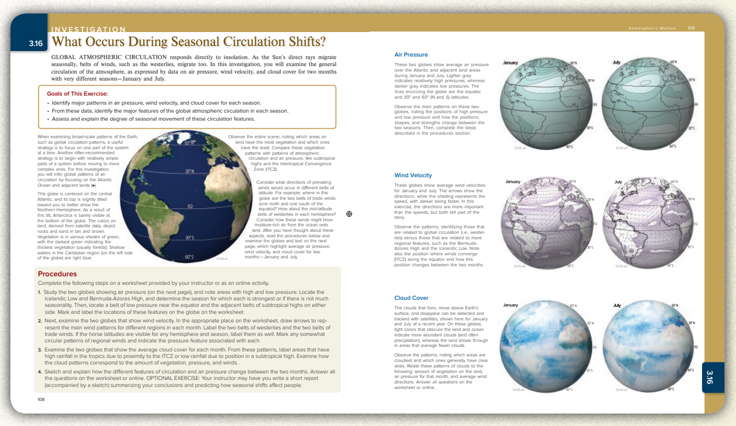
Connections Two-Page Spread

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.



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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

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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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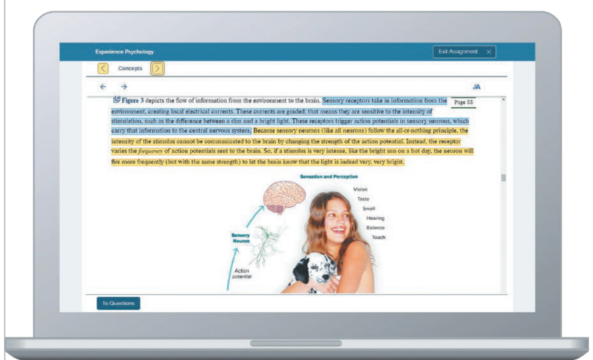

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Julia K. Johnson is currently a full-time faculty member in the School of Earth and Space Exploration at Arizona State University. Her M.S. and Ph.D. research involved structural geology and geoscience education research. She teaches introductory geoscience 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.

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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.

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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.

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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.

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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.

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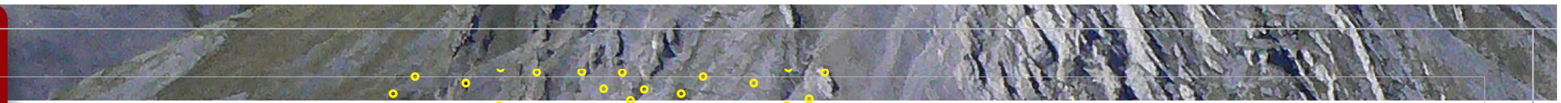


CHAPTER 1

The Nature of Physical Geography

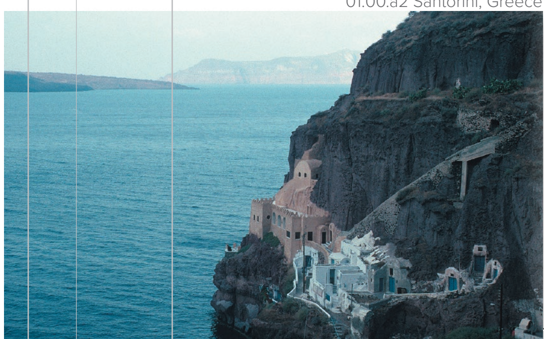
THE EARTH HAS A WEALTH of intriguing features, from dramatic mountains to intricate coastlines and deep ocean trenches, from lush, beautiful valleys to huge areas of sparsely vegetated sand dunes. Above the surface is an active, ever-changing atmosphere with clouds, storms, and variable winds. Occupying 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.

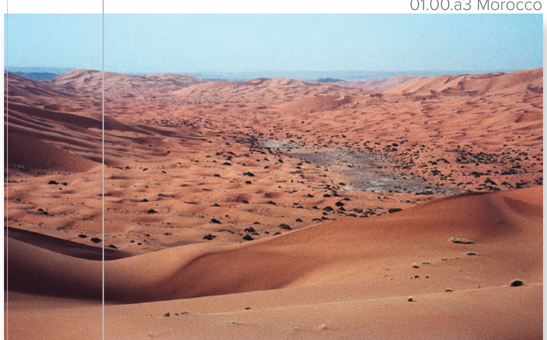
01.00.a2 Santorini, Greece



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.

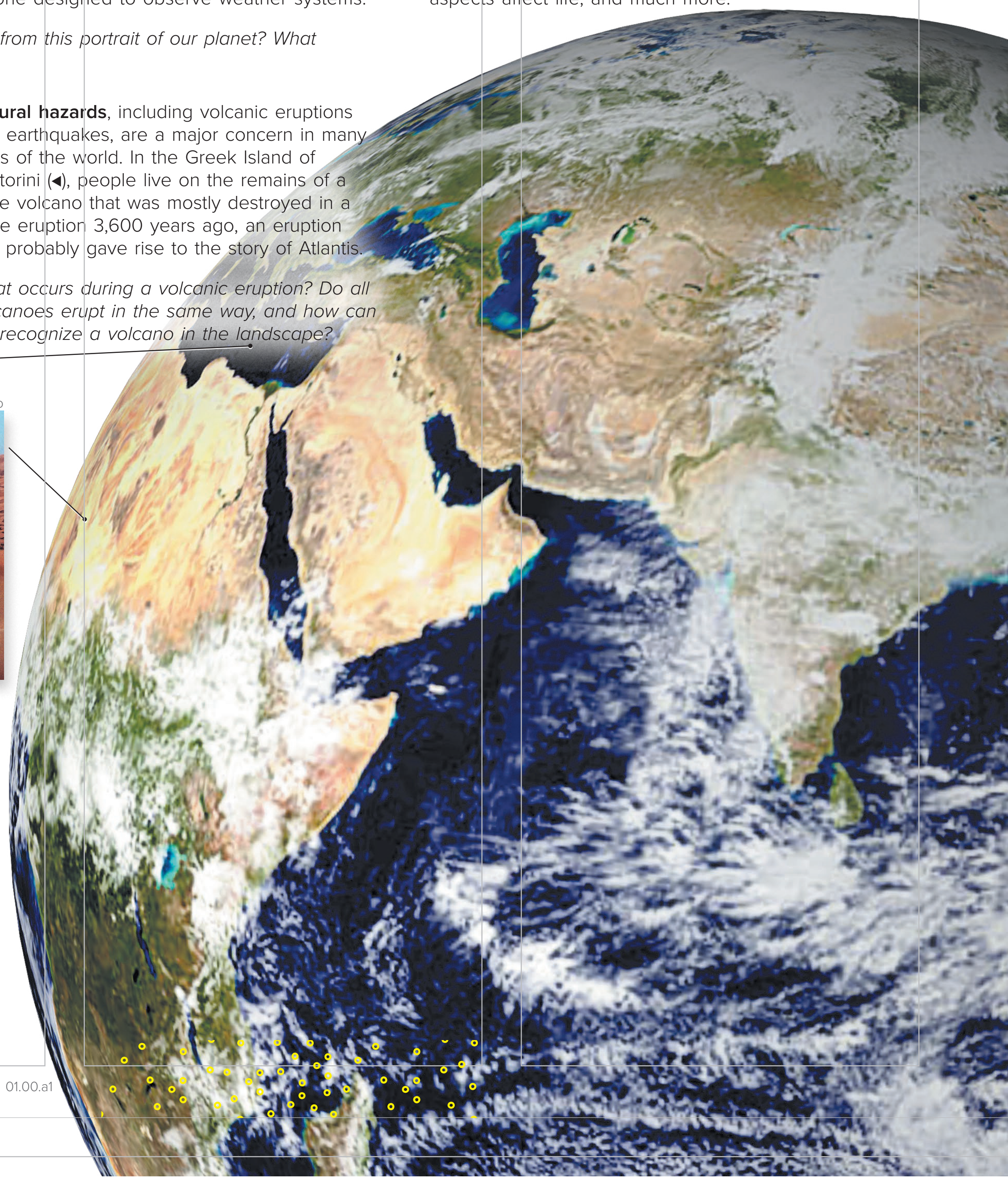
What occurs during a volcanic eruption? Do all volcanoes erupt in the same way, and how can we recognize a volcano in the landscape?

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?



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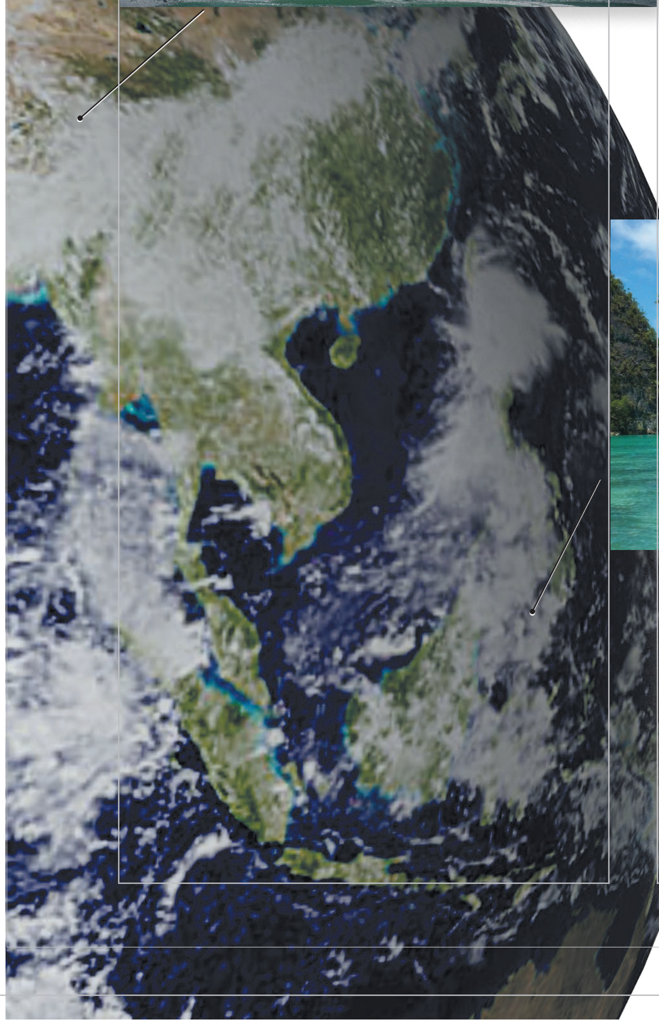
TOPICS IN THIS CHAPTER

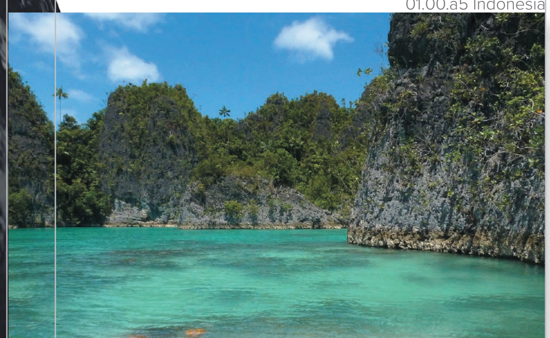


01.00.a4 Tibet

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.

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1.1 What Is Physical Geography?

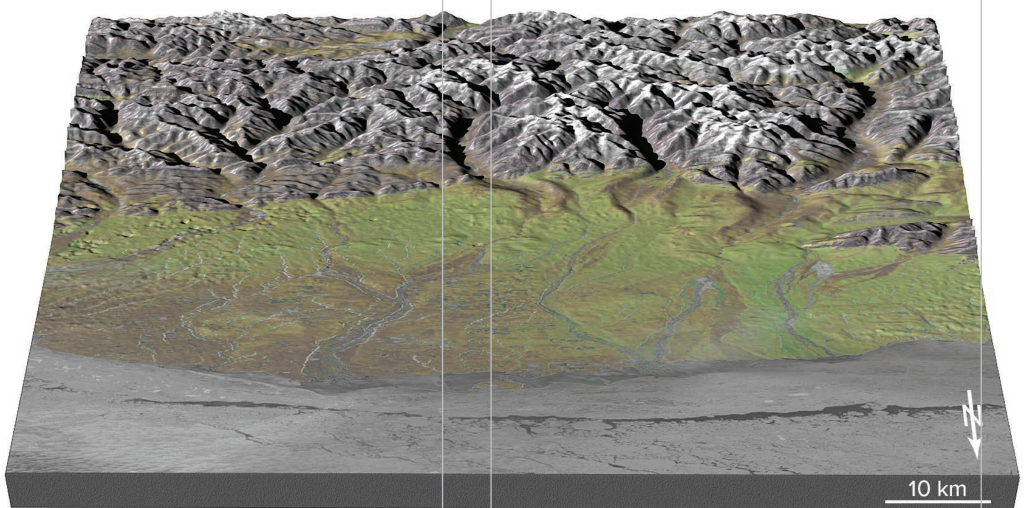
PHYSICAL GEOGRAPHY IS THE STUDY of spatial distributions of phenomena across the landscape, processes that form and change those distributions, and implications for those distributions on people, animals, and plants. Geography is both a natural and a social science. Geographers think broadly, emphasizing 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?

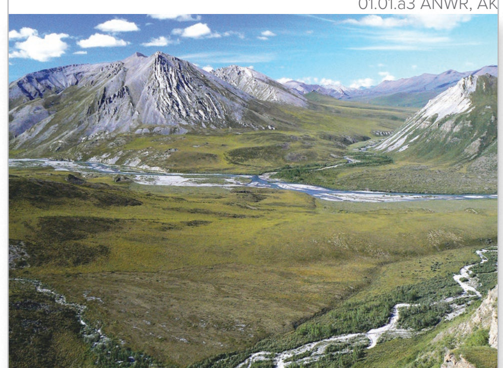
4. The issues of ANWR nicely illustrate why we would use a geographic approach. Most of the questions we asked here have a *spatial component*, as indicated by the word "where," and could be best answered with some type of map. The questions also have an explicit or implicit societal component, such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

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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

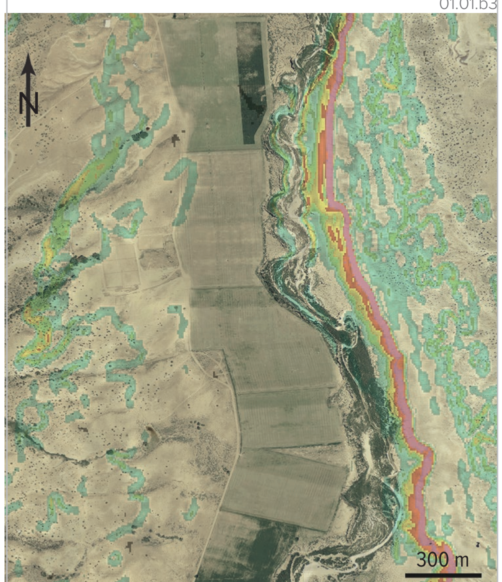
1. The snow-clad mountains, partially covered with clouds, indicate the presence of water, an essential ingredient for life. The mountains have a major influence on water in this scene. Melted snow flows downhill toward the lowlands, to the horses and cows. The elevation and shape of the land influence 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

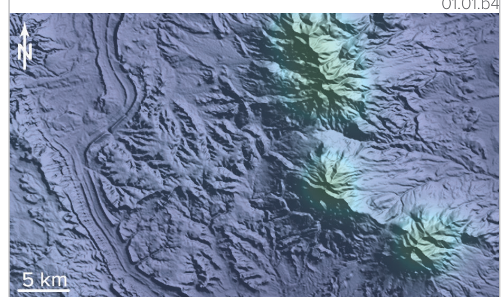
3. This aerial photograph (a photograph taken from the air, like from a plane or drone) gives a better view of the spatial distribution of the green pasture. It reveals the shape of the pasture, and we could measure its length, width, and area. Such measurements would help us decide how many horses and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

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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.

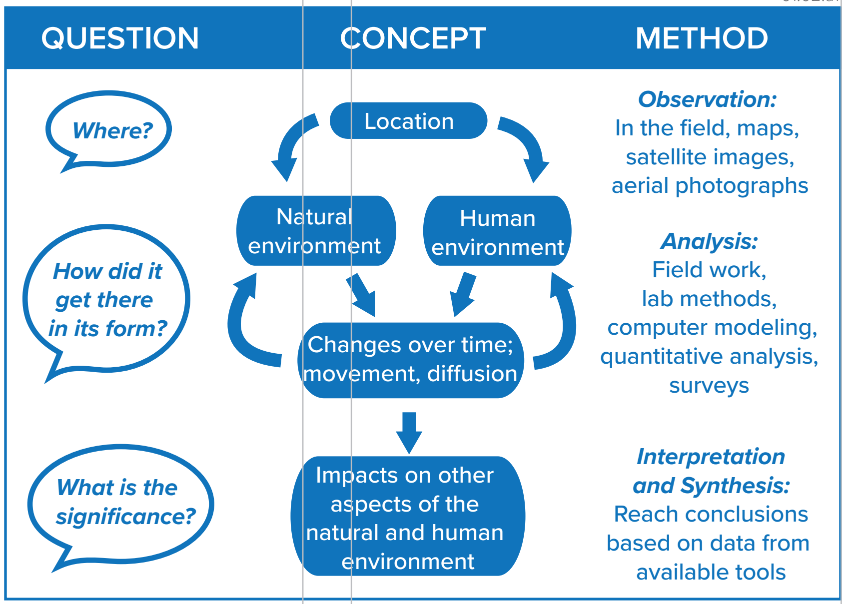
A How Do Geographers Approach Problems?

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

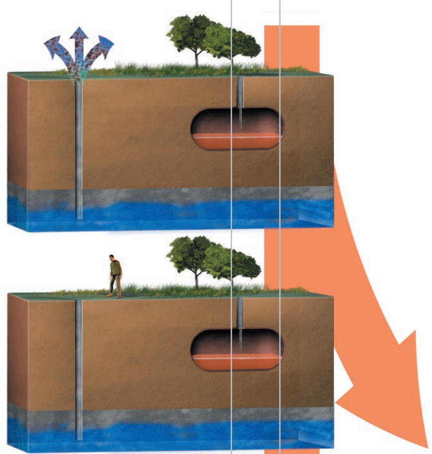
Quantitative data involve numbers that represent measurements. Most result from scientific instruments, such as this thermal camera that records temperatures on the volcano, or with measuring devices like a compass. We could also collect quantitative measurements about gases released into the air.

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

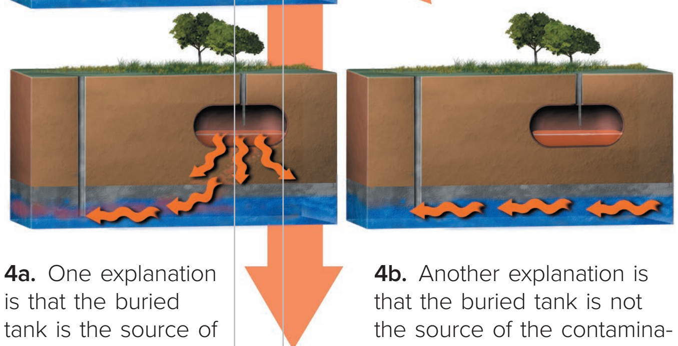


1. Someone makes the *observation* that groundwater from a local well near an old buried gasoline tank contains gasoline. The first step in any investigation is to make observations, recognize a problem, and state the problem clearly and succinctly. Stating the problem as simply as possible helps focus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

Questions Derived from Observations

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

Proposed Explanations and Predictions from Each Explanation



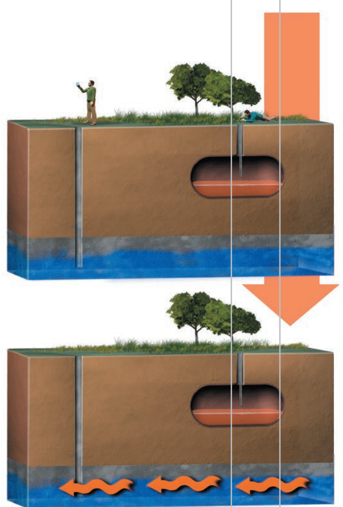
3. Scientists often propose several explanations, referred to as *hypotheses*, vetted by initial evidence, to explain what they observe. A hypothesis is a causal explanation that can be tested, either by conducting additional investigations or by examining data that already exist.

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.

1.2

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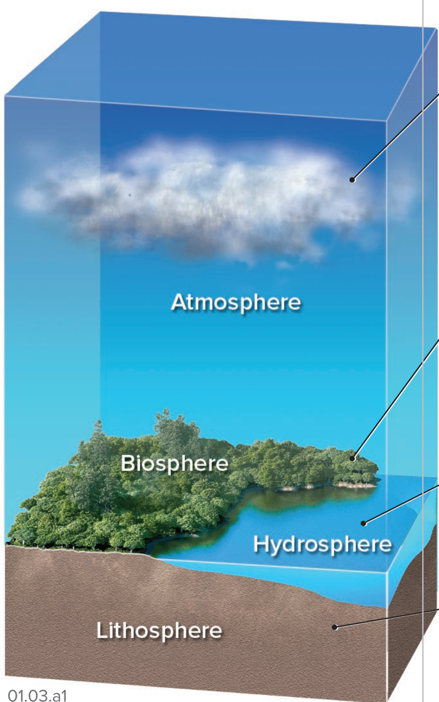
1.3 How Do Natural Systems Operate?

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.



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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.

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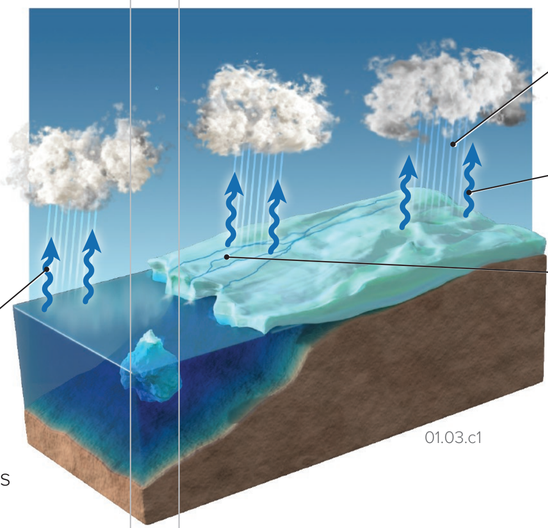
C How Do Earth Systems Operate?

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.



01.03.c1

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

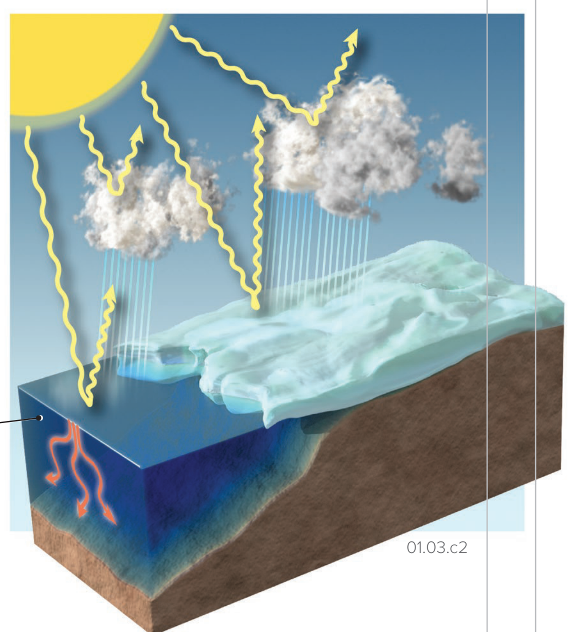
6. The movement of matter and energy carried in the various forms of water is an example of a *dynamic system*—a system in which matter, energy, or both, are constantly changing their position, amounts, or form.

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*.



01.03.c2

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.

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1.4 What Are Some Important Earth Cycles?

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

A What Is Cycled and Moved in the Atmosphere?

Atmospheric processes involve the redistribution of *energy* and *matter* from one part of the atmosphere to another. Moving air masses have *momentum*, which can be transferred from one object to another.

Energy

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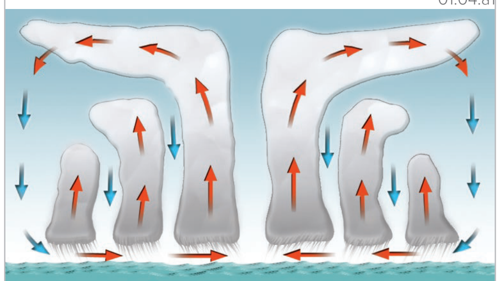

Storage and transfer of energy are the drivers of Earth's weather and climate. Energy can be moved from one part of the atmosphere to another, such as by air currents associated with storms (▲). Also, energy is released or extracted from the local environment when water changes from one state of matter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

Matter

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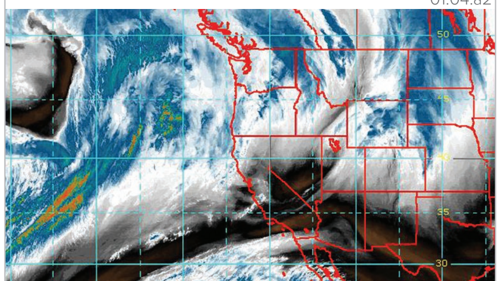
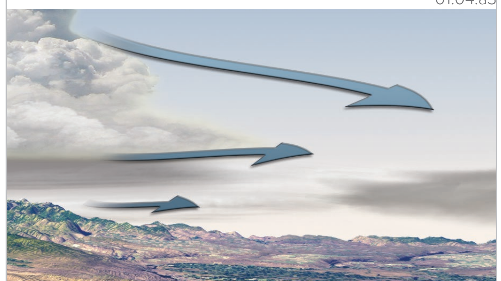


Water in all of its forms and other matter moves globally, tending to disperse, but other factors prevent an even spatial distribution. As a result, some regions are more humid and cloudy than others, as shown in this satellite image (▲) of water vapor (blue is more, brown is less). Also, water cycles between vapor, liquid, and solid states.

Momentum

01.04.a3



Moving air masses have *momentum*, which is defined as mass times velocity. A dense, fast-moving dust storm has more momentum than a gentle breeze in dust-free air. Winds near the surface are slowed by interactions with trees, hills, buildings, etc. Winds aloft are faster (▲) and can transfer their momentum downward.

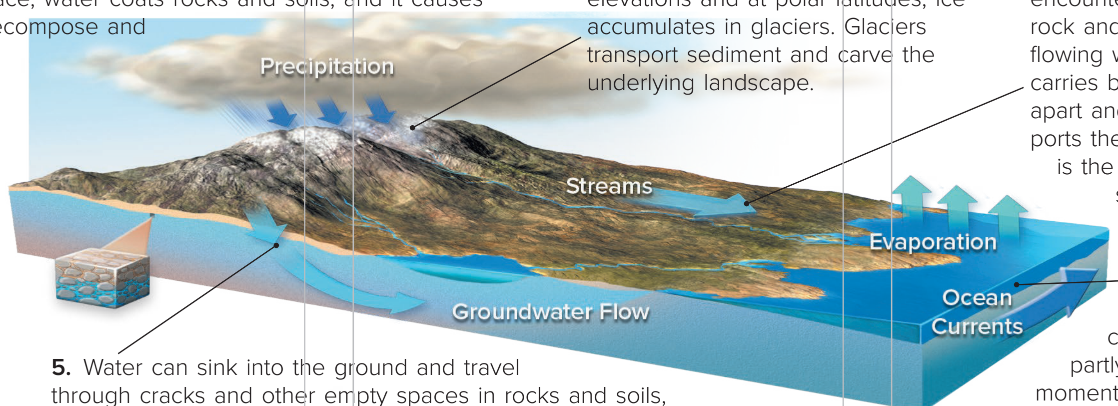
B How Are Matter and Energy Moved in the Hydrosphere?

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

1. Water vapor in the atmosphere forms drops, which can remain suspended in the air as clouds or fall to the ground as *precipitation*. Once on the surface, water coats rocks and soils, and it causes these solids to decompose and erode.

2. When winter snows do not melt annually, as is common at higher elevations and at polar latitudes, ice accumulates in glaciers. Glaciers transport sediment and carve the underlying landscape.

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



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4. The uppermost part of oceans is constantly in motion, partly due to transfer of momentum between winds in the atmosphere and the ocean surface. Winds over the oceans cause waves that erode and shape shorelines.

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

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

C What Processes Can Affect Materials of the Lithosphere?

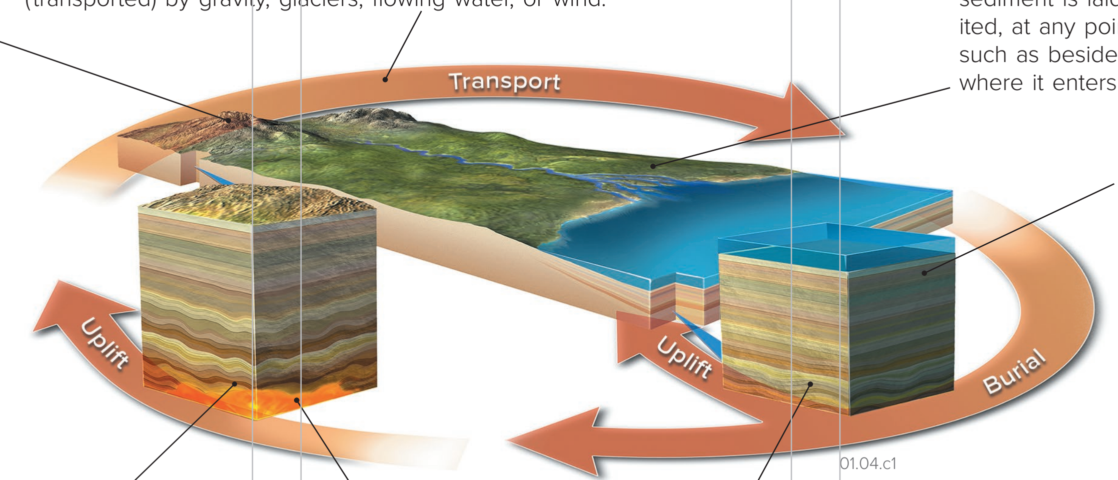
Materials on and below Earth's surface can be acted on by a wide range of processes that bury, uplift, move, or otherwise affect the materials. The movement of matter and energy on and below Earth's surface at timescales from seconds to billions of years involves diverse processes, such as erosion, burial, melting, and uplift. This system is called the *rock cycle*.

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

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

3. *Deposition:* After transport, the sediment is laid down, or deposited, at any point along the way, such as beside the stream, or where it enters a lake or the sea.

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



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8. *Uplift:* Deep rocks may be uplifted back to the surface where they are again exposed to weathering.

7. *Solidification:* As magma cools, either slowly at depth or quickly after being erupted onto the surface, it begins to crystallize and solidify into rock.

6. *Melting:* A rock exposed to high temperatures may melt and become molten, forming *magma*.

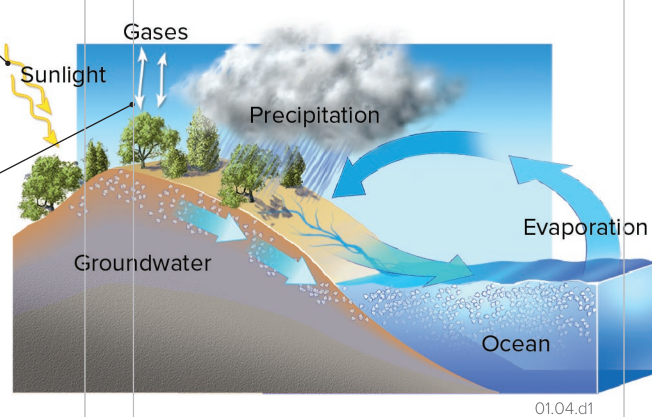
5. *Deformation and Related Processes:* Rock can be subjected to strong forces that squeeze, bend, and break the rock, causing it to deform. The rock might even be heated and deformed so much that it is changed into a new rock type.

D What Cycles and Processes Are Important in the Biosphere?

The biosphere includes life and all of the places it exists. It overlaps the atmosphere, hydrosphere, and lithosphere, extending well into the atmosphere, to kilometers beneath sea level in the oceans, and to some depths below Earth's surface and the seafloor. Life interacts with the other three spheres, forming a number of important cycles.

1. The Sun is the ultimate source of energy for plants, as well as movement of matter and energy in the atmosphere and most movement of material on Earth's surface.

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



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

3. Life interacts with the hydrologic cycle. Plants take in water from the rocks and soil, which may have arrived from lakes and other bodies of surface water, or directly from the atmosphere, as during precipitation. Plants then release some water back into the environment.

4. Life also interacts with aspects of the rock cycle. Plants help break down materials on Earth's surface, such as when a plant root pushes open fractures in rocks and soil. Plants help stabilize soils, inhibiting erosion, by slowing down the flow of water, allowing it to remain in contact with rocks and soil longer. This increases the rate at which weathering breaks down materials. Humans have altered this process by removing vegetation.

Before You Leave This Page

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

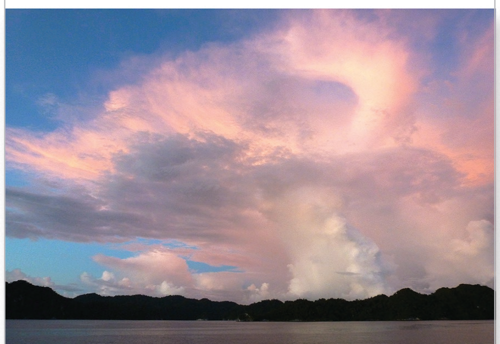
1.5 How Do Earth's Four Spheres Interact?

ENERGY AND MATTER MOVE within and among the atmosphere, hydrosphere, lithosphere, and biosphere. There are various expressions of the interactions, many of which we can observe in our daily lives. In addition to natural interactions, human activities can affect interactions between the spheres, as occurs when humans clear forests to make room for development. Changes in a component of one sphere can cause impacts that affect components of other spheres.

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

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

Atmosphere-Hydrosphere



01.05.a1 Indonesia

The Sun's energy evaporates water from the ocean and other parts of the hydrosphere, moving the water molecules into the atmosphere. The water vapor can remain in the atmosphere or can form clouds by condensing into tiny drops of water or forming ice crystals. Under certain conditions, the water returns to the surface as precipitation.

Atmosphere-Lithosphere

01.05.a2 Mount Veniaminof, AK

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

Atmosphere-Biosphere

01.05.a3 Indonesia

Plants and animals utilize precipitation from the atmosphere. Some plants can extract moisture directly out of the air without precipitation. Broad-scale circulation patterns in the atmosphere are a principal factor in determining an area's climate, and the climate directly controls the types of life that inhabit a region.

Hydrosphere-Lithosphere

01.05.a4 Glacier Parkway, Alberta, Canada

Channels within a stream generally bend back and forth as the water flows downhill. The water is faster and more energetic in some parts of the stream than in others, and so it erodes into the streambed and riverbank. In less energetic sections, sediment is deposited in the bed, like the gravel in this photograph. Earth's surface can be uplifted or dropped down, as during an earthquake, and the resulting changes can influence the balance of erosion and deposition.

Hydrosphere-Biosphere

01.05.a5 Raja Ampat, Indonesia

Oceans contain a diversity of life, from whales to single-celled algae, and everything in between. An especially life-rich environment forms when living organisms extract materials dissolved in or carried by seawater to produce the hard parts of corals, shells, and sponges in coral reefs. At greater ocean depths, where waters are colder, shells and similar biological materials dissolve, transferring material back to the seawater.

Lithosphere-Biosphere

01.05.a6 Near Badlands National Park, SD

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

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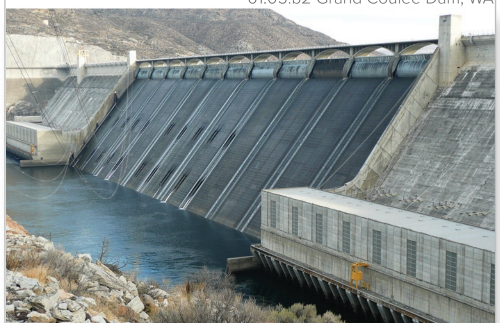
B To What Extent Do Humans Influence Interactions Between the Spheres?

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

01.05.b1 Western Alabama

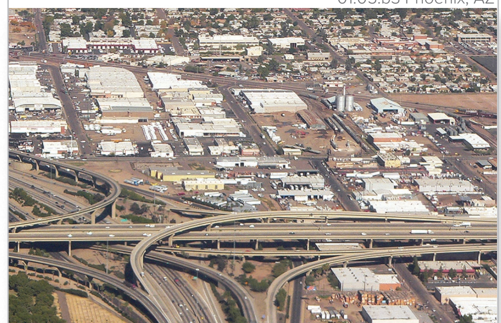
Humans clear forests, a critical part of the biosphere, to provide lumber and grow food. In addition to the loss of habitat for plants and animals, deforestation reduces the amount of CO_2 that can be extracted out of the atmosphere and stored in the carbon-rich trunks, branches, and leaves of plants.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

01.05.b2 Grand Coulee Dam, WA



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

01.05.b3 Phoenix, AZ



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

The Geographic Approach to Understanding Interactions Between Earth's Spheres

Understanding interactions between Earth's four spheres has been important since ancient times for navigation, planning, and other purposes. The examples above illustrate current societal issues that should also be considered from a spatial perspective—the percentage decrease in the area of rain forests, the outline of areas that will be flooded by construction of a dam, or the patterns of population growth and the resulting changes in local temperatures. Understanding location and spatial distributions has always been important because these factors are crucial in understanding the environment or identifying possible sites for any human activity. For example, what spatial factors should be considered when planning a new subdivision or a new business? Geographic factors can be the difference between success and failure. The map shown here depicts the average precipitation in the lower 48 states, with purple and blue designating the highest average annual precipitation, red and orange indicating the lowest precipitation, and green and yellow designating intermediate precipitation. How would you describe some of the main patterns? Where are the highest and the lowest precipitation amounts? Why are these wet or dry areas located where they are? What are some implications of the spatial distribution of high-precipitation versus low-precipitation regions? How might these variations in precipitation influence agriculture, human or animal disease, insect infestations, or the water supplies of the growing desert cities of the U.S. Southwest? Geographers address these and many other types of questions as part of their work. This work occurs in universities and colleges, in local and larger governments, in many different types of business, and for nonprofit and nongovernmental organizations.

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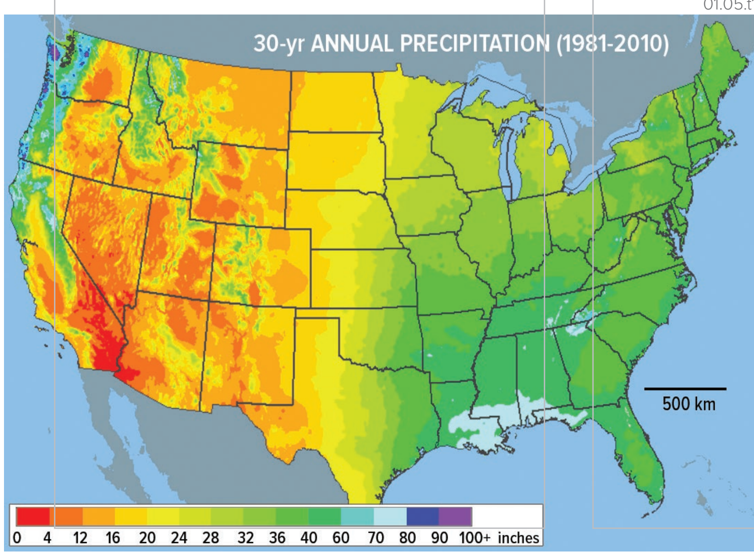

Before You Leave This Page

- ✓ Provide an example of an interaction between each pair of spheres.
- ✓ Describe examples of how humans can affect the natural system in each of the four spheres.
- ✓ Describe why geographic factors are important when considering environmental issues or when evaluating potential sites for a new agricultural area or business.

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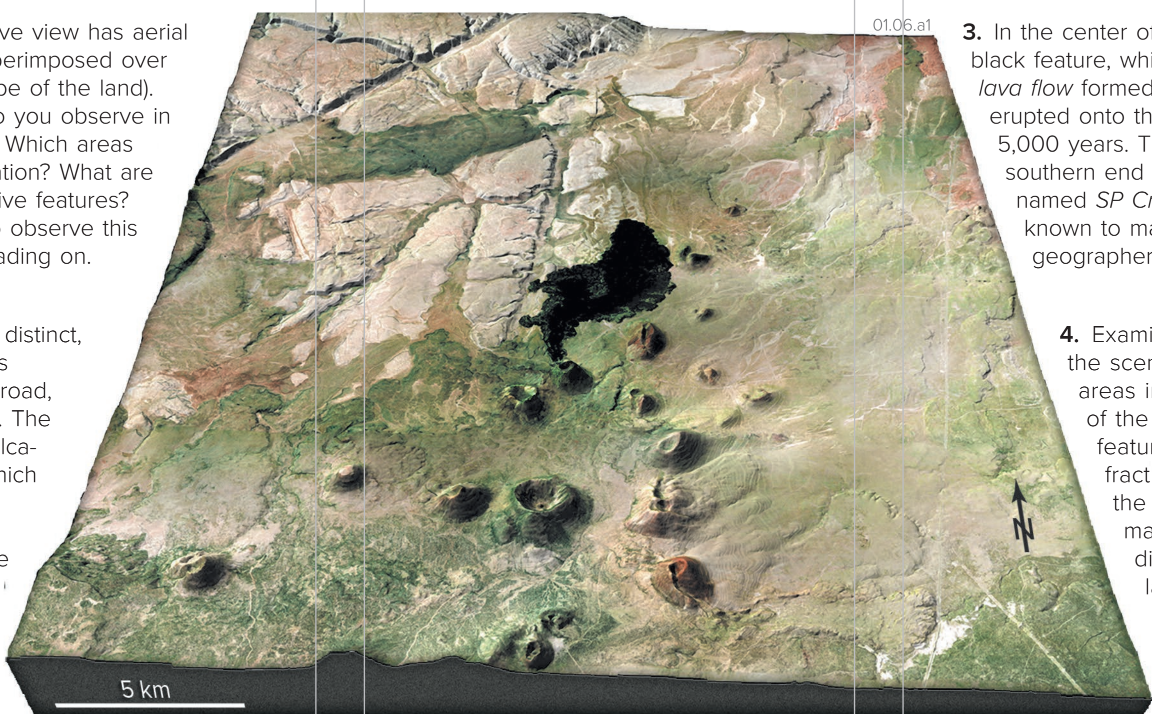
1.6 How Do We Depict Earth's Surface?

WE COMMONLY REPRESENT features like mountains, hillslopes, and river valleys with a *topographic map* or *shaded-relief map*, each of which is useful for certain purposes. Some maps allow us to visualize the landscape and navigate across the land, whereas others permit the quantitative measurement of areas, directions, and steepness of slopes.

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

Maps are the primary way we portray the land surface. Some maps depict the shape and elevation of the land surface, whereas others, like a soil map, show the materials on that surface. Views of SP Crater in northern Arizona provide a particularly clear example of the relationship between the land surface and different types of maps.

01.06.a1



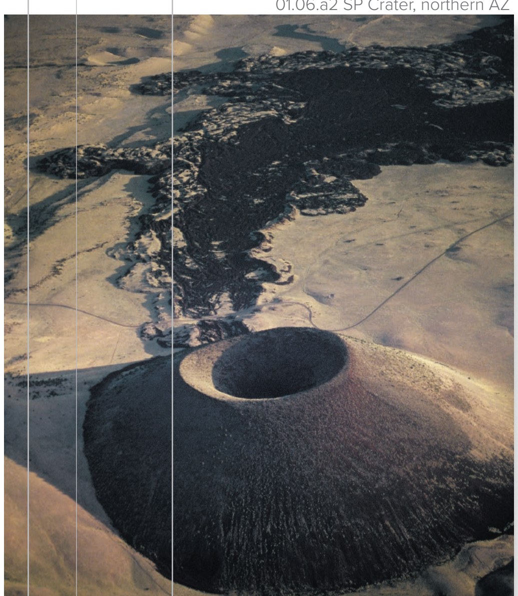
1. This perspective view has aerial photography superimposed over topography (shape of the land). What features do you observe in the topography? Which areas are high in elevation? What are the most distinctive features? Take a minute to observe this scene before reading on.

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

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

4. Examine other features in the scene. Note the light-gray areas in the upper left parts of the image, and the linear features formed by fractures that cut across the gray rocks. Different materials are forming different types of landscapes. This entire area has a relatively dry climate, with few trees to obscure the landform features.

01.06.a2 SP Crater, northern AZ



01.06.a3 SP Crater, northern AZ

5. This aerial photograph (◄) shows SP Crater and the dark lava flow that erupted from the base of the volcano. Note that the slopes of the volcano are much steeper than those of the surrounding land.

6. This photograph (▲), taken from the large crater south of SP Crater, shows the crater (on the left) and several other volcanoes. The view is toward the north. Try to match some of the features in this photograph with those shown in the larger perspective view.

Before You Leave These Pages

- ✓ Describe how shaded relief and topographic maps depict the surface.
- ✓ Describe what contours on a topographic map represent, how the shapes of contours reflect the shapes of features, and how contour spacing indicates the steepness of a slope.
- ✓ Sketch and explain the terms *elevation*, *depth*, *relief*, and *slope*; include how we express the steepness of a slope.

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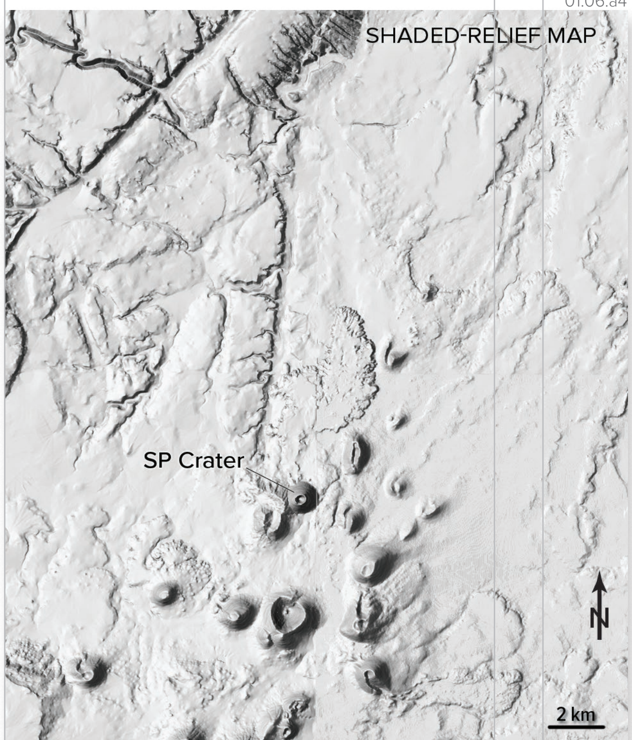
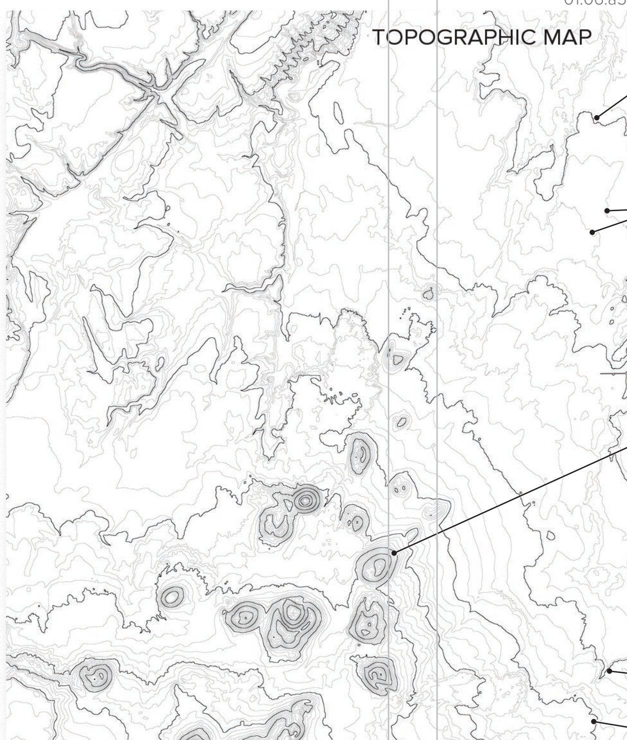
7. A *shaded-relief map* (▾) emphasizes the shape of the land by simulating light and dark shading on the hills and valleys. The individual hills on this map are volcanoes. The area is cut by straight and curving stream valleys that appear as gouges in the landscape.

01.06.a4



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

01.06.a5



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

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

11. Contour lines are more closely spaced where the land surface is relatively steep, such as on the slopes of the volcano. Note how the two-dimensional shapes of the contours reflect the three-dimensional shapes of the different volcanoes.

12. In a valley, contours bend into higher terrain, forming concave (V) shapes. For ridges, contours bend out from higher terrain, forming convex shapes.

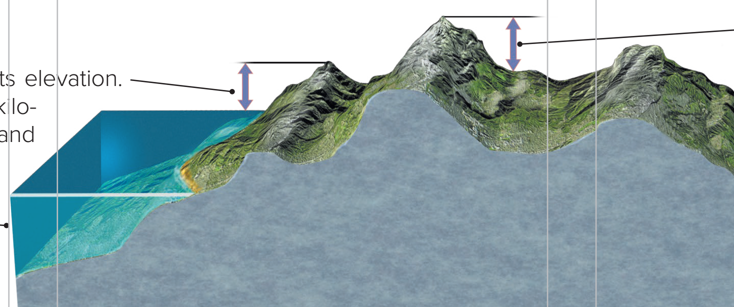
B How Do We Refer to Differences in Topography?

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

Elevation, Depth, and Relief

1. The height of a feature above sea level is its elevation. Scientists describe elevation in *meters* (m) or kilometers (km) above sea level, but some maps and most signs in the U.S. list elevation in feet (ft).

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



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

Slope and Gradient

4. One way to represent the topography of an area, especially the steepness of the land surface, is to envision an imaginary slice through a terrain, like this one through SP Crater (▸). The dark line shows the change in elevation across the land surface and is a *topographic profile*. Cliffs and slopes that drop sharply in elevation are *steep* slopes, whereas topography that is less steep is referred to as being *gentle*, as in a gentle slope.

01.06.b2 SP Crater, northern AZ

5. We describe steepness of a slope in *degrees* from horizontal. The eastern slope of SP Crater has a 26-degree slope (26° slope). We also talk about *gradient*—a 26° slope drops 490 meters over a distance of one kilometer, typically expressed as 490 m/1,000 m or simply as 0.49.

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1.7 What Do Latitude and Longitude Indicate?

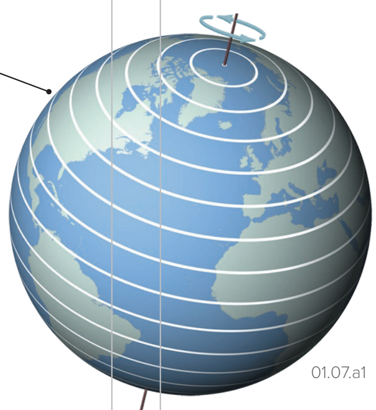
IMAGINE TRYING TO DESCRIBE the location of an "X" on a featureless sphere. What system would you devise to convey the location? If the sphere did not have any markings or seams, we would need to first establish a frame of reference—a place on the sphere from which to reference the location of the X. For these reasons, we have devised systems of imaginary gridlines on the Earth. These are referenced as angles from known points within or on the Earth. The most commonly used imaginary gridlines are *latitude* and *longitude*, which are displayed on many maps and provided by the location capabilities of many cellular phones.

A How Do We Represent Locations on a Globe?

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

Parallels

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



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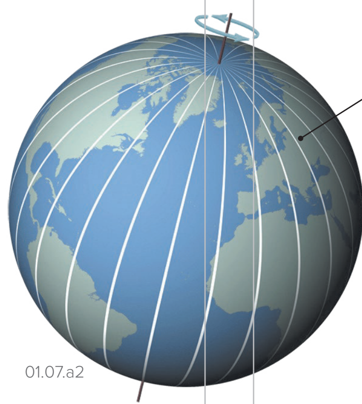
2. If we traveled along one of these lines (a parallel line), we would stay at the same distance from the pole as we encircled the planet. In other words, our position in a north-south framework would not change.

Meridians



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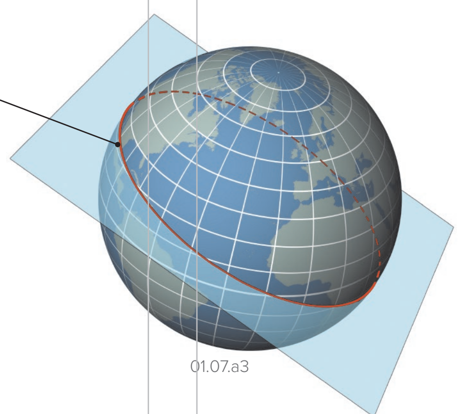
3. Lines that encircle the globe from North Pole to South Pole are called *meridians*. Meridians do not stay the same distance apart and are not parallel. Instead, meridians are widest at the equator and converge toward each pole. A meridian would be the path traveled if you took the most direct route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

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

Great Circles

5. The intersection of a plane and a sphere is an inclined, circular line that surrounds the sphere. If the plane passes through the center of the sphere, we call the resulting intersection a *great circle*. A great circle represents the shortest distance between two points on a sphere and so is the path airlines travel between destinations.



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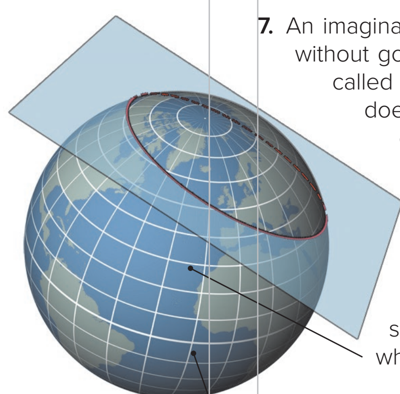
6. A great circle divides the sphere into two equal halves. The equator is a great circle, separating the Earth into two hemispheres—the *Northern Hemisphere* north of the equator and the *Southern Hemisphere* south of the equator. A north-south oriented great circle is used to separate the *Western Hemisphere*, which includes North and South America, from the *Eastern Hemisphere*, which includes Europe, Asia, Africa, and Australia. Antarctica, over the South Pole, and the Arctic Ocean, over the North Pole, each straddle the great circle between the Eastern Hemisphere and Western Hemisphere.

Small Circles

7. An imaginary plane that intersects a sphere without going through Earth's center is called a *small circle*. A small circle does not divide the globe into equal halves.



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8. Note that all parallels, which are oriented east-west, are small circles, except the equator, which is a great circle.

9. In contrast, each north-south meridian, when paired with its counterpart on the other side of the globe, forms a great circle. Any such pair of meridians divides the globe into two equal halves. When viewed together, parallels and meridians divide the planet into a grid of somewhat rectangular regions. Such regions encompass greater area near the equator than near the poles, due to the convergence of meridians toward the poles.

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B What Are Latitude and Longitude?

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

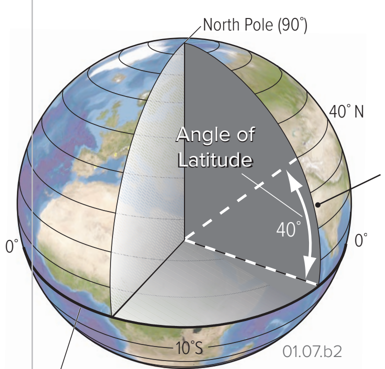
1. To navigate from New York to Moscow, we can tell from this map (▶) that we need to go a long way to the east and some amount to the north. These directions, although accurate, would not be good enough to guide us to Moscow. We need to specify the locations of each place more precisely and then figure out the shortest flight path. Fortunately, we can find on the Internet that the location of New York City, as given by coordinates, is 40.7142° N, 74.0064° W. The location of Moscow is 55.7517° N, 37.6178° E. Now if we only knew what these numbers signify!

01.07.b1

2. Before you go any further, note the yellow line on this map, which represents the shortest route between New York and Moscow. It does not look like the shortest route on this flat, two-dimensional map, but it is indeed the shortest route on the three-dimensional globe. What type of path do you think this flight route follows? It is a great circle.

Latitude

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



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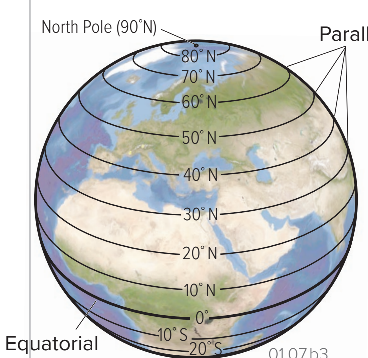
4. The angle created by drawing lines connecting the position of an object on the Earth's surface to the center of the Earth, and then to the equator, defines the number of degrees of latitude of the object's position. In the Northern Hemisphere, latitude is expressed as degrees north. In the Southern Hemisphere, latitude is often expressed as degrees south or as negative degrees.



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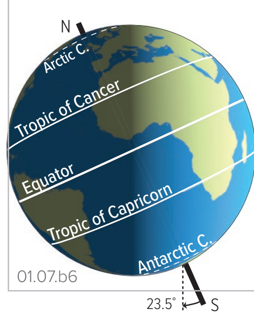
5. Parallels of latitude run east-west around the Earth. The zero line of latitude is the equator, with the values increasing to 90 at the North Pole and South Pole. There are ten million meters from the equator to the North and South Poles, so one degree of latitude is approximately 111 km (69 miles).

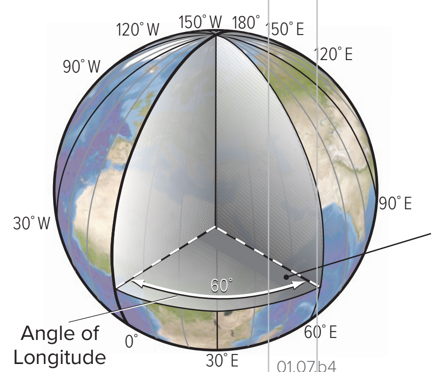
6. In addition to the equator, there are a few lines of latitude that are especially important. These include the *Tropic of Cancer* and *Tropic of Capricorn*, which are 23.5° north and south of the equator, respectively. Also important are the *Arctic Circle* and *Antarctic Circle*, which are 66.5° north and south of the equator (23.5° away from the corresponding pole). As discussed later, the 23.5° angle is how much the Earth's axis is tilted with respect to the Sun.



01.07.b6

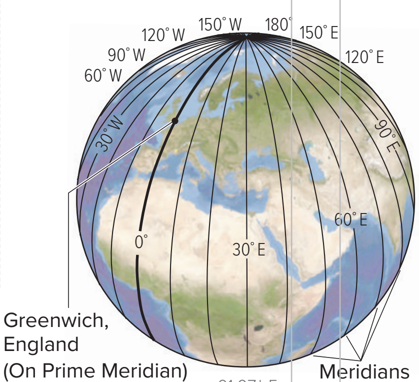
Longitude

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



01.07.b4

8. As a starting point, a zero-degree meridian is defined as the north-south line that passes through Greenwich, U.K.—this is called the *Prime Meridian*. The angle created by the object's position, the center of the Earth, and the Prime Meridian defines that object's longitude, given as degrees east or west of the Prime Meridian. Meridians west of the Prime Meridian often are expressed as negative degrees.



01.07.b5

9. Meridians of longitude run north-south. They are widest at the equator (where a degree of longitude is also about 111 km) and converge at higher latitudes until they meet at the poles. Starting at the zero meridian through Greenwich, values increase toward 180° as they approach the *International Date Line*, an imaginary line that runs through the middle of the Pacific Ocean (not shown; on the opposite side of the globe).

Before You Leave This Page

- ✓ Sketch and explain what is meant by a parallel, meridian, great circle, and small circle.
- ✓ Sketch and explain the meaning of latitude and longitude, indicating where the zero value and maximum value are for each measurement.

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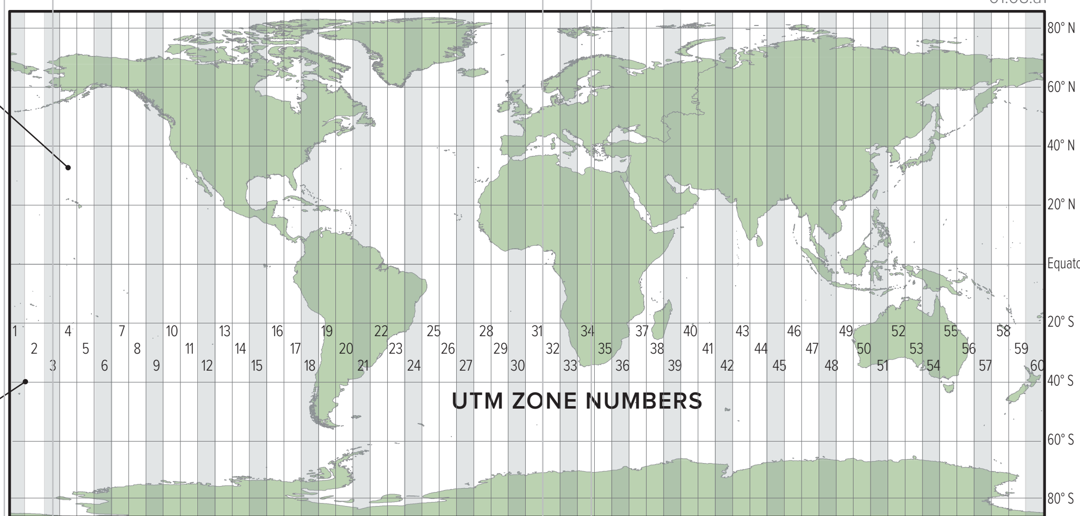
1.8 What Are Some Other Coordinate Systems?

WE USE OTHER SYSTEMS besides latitude and longitude to describe location. These include the Universal Transverse Mercator (UTM) system, the State Plane Coordinate System (SPCS), and the Public Land Survey System (PLSS). Each is useful for certain applications, and some are used to specify the location of real-estate properties appearing on legal documents associated with purchasing a house. Therefore, they are relevant to most citizens.

A How Do We Use the UTM System?

Maps can show large regions, even the entire world. The main considerations for displaying large regions arise mostly from a need to depict locations on a three-dimensional sphere accurately using a two-dimensional map. One solution to this challenge is the *Universal Transverse Mercator* (UTM) system, a method of identifying locations across the nonpolar part of the Earth. UTM is the most useful method of location for people who frequently hike or camp, or for people who work outdoors.

01.08.a1



1. The UTM system slices the nonpolar region into 60 north-south zones, each 6° of longitude wide. The slices are numbered from 1 to 60, with numbers increasing eastward from the International Date Line. A slice comprises two UTM zones, one in the Northern Hemisphere and another in the Southern Hemisphere. For example, most of Florida is in UTM zone 17 N, whereas the southern tip of South America is mostly in UTM Zone 19 S. What is the UTM zone for the place where you live?

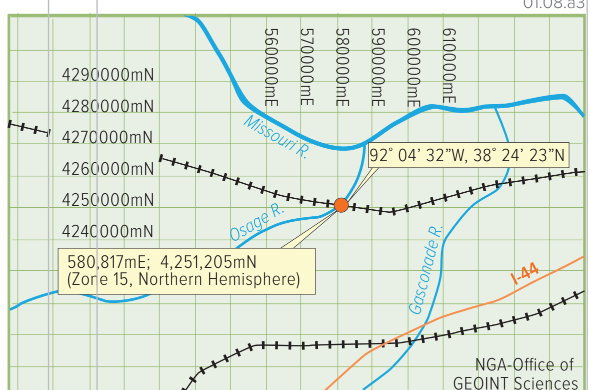
2. The slices are further subdivided into grid zones, each 20° of latitude long, as shown by the rectangles on this map. The purpose of UTM zones is to ensure that location is portrayed accurately in the middle of each division, as distortion increases toward the edges. Due to large distortions that occur in the UTM system near the poles, UTMs are typically only used between 80° N and 80° S latitudes (we generally do not use UTM within 10° of the poles).

3. For a location within a grid zone, we specify coordinates as *eastings* and *northings*. Eastings are a measure of the number of meters east or west of the central meridian for that zone. Northings are a measure of the position north or south of the equator. The aerial photograph below shows the horse and cow pasture shown earlier in this chapter, but this time with a UTM grid labeled with eastings (along the bottom of the map) and northings (along the left side of the map).

01.08.a2

4. The advantage of the UTM system is that it is a "square" grid system measured in meters rather than degrees, so it is convenient for measuring direction and distance. Note how useful this grid and UTM system would be if you were riding around trying to record the location of each horse in the pasture. Two horses (not visible here) are grazing at an easting of 495250 and a northing of 4214100; can you determine about where these horses are? Are they in the green pasture?

01.08.a3



5. We can specify locations using several systems and convert from one location system to another. The map above shows the position of a site expressed in both latitude-longitude (commonly called "lat-lon") and UTM coordinates. There are Internet sites that allow easy conversion from lat-lon to UTM and vice versa. To go from UTM to lat-lon, you have to specify the UTM zone, which can be determined using the large map above.

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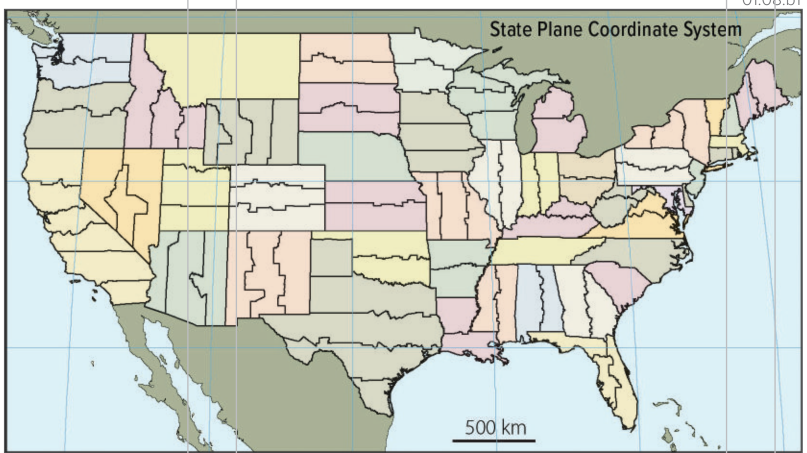
B How Do We Describe Locations Using the State Plane Coordinate System?

The State Plane Coordinate System (SPCS) is a third system for mapping, used only in the U.S. SPCS ignores the distortion caused by the curvature of the Earth by treating the surface as a plane, so it should only be used for smaller areas like states or parts of states. As a result, the system can use X-Y coordinates to represent positions, simplifying land surveys and calculations of distances and areas. Another advantage is that the type of map is customized for the geographic orientation of the state or section of the state, to minimize distortion for that area.

In the SPCS, most states are subdivided into two or more zones called *state plane zones*; some states are a single zone. Alaska has 10 zones and Hawaii has five zones. The boundaries of the zones generally are east-west or north-south, but they are not straight, following local county boundaries (trying to keep a county within a single zone).

01.08.b1

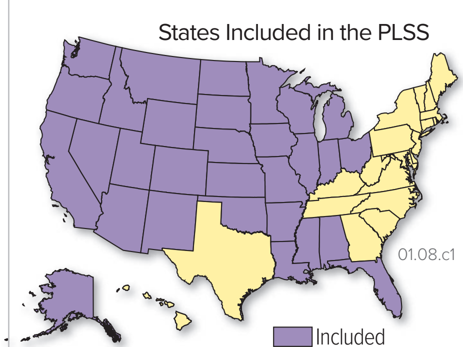


States that are elongated east-west, such as Tennessee, use different map approaches to generate the state plane coordinates than states like Illinois that are elongated north-south. The goal is to customize the drawing of the map so as to minimize the distortion that is always present when trying to show features of a spherical Earth on a flat piece of paper. So local U.S. maps, such as for flood zones, roads, or property delineation, are likely to use the SPCS. If you buy a house in the U.S., the legal documents will likely use SPCS to specify its location, perhaps accompanied by a survey in UTM.

C How Do We Describe Location Using the Public Land Survey System?

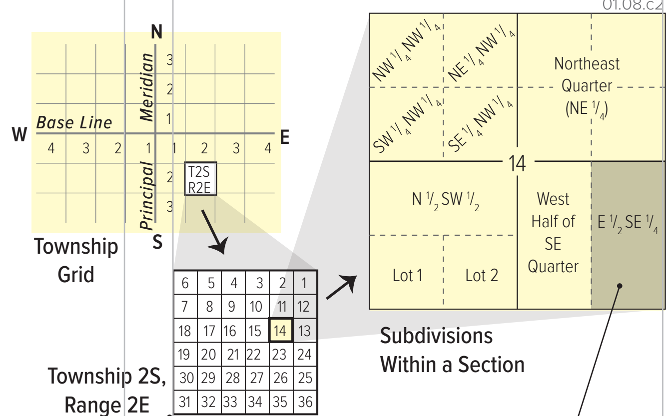
The Public Land Survey System (PLSS) is another system used in the U.S. for specifying the location of lands and for subdividing larger land parcels into smaller ones. When you hear someone refer to a "section of land" or a "quarter-section," they are talking about PLSS. The PLSS is also called the Township-Range Survey System.

1. The Public Land Survey System was designed later than the SPCS, after improved surveying technologies and protocols had been developed. As a result, the PLSS is most widely used in states that had not already been surveyed using SPCS. Examine the map below to see which states use PLSS.



2. PLSS is based around some initial point. From this point, a Principal Meridian extends both north and south and a Base Line extends both east and west. Beginning at the Principal Meridian, the land is subdivided into six-mile-wide, north-south strips of land called ranges. Beginning at the Base Line, the land is subdivided into six-mile-wide, east-west strips of land called townships.

01.08.c2



3. Each square of the township-range grid is six miles in an east-west direction and six miles in a north-south direction, so it is 36 mi² in area. Each grid square is further subdivided into 36 sections that are each one square mile in area, numbered as shown above. Township and range lines and section boundaries are included on many topographic maps.

4. Each one-square-mile section can be further divided into quarters, eighths, and even smaller subdivisions. The rectangle in the southeastern corner of Section 14 would be described as being in the eastern half of the southeast quarter of Section 14, Township 2 South and Range 2 East. This is abbreviated: E1/2 SE1/4, S. 14, T2S, R2E.

Before You Leave This Page

- ✓ Describe the UTM system, how positions are expressed, and some of its advantages.
- ✓ Describe the State Plane Coordinate System and its main advantages.
- ✓ Describe the Public Land Survey System and how areas of land are subdivided.

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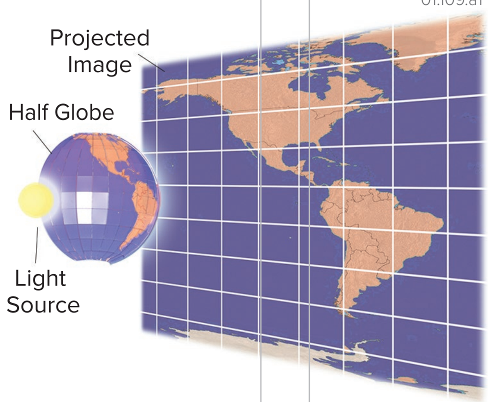
1.9 How Do Map Projections Influence the Portrayal of Spatial Data?

EARTH IS NOT FLAT, so a flat map cannot portray all locations accurately. An ideal map would preserve directions, distances, shapes, and areas, but it is not possible to preserve all four of these accurately. Instead, either the *shape* of features on a map, such as country outlines, is preserved or the *area* of features is preserved, but never both at the same time. Many map projections depict both shape and area somewhat inaccurately, as a trade-off, so that neither will be shown more inaccurately. *Cartographers* (map makers) have developed different ways of projecting our three-dimensional world onto a flat map, and each approach is called a *map projection*. The particular type of projection is chosen based on the intended use of the map. We commonly use different map projections for different purposes.

A What Is the Rationale Behind Map Projections?

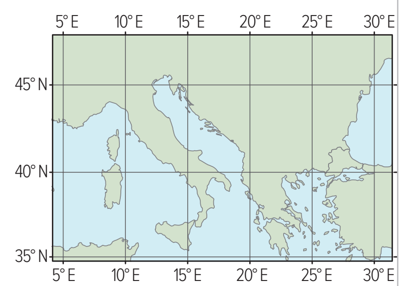
1. A *map projection* is a mathematical algorithm used to represent places on a three-dimensional spherical Earth on a flat map. Imagine shining a light through a partially transparent globe and observing the image projected on the back wall (▶). This is what a map projection does, but in a quantitative way. While many projections exist, the best projection for a given map will introduce the least distortion for the key areas being shown. Whenever a map is made, some distortion is introduced by the projection. It is impossible to avoid distorting either shapes or areas, or doing some distortions of each. Globes showing different views of the Earth are presented in Appendix 1.9Q.

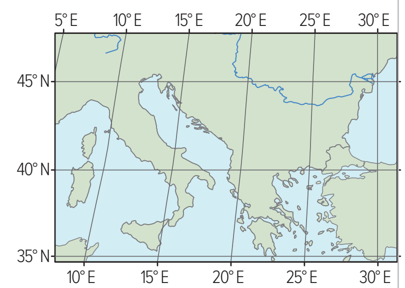


2. Some map projections attempt to preserve shapes, and are called *conformal projection*. If shapes are preserved (▶), directions may be preserved but areas are distorted or scale and distances will vary across the map. These imperfections get worse for maps that show larger areas.

3. In *equal-area projections*, areas are preserved but shape is distorted (▶). Compass directions cannot be shown correctly, so such a map should not be used for navigation or to show direction. If the proper projection is selected for a given application, distortions are minimized for the aspect (e.g., shape) that is most important and for the region of most interest.

01.09.a2–3

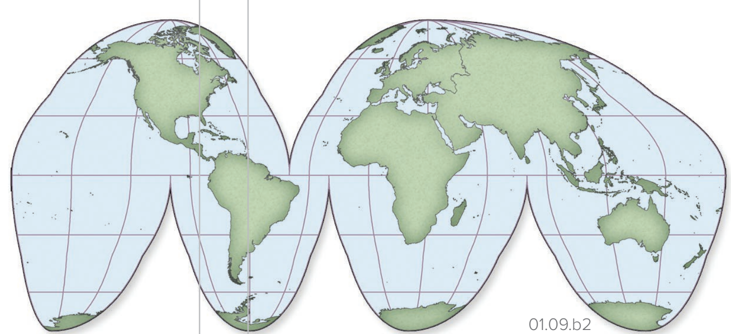




B What Are the Major Types of Projections and What Advantages Does Each Offer?

Sinusoidal

1. Perhaps the easiest projection to visualize conceptually is to imagine peeling an orange and slicing it in a few strategic places to allow it to be flattened without buckling (▼). *Sinusoidal projections* work on this same premise. If the map can be interrupted so that areas of lesser significance for a given application are not shown, then less distortion exists in the areas that are shown. Straight, parallel lines remain so, and have their correct length. Meridians become progressively longer toward the edges of each lobe of the map. While areas are preserved, shape distortion increases near the edges of each lobe.



2. The shape distortion problem in such projections can be mitigated by increasing the number of central meridians around which accuracy is preserved (▲). However, this comes at the expense of having more areas of interrupted coverage. Notice how the central meridians are straightest and appear at right angles to the parallels at the equator. These are the areas that are depicted most accurately for this type of projection. The most common type of map using this projection strategy is called a *Goode projection*.

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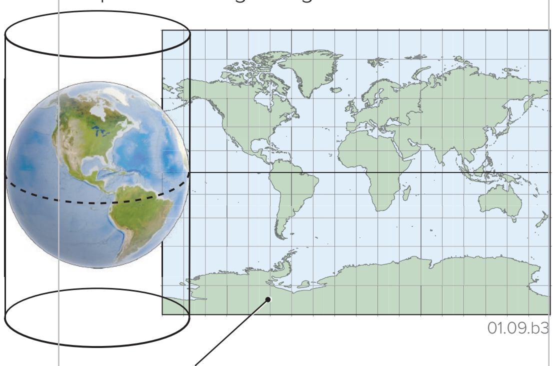
Cylindrical

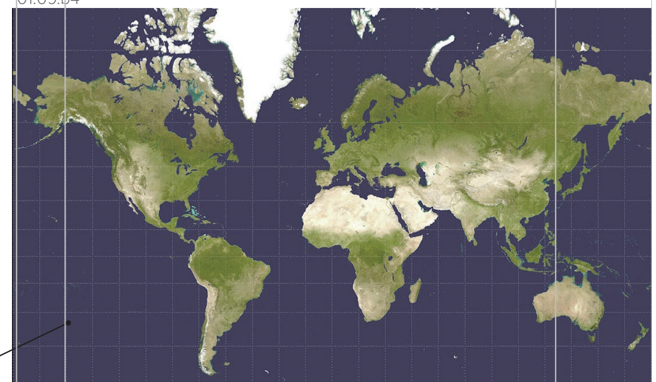
3. In *cylindrical projections*, the globe is transformed to a flat page by projecting a globe outward onto a cylinder. The projection starts at a line, called the *standard line*, where the globe touches the cylinder, usually at the equator. These types of map projections have no distortion at the standard line, but distortion becomes worse with increasing distance from the standard line. The resulting maps portray parallels of latitude as straight lines with the same length as the equator (that is, distorted in length and distance) and depict meridians also as straight lines intersecting the parallels at right angles.



01.09.b3

4. Cylindrical projections (◀) depict compass directions as straight lines, so they are excellent for navigation or to show direction. However, because the meridians are depicted (falsely) as being parallel to each other, east-west exaggeration of distances is severe, particularly in high latitudes. To allow these maps to be conformal (preserve shapes), north-south distances are stretched to match the east-west exaggeration. This makes high-latitude areas greatly exaggerated in size, but they retain shapes.

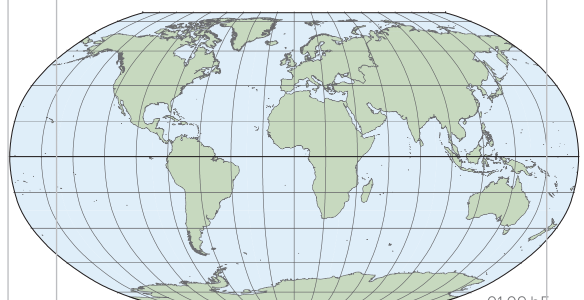
01.09.b4



5. High-latitude distortion increases to such an extent that the poles cannot be shown.

6. The most familiar type of cylindrical projection is the Mercator map, which became an important tool in the Age of Exploration. The part of the map at the right, which is a *Mercator projection*, portrays Greenland as being larger than the conterminous U.S. Is this true?

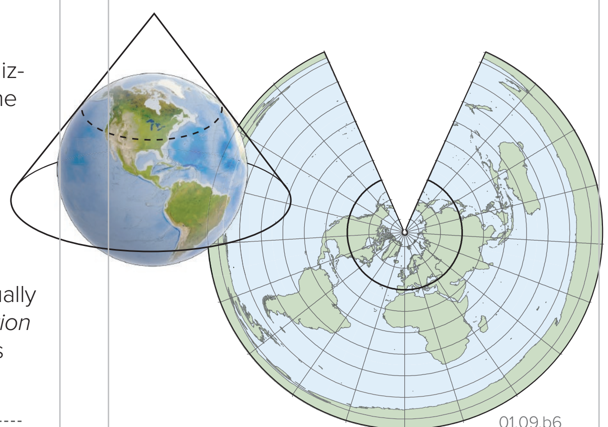
7. Some maps blend aspects of a cylindrical map with other types of projections. The *Robinson projection* (▶) is a commonly used projection of a world map, especially in textbooks. It represents a compromise between conformal and equal-area projections. The meridians curve gently, and the parallels are straight lines horizontally across the map. A feature it shares with cylindrical maps is severe distortion near the poles.



01.09.b5

Conical

8. *Conical projections* involve conceptualizing a cone over the globe, usually with the apex of the cone (▶) vertically above the pole. No distortion occurs along the arc where the globe touches the cone—the standard line, usually a parallel of latitude. If the cone slices through the globe and intersects the surface along two arcs (usually parallels of latitude), a *polyconical projection* results. In either case, distortion increases with distance away from these arcs.



01.09.b6

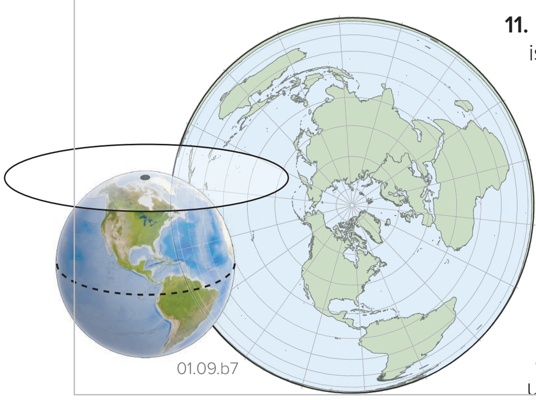
9. In conical projections, parallels are concentric circles and meridians are lines radiating from the center of curvature of the parallels. This family of projections is neither conformal nor equal area.

10. Conical projections can only show half of the Earth since regions that curve underneath the globe cannot be projected. This type of map works best when the area mapped is small in latitudinal extent. Notice how poorly this projection performs for showing a large area (◀).

Planar

11. In *planar projections*, the plane onto which the map is projected touches the globe in a single point, which becomes the center of the map. Distortion increases away from this point, and any straight line from this point is a line of true direction. Again, only half of Earth can be shown on such a map.

12. The pole is a focus in a type of planar projection called a *polar stereographic projection*. Scale becomes exaggerated toward the equator, but all lines connecting the shortest distance between two points on the sphere (great circles) are shown as straight lines. Planar projections are useful, therefore, for air navigation.



01.09.b7

Before You Leave This Page

- ✓ Describe what a map projection is, and how different types of map projections are created.
- ✓ Summarize the principles that should be taken into account when selecting the proper map projection.
- ✓ Explain the advantages and disadvantages of sinusoidal, cylindrical, conical, and planar projections.

1.10 How Do We Use Maps and Photographs?

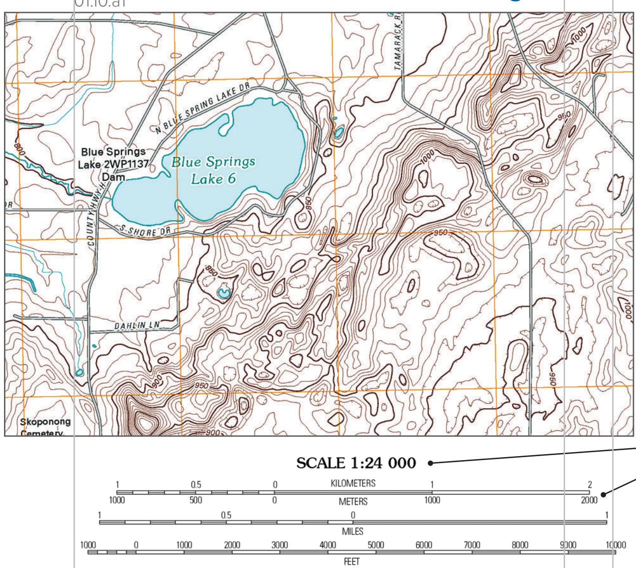
MAPS ARE AMONG OUR MOST IMPORTANT TOOLS for depicting and analyzing spatial information, whether we are interested in environmental issues or election results. Cartographers generate different kinds of maps for showing Earth's weather and climate, landscape features, and the distribution of plants, animals, or many other types of variables. Some cover small areas of Earth's surface, whereas others cover entire continents or the planet itself.

A How Much Area Do Maps Portray?

If we are hiking across the landscape, we want a detailed map that shows the location of every hill and valley. If we are interested in regional or global climate, we may want a map showing average temperatures for several adjacent states or for the entire planet. We use the general term *scale* to describe how much area the map shows. More specifically, scale is the ratio of the distance on a map to the actual distance (in the same units) on Earth.

Large-Scale Maps

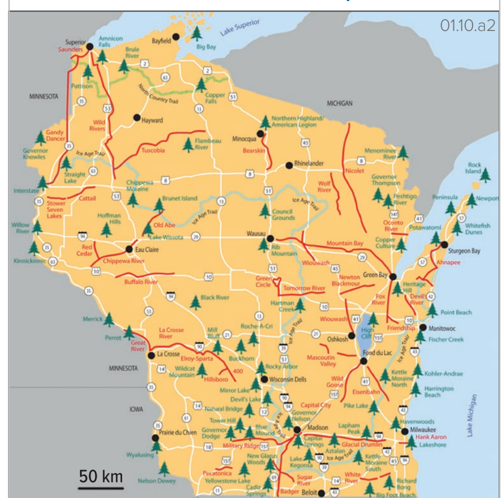
01.10.a1



1. This topographic map (◄) shows hills and lakes that formed as glacial features in Kettle Moraine State Forest in central Wisconsin. We can convey the scale of the map in three ways. First, we can report the scale with words—on the original version of this map (reduced here to fit on the page), one cm on the map equals 24,000 cm on the surface. Second, we can report this same information as a ratio of a distance on the map to the actual distance on the ground, which is called the map's *representative fraction;* for the original version of this map the representative fraction is 1:24,000, as reported on the map. Third, most maps include some type of visual *bar scale*.

2. The original scale of this map, 1:24,000, is the typical scale used in the U.S. for topographic maps, with one inch equaling 2,000 feet. A map like this, which shows a local area, has a large representative fraction. It would require a relatively large map to show a large area— so it is called a *large-scale map*.

Small-Scale Maps



01.10.a2

3. The map above shows state parks, forests, and recreation areas in Wisconsin. This type of regional map portrays a relatively large area with a relatively small map—such a map has a small representative fraction and is a *small-scale map*.

B How Are Maps Made?

Originally, topographic maps were produced by sending a team of surveyors out in the field and having them map the area, drawing lines on paper maps, and taking notes. Today, such maps can be produced directly from laser and radar measurements from orbiting spacecraft or from pairs of photographs taken from slightly different perspectives.

1. Aerial photographs are typically taken from a plane, drone, or satellite as it flies across the terrain. The onboard, downward-pointing camera takes photographs at specific intervals in such a way as to provide some overlap between the area captured by two successive photographs. The perspective of the camera is slightly different between the two photographs in the same way that our two eyes simultaneously have slightly different perspectives of the same scene. Test this concept by looking at your surroundings, closing one eye at a time, and noting how objects shift slightly in position relative to one another. The shift is related to their difference in distance from us.

01.10.b1–2 Arabia Terra, Mars

2. Two aerial photographs that have overlapping coverage and slightly different perspectives (◄) are called a *stereo pair*, usually generated by two images taken seconds apart while the plane, drone, or satellite is moving. In other cases, both images are taken at the same time but by two different cameras placed a specific distance apart. When the two photographs of a stereo pair are placed at a proper distance side by side, a tool called a *stereoscope* enables us to see the scene in 3D, with the hills appearing to stand in relief above valleys. Such stereo pairs can be used to make a topographic map.

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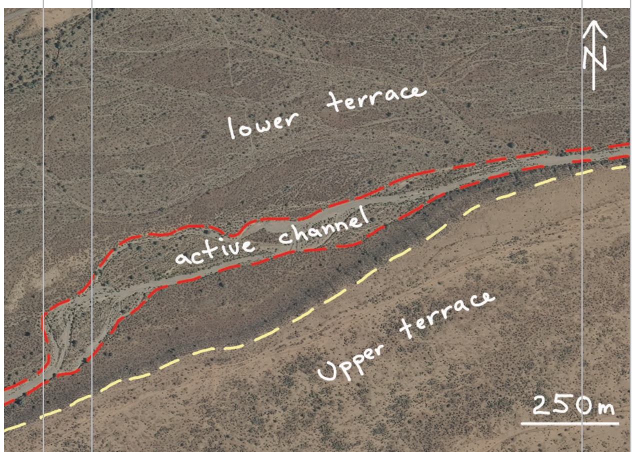
C How Can Maps Be Used for Reporting Information?

Sometimes we make new maps in the field, such as by using surveying equipment to make a topographic map that depicts the shape of topography. In most cases, we use existing maps, like the ones shown previously, and use GPS to locate the things we observe, such as the locations of glacial features or certain types of trees. In either case, this type of map actually produces new knowledge and is therefore a form of *primary data.*

To conduct field studies in an area, we could visit the field site with an appropriately detailed map or aerial image, representing a *base map* upon which observations can be plotted. The base map can be a large-scale topographic map or a detailed aerial photograph (▶). Observations and other information are plotted directly on the base map or on a partially transparent overlay. Alternatively, locations can be determined with a handheld GPS device where the coordinates are saved and later mapped using a computer-based mapping program.



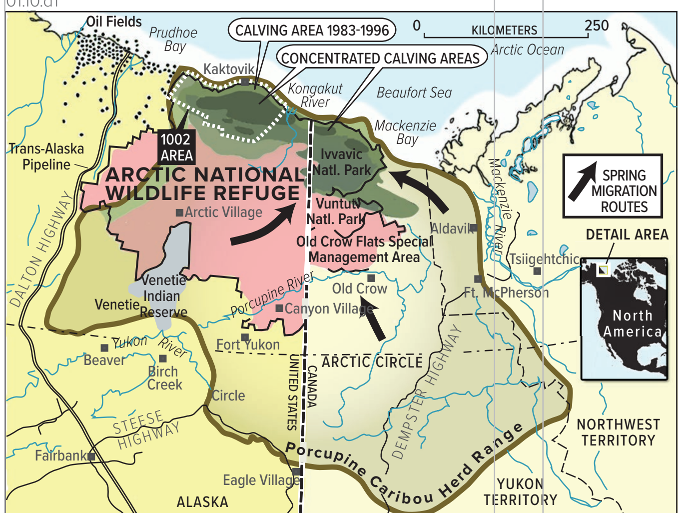
01.10.c1 Queen Creek, AZ

This aerial photograph shows different materials on the surface of several levels (elevations) along a desert river channel. The gray part, bounded by the dashed red lines, represents the active channel and related areas that are flooded during most years. The lower terrace is slightly higher in elevation above the channel and is flooded less frequently. The upper terrace is high enough to avoid any flooding. This map was produced by walking through the field area and drawing on the aerial photograph the boundaries between different areas. This map would be useful for determining flooding potential and other types of land-use planning.

D How Can Maps Be Used to Analyze and Interpret the Environment?

Preexisting maps become the basis for various interpretations. For example, the annotated aerial photograph above could be used to plan the location of a subdivision, especially deciding where *not* to build. A preexisting map that is used for providing the input for answering some other question is a type of *secondary data* source.

01.10.d1

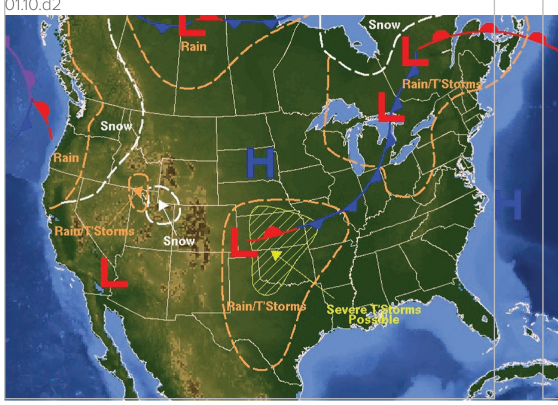


1. Many maps (◀) contain a combination of data and interpretations. Examine this map of the Arctic National Wildlife Refuge (ANWR), and identify aspects that are data versus those aspects that represent some type of interpretation. Then continue reading below.

2. *Data*—Some features on this map would be considered data. These include the outline of the coastline, the boundary between Alaska and Canada, the locations of rivers and roads, and the outline of ANWR.

3. *Interpretations*—Other aspects of the map are interpretations, which commonly represent an expert's opinion of a situation. On this map of ANWR, interpretations include the migration routes of caribou (the large black arrows) and the locations where caribou give birth to their calves (calving areas, in green). This map, consisting of data and interpretations, would be considered a secondary data source. It might be used to determine which areas are permissible for drilling.

01.10.d2



4. Surface weather maps (◀) also include data and interpretations. The coastlines and state outlines are clearly data. Weather maps also show both computerized and human interpretation of the location of areas of relatively high (H) and low (L) atmospheric pressure, and weather fronts—lines interpreted to mark the boundary between air of very different temperatures and humidity. The triangles and semicircles point in the direction of frontal movement, another interpretation. Dashed lines outline general areas of rain or snow. Such maps help predict today's and tomorrow's weather.

Before You Leave This Page

- ✓ Explain the difference between large-scale and small-scale maps and when you would use each.
- ✓ Describe how we can use maps to record new information.
- ✓ Describe how we can use maps to analyze and interpret existing information about the environment.

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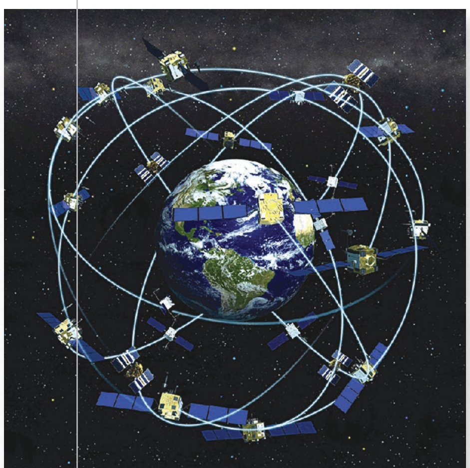
1.11 How Do We Use Global Positioning Systems and Remote Sensing?

THE GLOBAL POSITIONING SYSTEM (GPS) and remote sensing have greatly increased the accuracy of geographic field studies and given geographers new methods for performing analyses. GPS helps geographers define spatial relationships among Earth's surface features, and a wide variety of remote-sensing techniques help geographers define regional patterns and monitor changing environmental conditions.

A What Is GPS?

GPS is familiar as a navigation system in our cars, cellular telephones, or handheld devices used for location and guidance. GPS detects and reports our accurate position on Earth's surface, including latitude, longitude, elevation, and even how fast we are traveling. This information comes from a series of satellites orbiting Earth that send radio signals to ground-based receivers, like the ones on our dashboards, or in our phones or handheld devices.



01.11.a1

The U.S. government launches, controls, and monitors a constellation of 24 satellites orbiting in six different planes around Earth (◀). Several generations of satellites currently operate in the GPS constellation (▶), with newer generations being deployed to improve accuracy and reliability.

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

01.11.a2

B How Do We Use GPS to Study Geographic Features?

GPS is used in a variety of applications from tracking wildlife migration or package delivery, to improving ocean and air travel. Farmers use GPS to harvest crops and improve yield. Geographers use GPS for a variety of activities, including monitoring changes in the environment, collecting more accurate field data when surveying or mapping, and making decisions about how to best prevent or address natural disasters. Geographers employ two types of GPS devices, the familiar handheld GPS and the differential GPS (DGPS).

01.11.b1

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

2. Geographers use handheld GPS mostly for field work, including mapping the locations of landscape features, determining locations of water and soil samples, and inventorying populations of plants and animals.

3. *Differential GPS* (DGPS) is the same as GPS but with a correction signal added to improve the precision and accuracy. Accuracy is enhanced because the correction signal performs an independent check of each GPS satellite's signal. DGPS provides accuracy of less than several meters.

4. Geographers use DGPS when precision is important, such as in surveys (▶) of changes in the land surface over timescales of decades or to gauge the erosion effects of a recent hurricane on a shoreline and its communities.

01.11.b2

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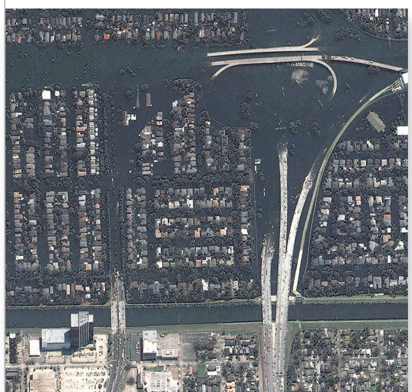
C What Is Remote Sensing?

The term *remote sensing* refers to techniques used to collect data or images from a distance, including the processing of such data, and the construction of maps using these techniques. Remote sensing can be carried out using a helicopter, airplane, drone, satellite, balloon, ship, or other vehicle, or it can be performed with instruments fixed on the land surface. The instrument-carrying vehicle or site is called the *platform*, and the instrument that collects the images and other data is the *sensor*. There are two general types of remote-sensing systems: *passive systems* and *active systems*.

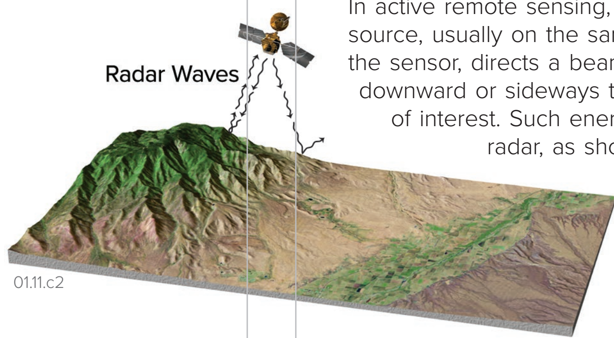
Passive Remote Sensing



01.11.c1 New Orleans, LA after Hurricane Katrina

In passive remote sensing, the sensor points at the area of interest and records whatever light, heat, or other energy is naturally coming from that region. Aerial photography and most satellite images, like the one to the left, are recorded by passive sensors. The sensors are tuned to collect specific types and wavelengths of energy, such as infrared, visible, and ultraviolet energy. Most sensors collect an array of similar frequencies.

Active Remote Sensing



01.11.c2

In active remote sensing, an energy source, usually on the same platform as the sensor, directs a beam of energy downward or sideways toward the area of interest. Such energy can include radar, as shown here, microwaves, laser light, or other types of energy. The sensor then measures how much of this energy returns to the platform and whether this energy has been modified by its interaction with the surface or atmosphere.

D What Types of Remote Sensing Are Used by Geographers?

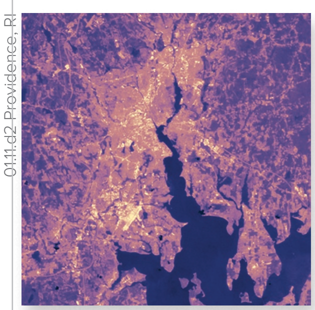
Geographers use various remote-sensing techniques, measuring various types of energy, to study Earth's atmosphere, hydrosphere, lithosphere, and biosphere. Geographers also document and investigate patterns in land use, vegetation cover, erosion rates, extent of pollution, ocean temperatures, and atmospheric water content and circulation. Objects reflect or emit different types of electromagnetic energy, such as visible light or microwaves, which we can measure to study different issues.

Visible and Near Infrared (IR)

01.11.d1 Washington, DC

1. Aerial photographs typically record visible light reflected off an area, but some photographs and many satellite images also record adjacent bands of infrared energy (near-IR). On near-IR images, vegetation commonly is depicted with a reddish tone, as in this image of Washington, D.C.

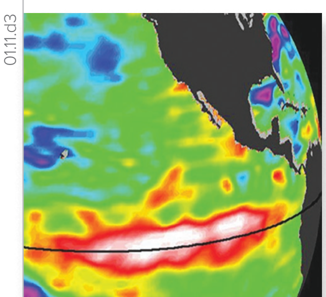
Thermal Infrared (IR)



01.11.d2 Providence, RI

2. Objects also emit energy, either from the internal heat of an object or from heat initially gained from the Sun. This image shows thermal-IR derived temperatures of Providence, Rhode Island, with lighter colors showing hotter areas in the city.

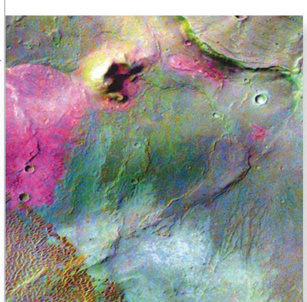
Microwave



01.11.d3

3. Images from microwave-sensing satellites and ground-based stations provide us with weather images in nightly newscasts. Microwaves can penetrate clouds and haze, providing a clear view of the ground at all times. They also can measure the height of the sea surface, as shown here.

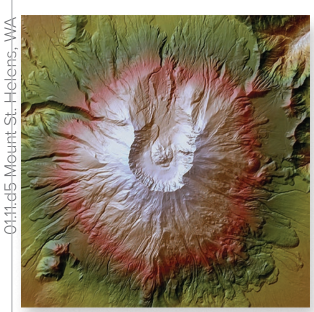
Multispectral



01.11.d4 Nili Patera, Mars

4. Some multipurpose satellites collect data at multiple wavelengths of energy and therefore have the name *multispectral*. Multispectral data are used for studying natural hazards, inventorying plant communities, tracking forest fires, and observing landscapes on other planets, as shown here.

Radar, Sonar, and Lidar



01.11.d5 Mount St. Helens, WA

5. *Radar*, *sonar*, and a newer technique called *lidar* all involve emitting waves of a certain wavelength and then measuring how much is reflected back to the sensor and the time required for the various beams to return. These data allow us to map the surface, like volcanic features.

Before You Leave This Page

- ✓ Explain what GPS is, how it works, and how we can use it to investigate geographic problems.
- ✓ Summarize what remote sensing is, explaining the difference between passive and active systems.
- ✓ Describe five types of remote-sensing data and one example of how each type is used.

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