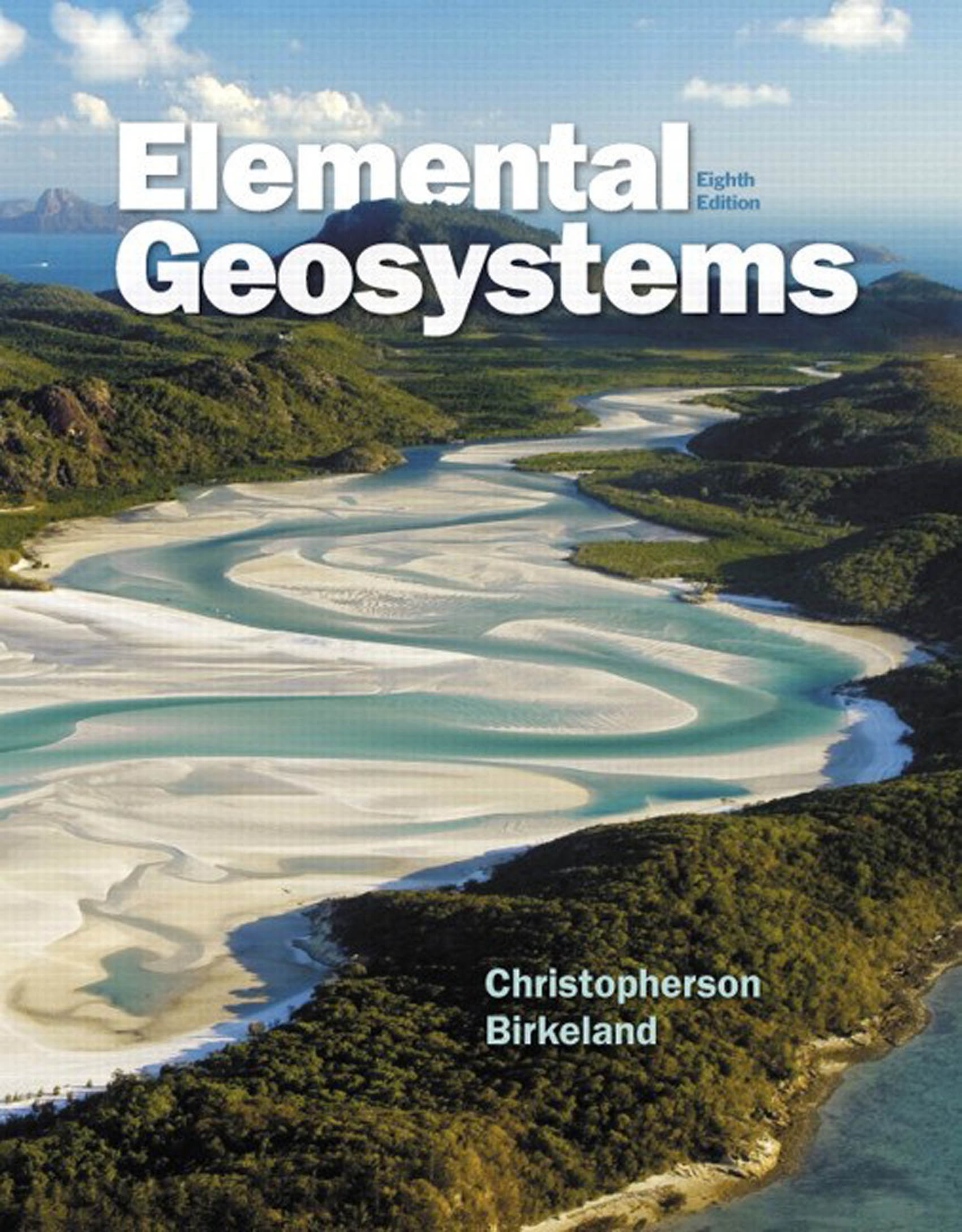
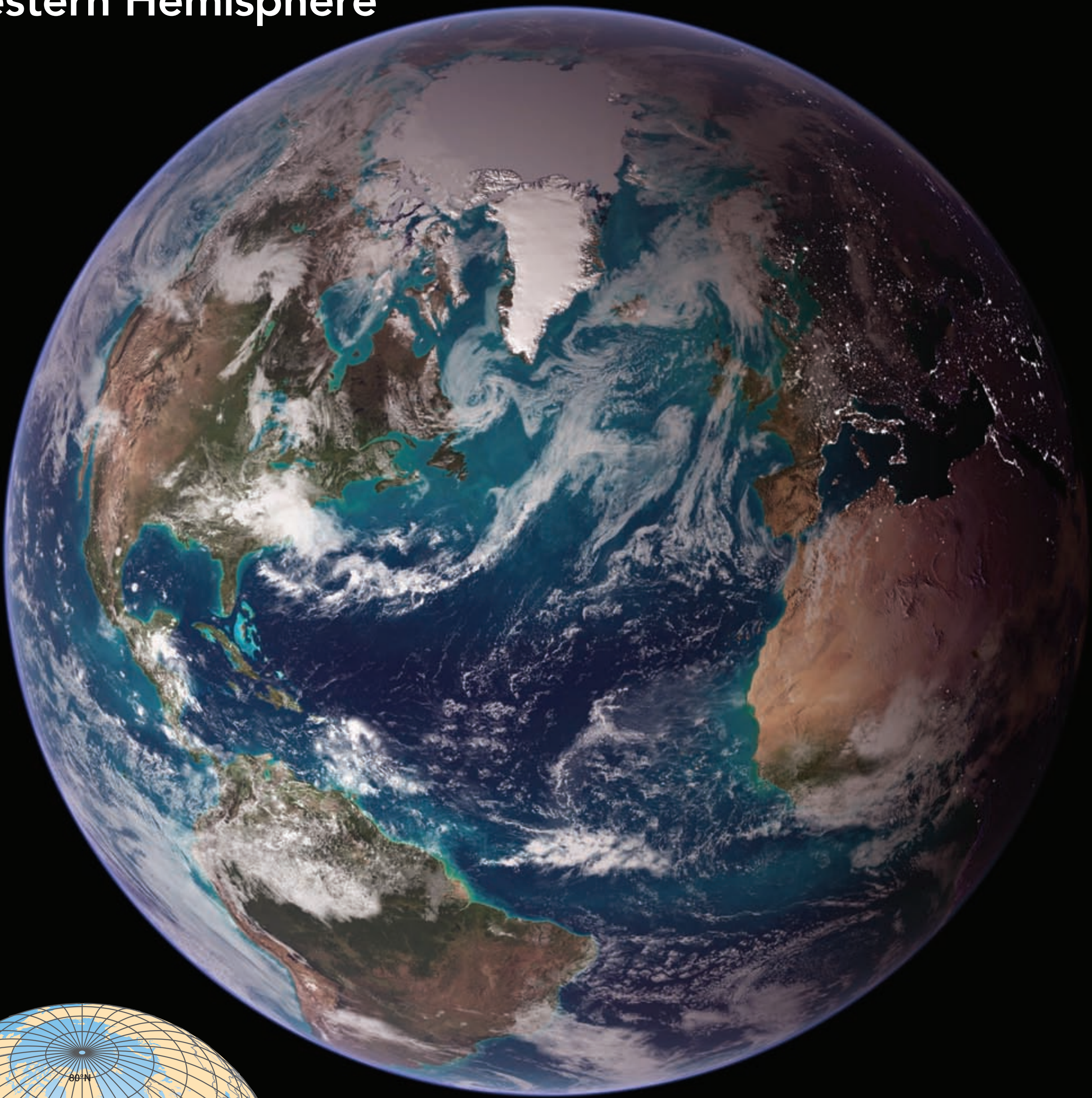
# Elemental Geosystems

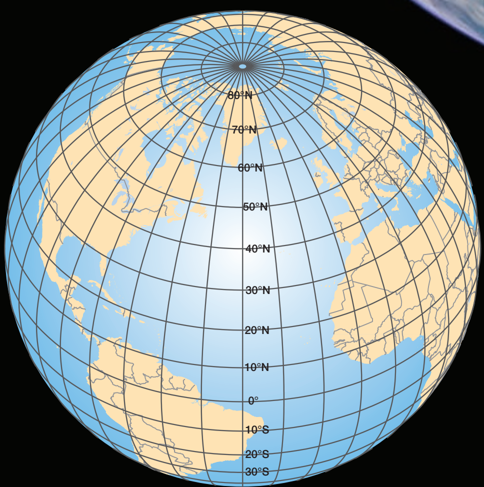
Eighth Edition

Christopherson
Birkeland



# Western Hemisphere

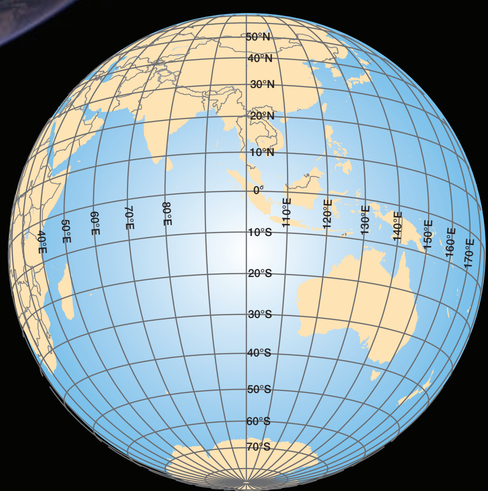





Multiple images from satellites *Terra*, *Aqua*, *Radarsat*, and *Defense Meteorological Satellite*, and from Space Shuttle *Endeavor's* radar data of topography, all merge in a dramatic composite to show the Western Hemisphere and Eastern Hemisphere of Earth. What indications do you see on these images that tell you the time of year? These are part of NASA's Blue Marble Next Generation image collection.

[NASA images by Reto Stöckli, based on data from NASA and NOAA.]

# Eastern Hemisphere



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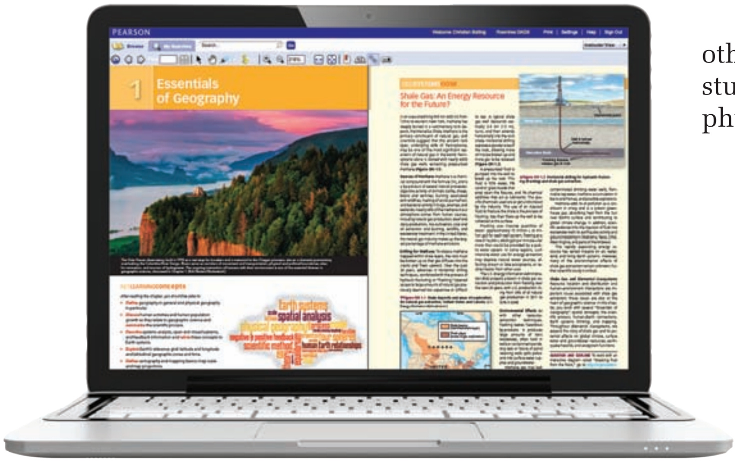

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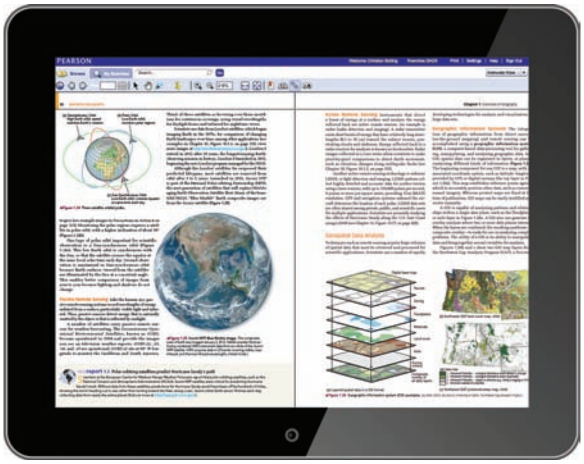

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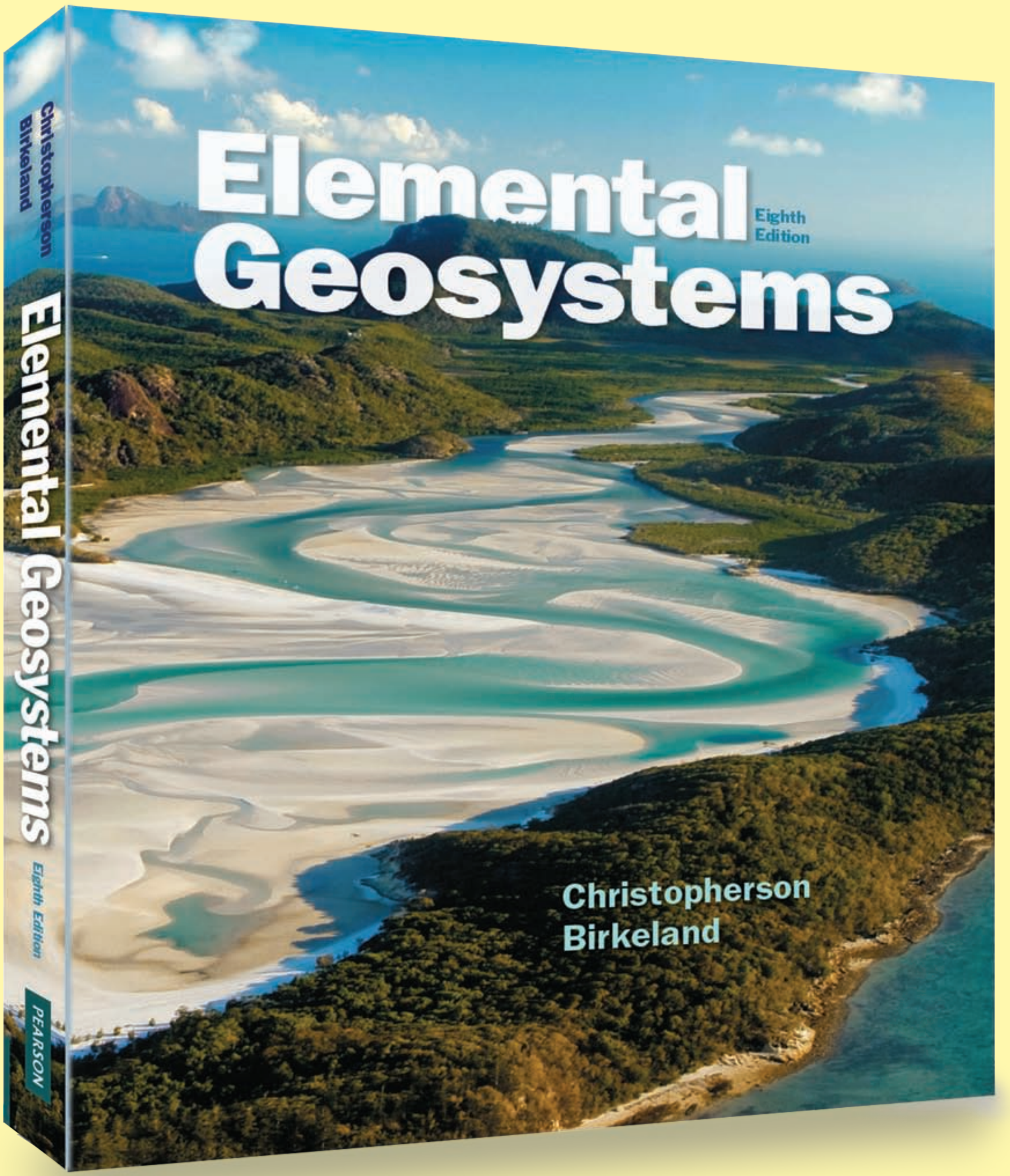
# A Virtual Field Trip Through Earth's Dynamic Systems

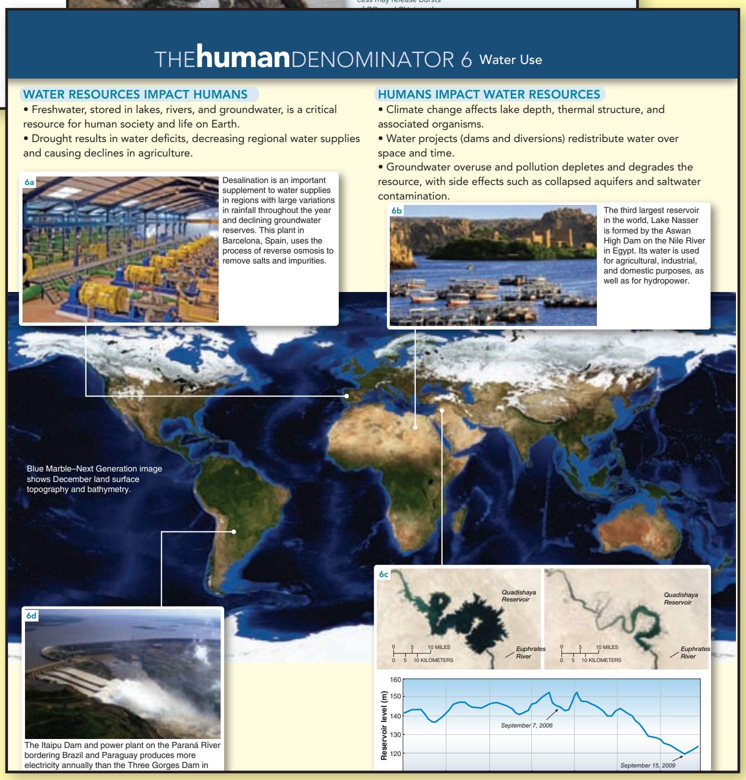


# Exploring Earth's Dynamic Systems

*Elemental Geosystems* is organized around the natural flow of energy, materials, and information, presenting subjects in the same sequence in which they occur in nature—an organic, holistic Earth systems approach that is unique in this discipline. Offering current examples and modern science, *Elemental Geosystems* combines a structured learning path, student-friendly writing, current applications, outstanding visuals, and a strong multimedia program for a truly unique physical geography experience.

▼ NEW! Chapter 8: **Climate Change.** Incorporating the latest climate change science and data, this new chapter covers paleoclimatology and mechanisms for past climatic change, climate feedbacks and the global carbon budget, the evidence and causes of present climate change, climate forecasts and models, and actions that we can take to moderate Earth's changing climate.

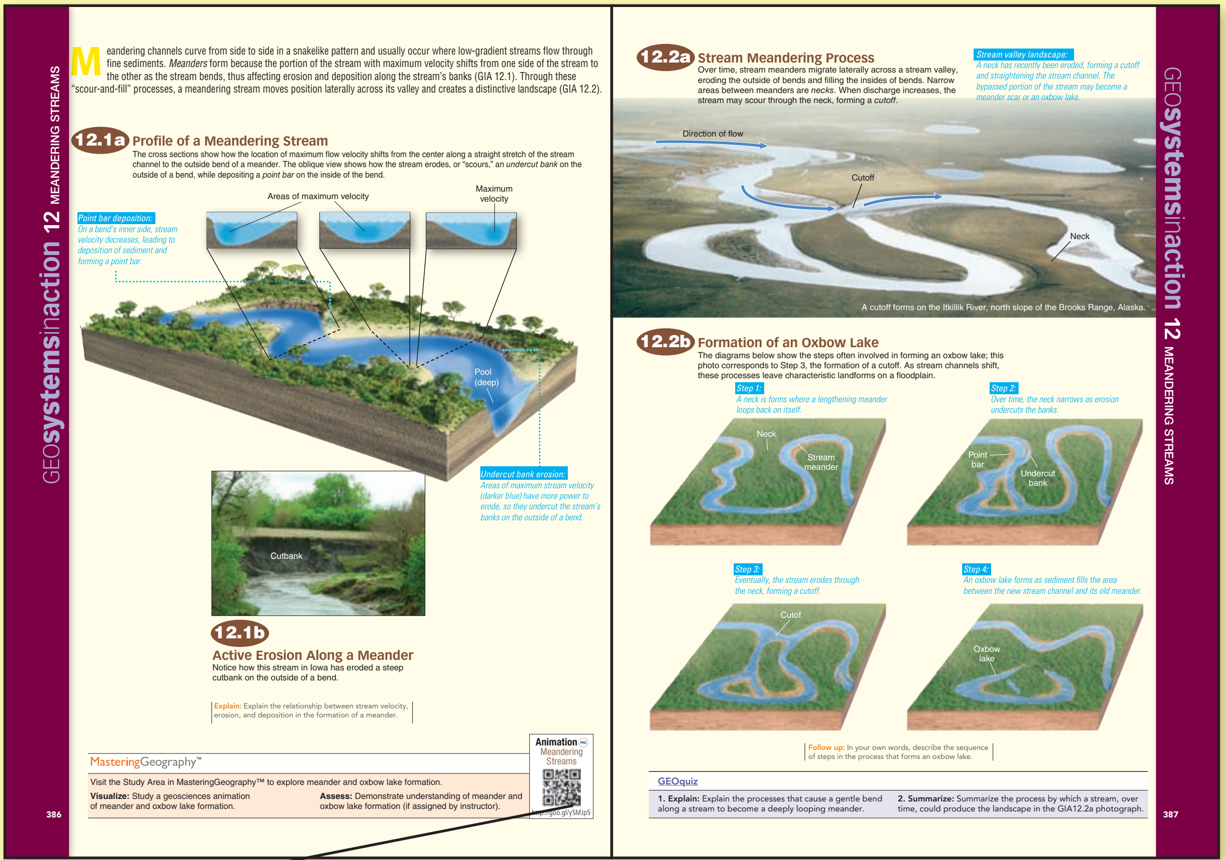





▶ NEW! *The Human Denominator* summarizes Human-Earth relationships, interactions, and challenges for the 21st century through dynamic visuals, including maps, photos, graphs, and diagrams.

# Visualizing Processes & Landscapes

▼ NEW! ***Geosystems in Action*** provide highly-visual presentations of core physical processes and critical chapter concepts.



GEOsystemsinaction 12 MEANDERING STREAMS

Meandering channels curve from side to side in a snakelike pattern and usually occur where low-gradient streams flow through fine sediments. *Meanders* form because the portion of the stream with maximum velocity shifts from one side of the stream to the other as the stream bends, thus affecting erosion and deposition along the stream's banks (GIA 12.1). Through these "scour-and-fill" processes, a meandering stream moves position laterally across its valley and creates a distinctive landscape (GIA 12.2).

**12.1a Profile of a Meandering Stream**

The cross sections show how the location of maximum flow velocity shifts from the center along a straight stretch of the stream channel to the outside bend of a meander. The oblique view shows how the stream erodes, or "scours," an *undercut bank* on the outside of a bend, while depositing a *point bar* on the inside of the bend.



**12.1b Active Erosion Along a Meander**

Notice how this stream in Iowa has eroded a steep cutbank on the outside of a bend.

**Explain:** Explain the relationship between stream velocity, erosion, and deposition in the formation of a meander.

MasteringGeography™

Visit the Study Area in MasteringGeography™ to explore meander and oxbow lake formation.

**Visualize:** Study a geosciences animation of meander and oxbow lake formation.

**Assess:** Demonstrate understanding of meander and oxbow lake formation (if assigned by instructor).

Animation: Meandering Streams http://goo.gl/ySMJp5

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**12.2a Stream Meandering Process**

Over time, stream meanders migrate laterally across a stream valley, eroding the outside of bends and filling the insides of bends. Narrow areas between meanders are *necks*. When discharge increases, the stream may scour through the neck, forming a *cutoff*.



A cutoff forms on the Itkillik River, north slope of the Brooks Range, Alaska.

**12.2b Formation of an Oxbow Lake**

The diagrams below show the steps often involved in forming an oxbow lake; this photo corresponds to Step 3, the formation of a cutoff. As stream channels shift, these processes leave characteristic landforms on a floodplain.



**Follow up:** In your own words, describe the sequence of steps in the process that forms an oxbow lake.

GEOquiz

**1. Explain:** Explain the processes that cause a gentle bend along a stream to become a deeply looping meander.

**2. Summarize:** Summarize the process by which a stream, over time, could produce the landscape in the GIA12.2a photograph.

GEOsystemsinaction 12 MEANDERING STREAMS

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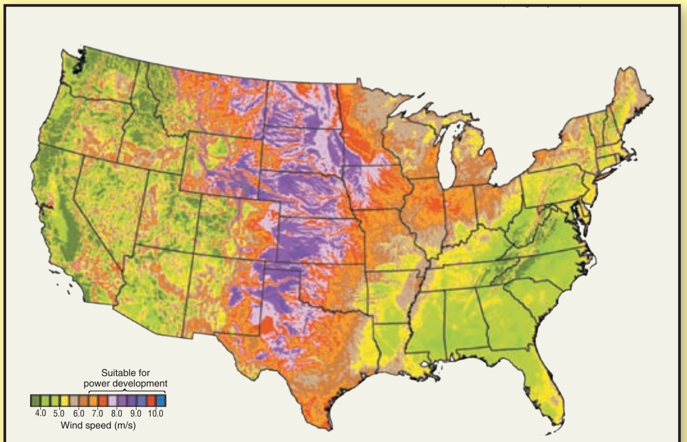
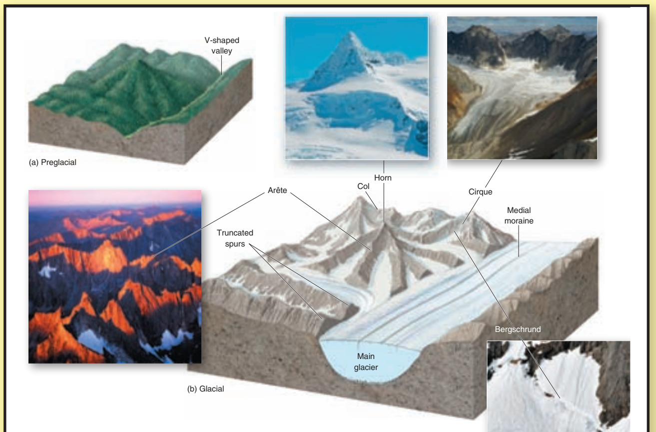
*Geosystems in Action* include links to mobile-ready media and MasteringGeography, as well as GeoQuizzes and integrated active learning tasks that ask students to analyze, explain, infer, or predict based on the information presented.





▲Figure 4.1.1 **Wind-speed map of the contiguous United States.** The map shows predicted average wind speeds at a height of 80 m (164 ft) above the ground. Areas with wind speeds greater than 6.5 m/s (21 ft/s) are considered suitable for power development. The map has a spatial resolution of 2.5 km (1.6 mi). [NREL and AWS Truepower.]





▲Figure 14.11 **An alpine valley, showing preglacial and glacial landscape.** Inset photos are of an arête in Canada, a horn in Antarctica, a cirque in Nepal, and a bergschrund in Spitsbergen. [Arete by Fred & Randi Hirschmann/RGB Ventures/SuperStock/Alamy. Cirque by Galen Rowell/Corbis. Horn and bergschrund by Bobbé Christopherson.]

▲ An unparalleled visual program includes a variety of illustrations, maps, photographs, and composites, providing authoritative examples and applications of physical geography and Earth systems science.

# Real World Applications

***Elemental Geosystems*** **integrates current real events and phenomena and presents the most thorough and integrated treatment of systems trends and climate change science, giving students compelling reasons for learning physical geography.**

▼ ***Geosystems Now*** open each chapter with interesting, current applications of physical geography and Earth systems science. New **Geosystems Now Online** features direct students online to related resources.

▼ ***Focus Studies*** present detailed discussions of critical physical geography topics, emphasizing the applied relevance of physical geography today.

GEOSYSTEMS**now**

## Sand Dunes Protect Coastlines during Hurricane Sandy

During the winter of 2013, several months after Hurricane Sandy, many residents along New Jersey's coastline added their discarded Christmas trees to carefully stacked lines of trees acting as "seeds" for new sand dune formation along several area beaches. The trees were intended to catch windblown sand to begin the dune formation process, in one of many such restoration efforts along the Atlantic coast. In the face of Sandy's winds, houses and neighborhoods with protective dunes in place experienced less damage than those that were more exposed to and closer to the ocean.

**Dune Protection versus Ocean Views** The effectiveness of dune systems as protection from wave erosion and storm surge during Hurricane Sandy, far from being a subtle statistical phenomenon, was easily observed by local residents. However, the fostering of large and sometimes obtrusive sand dunes near the shoreline is controversial in coastal communities with million-dollar homes. For such dunes to function as barriers to erosion, they must sit between ocean-front property and the sea, thus blocking ocean views and decreasing property values (**Figure GN 13.1**). For many landowners, establishing dunes for storm protection means financial loss in the short term, even if long-term protection is the result.

**Video** The Making of a Superstorm http://goo.gl/k6HaNa

**Coastal Dune Geomorphology** Coastal sand dunes consist of sediment supplied by the work of ocean waves and by fluvial processes that move sediment onto deltas and estuaries. Once sand is deposited on shore, it is reworked by wind processes into the shape of dunes. Dunes along seacoasts are either *foredunes*, where sand is pushed up the seaward-facing slope, or *backdunes*, which form farther away from the beach and are protected from onshore winds (blowing toward the beach); backdunes are more stable and may be hundreds of years old. Most areas of coastal dunes are relatively small in size (especially when compared with desert dune fields that may cover large portions of continents).

Along the Atlantic coast, foredunes are moving inland as sea level rises and storm energy increases with climate change. In developed areas, this landward retreat of foredunes impinges on human development. When storms occur, dune movement is intensified, and either dune erosion or sand deposition, or both, occurs within the developed area of the coast (**Figure GN 13.2**).

**Video** Hurricane Sandy http://goo.gl/Yj3FWj

**Dune Restoration Efforts** The establishment of new foredunes replenishes the sand supply and protects structures and infrastructure, making this a potentially worthwhile investment of money and effort for communities along the New Jersey shoreline. Many experts point out that dunes are *not* a guarantee of storm protection and that Sandy's winds and storm surge were strong enough to erode some large natural dune systems along the Atlantic Seaboard. However, in Bradley Beach, New Jersey, where the storm eroded several miles of restored dunes about 4.6 m (15 ft) in height, the community still escaped excessive damage, since the dunes absorbed much of the storm's impact.

Thus, many local communities are supporting dune restoration, as evidenced by the 2013 Christmas tree initiative. Because vegetation is important for dune stabilization, the planting of grasses is another protective strategy being embraced by New Jersey residents. In this chapter, we discuss coastal systems, wind processes, and dune formation.

**QUESTION AND EXPLORE** For information and links to research on dunes in New Jersey and along the Atlantic coast, see **http://marine.rutgers.edu/geomorph/geomorph/_pages/dunes.html**. More on coastal dune geomorphology is at **http://www.nature.com/scitable/knowledge/library/coastal-dunes-geomorphology-25822000**. MG


▲**Figure GN 13.2 Coastal damage from Sandy in Mantoloking, New Jersey.** View looking west before and after Hurricane Sandy. The yellow arrow points to the same feature in each image. [USGS.]

◄**Figure GN 13.1 Constructed dunes.** Restored sand dunes shield homes in Mantoloking, New Jersey, from an incoming nor'easter a few weeks after Hurricane Sandy. [Sharon Karr/FEMA.]

**focusstudy 10.1** Natural Hazards

## Earthquakes in Haiti, Chile, and Japan: A Comparative Analysis

In 2010 and 2011, three quakes struck areas near major population centers, causing massive destruction and fatalities. These earthquakes—in the countries of Haiti, Chile, and Japan—all occurred at plate boundaries and ranged in magnitude from M 7.0 to M 9.0 (**Figure 10.1.1** and **Table 10.1.1**).

### The Human Dimension

The 2010 Haiti earthquake hit an impoverished country where little of the infrastructure was built to withstand earthquakes. Over 2 million people live in the capital city of Port-au-Prince, which has been destroyed by earthquakes several times, mostly notably in 1751 and 1770. The total damage there from the 2010 quake exceeded the country's $14 billion gross domestic product (GDP). In developing countries such as Haiti, earthquake damage is worsened by inadequate construction, lack of enforced building codes, and the difficulties of getting food, water, and medical help to those in need (Figure 10.1.1a).

The Maule, Chile, earthquake, which occurred just 6 weeks later, caused only minimal damage, in large part due to the fact that the country enacted strict building codes in 1985 (Figure 10.1.1b). The result was a fraction of the human cost compared to the Haiti earthquake.

The Japan quake resulted in an enormous and tragic human fatality count (Figure 10.1.1c), mainly due to the massive Pacific Ocean tsunami (defined as a set of seismic sea waves; discussed in Chapter 13). When an area of ocean floor some 338 km (N–S) by 150 km (210 mi by 93 mi) snapped and was abruptly lifted as much as 80 m


(a) Destruction in Port-au-Prince, Haiti, in 2010. The quake epicenter was along multiple surface faults and a previously unknown subsurface thrust fault.

(b) A collapsed bridge in Santiago, Chile, after the M8.8 earthquake hit Maule, 95 km (60 mi) away. The epicenter was on a convergent plate boundary between the Nazca and South American plates.

**MG MapMaster** World/PhysicalEnvironment Tsunami Hazard


(c) Honshu Island, Japan, after the quake and tsunami. The epicenter was on a convergent plate boundary between the Pacific and North American plates.

(d) Tsunami moves ashore, Iwanuma, Japan. Iwanuma is 20 km (12.4 mi) south of Sendai, the city closest to the epicenter.

▲**Figure 10.1.1 The 2010–2011 Haiti, Chile, and Japan earthquakes and the 2011 Japan tsunami.** [(a) Julie Jacobson/AP Images. (b) Martin Bernetti/Getty Images. (c) and (d) Kyodo/Reuters.]

► ***GeoReports*** offer a wide variety of brief interesting facts, examples, and applications to complement and enrich the chapter reading.

**GEOreport 5.2** Mountains cause record rains

Mount Waialeale, on the island of Kaua'i, Hawai'i, rises 1569 m (5147 ft) above sea level. On its windward slope, rainfall averaged 1234 cm (486 in., or 40.5 ft) a year for the years 1941–1992. In contrast, the rain-shadow side of Kaua'i received only 50 cm (20 in.) of rain annually. If no islands existed at this location, this portion of the Pacific Ocean would receive only an average 63.5 cm (25 in.) of precipitation a year. (These statistics are from established weather stations with a consistent record of weather data; several stations claim higher rainfall values, but do not have dependable measurement records.)

Cherrapunji, India, is 1313 m (4309 ft) above sea level at 25° N latitude, in the Assam Hills south of the Himalayas. Summer monsoons pour in from the Indian Ocean and the Bay of Bengal, producing 930 cm (366 in., or 30.5 ft) of rainfall in 1 month. Not surprisingly, Cherrapunji holds the all-time precipitation record for a single year, 2647 cm (1042 in., or 86.8 ft), and for every other time interval from 15 days t

**GEOreport 13.3** Ocean acidification impacts corals

As the oceans absorb more excess carbon dioxide, their acidity increases and potentially damages coral formations, an interaction that scientists are actively researching. A 2013 study examined Mediterranean red coral (*Corallium rubrum*) colonies under more acidic conditions in a laboratory and discovered reduced growth rates of 59% and abnormal skeleton development when compared with colonies growing under current ocean conditions. The test conditions were at a pH of 7.8 (which would occur w

**GEOreport 16.1** Sea turtles navigate using Earth's magnetic field

The fact that birds and bees can detect the abiotic influence of Earth's magnetic field and use it for finding direction is well established. Small amounts of magnetically sensitive particles in the skull of the bird and the abdomen of the bee provide compass directions. Recently, scientists found that sea turtles detect magnetic fields of different strengths and inclinations (angles). This means that the turtles have a built-in navigation system that helps them find certain locations on Earth. Loggerhead turtles hatch in Florida, crawl into the water, and spend the next 70 years traveling thousands of miles between North America and Africa around the subtropical high-pressure gyre in the Atlantic Ocean. The females return to where they were hatched to lay their eggs. In turn, the hatchlings are imprinted with magnetic data unique to the location of their birth and then develop a more global sense of position as they live a life swimming across the ocean.

# A Refined Learning Path

***Elemental Geosystems* provides a structured learning path that helps students achieve a deeper understanding of physical geography through active learning.**

KEYLEARNING**concepts**

*After reading the chapter, you should be able to:*

- *Sketch* a basic drainage basin model and *identify* different types of drainage patterns by visual examination.
- *Explain* the concepts of stream gradient and base level and *describe* the relationship between stream velocity, depth, width, and discharge.
- *Explain* the processes involved in fluvial erosion and sediment transport.
- *Describe* common stream channel patterns and *explain* the concept of a graded stream.
- *Describe* the depositional landforms associated with floodplains and alluvial fan environments.
- *List* and *describe* several types of river deltas and *explain* flood probability estimates.

▲ ***Key Learning Concepts*** at the beginning of every chapter help students identify the key knowledge and skills they will acquire through study of the chapter.

▼ ***Key Learning Concepts Reviews*** at the end of each chapter feature summaries, narrative definitions, a list of key terms with page numbers, and review questions.

KEYLEARNING**concepts**review

*Sketch* a basic drainage basin model and *identify* different types of drainage patterns by visual examination.

**Fluvial** processes are stream-related. The basic fluvial system is a **drainage basin**, or *watershed*, which is an open system. *Drainage divides* define the catchment (water-receiving) area of a drainage basin. In any drainage basin, water initially moves downslope in a thin film of **sheetflow**, or *overland flow*. This surface runoff concentrates in *rills*, or small-scale downhill grooves, which may develop into deeper *gullies* and a stream course in a valley. High ground that separates one valley from another and directs sheetflow is an *interfluve*. Extensive mountain and highland regions act as **continental divides** that separate major drainage basins. Some regions, such as the Great Salt Lake Basin, have *internal drainage* that does not reach the ocean, the only outlets being evaporation and subsurface gravitational flow.

*Drainage density* is determined by the number and length of channels in a given area and is an expression of a landscape's topographic surface appearance. **Drainage pattern** refers to the arrangement of channels in an area as determined by the steepness, variable rock resistance, variable climate, hydrology, relief of the land, and structural controls imposed by the landscape. Seven basic drainage patterns are generally found in nature: dendritic, trellis, radial, parallel, rectangular, annular, and deranged.

**fluvial (p. 374)**
**drainage basin (p. 374)**
**sheetflow (p. 375)**
**continental divide (p. 375)**
**drainage pattern (p. 377)**

1. Define the term *fluvial*. What is a fluvial process?
2. What role is played by rivers in the hydrologic cycle?
3. What are the five largest rivers on Earth in terms of discharge? Relate these to the weather patterns in each area and to regional potential evapotranspiration (PE) and precipitation (P)—concepts discussed in Chapter 6.
4. What is the basic organizational unit of a river system? How is it identified on the landscape? Define the several relevant key terms used.
5. In Figure 12.3, follow the Allegheny–Ohio–Mississippi river system to the Gulf of Mexico.

*level* occurs when something interrupts the stream's ability to achieve base level, such as a dam or a landslide that blocks a stream channel.

**Discharge**, a stream's volume of flow per unit of time, is calculated by multiplying the velocity of the stream by its width and depth for a specific cross section of the channel. Streams may have *perennial*, *ephemeral*, or *intermittent* flow regimes. Discharge usually increases in a downstream direction; however, in rivers in semiarid or arid regions, discharge may decrease with distance downstream as water is lost to evapotranspiration and water diversions.

A graph of stream discharge over time for a specific place is called a **hydrograph**. Precipitation events in urban areas result in higher peak flows during floods. In deserts, a torrent of water that fills a stream channel during or just after a rainstorm is a **flash flood**.

**gradient (p. 379)**
**base level (p. 379)**
**discharge (p. 379)**
**hydrograph (p. 380)**
**flash flood (p. 381)**

7. Explain the base level concept. What happens to a stream's base level when a reservoir is constructed?
8. What was the impact of flood discharge on the channel of the San Juan River near Bluff, Utah? Why did these changes take place?
9. Differentiate between a natural stream hydrograph and one from an urbanized area.

*Explain* the processes involved in fluvial erosion and sediment transport.

Water dislodges, dissolves, or removes surface material and moves it to new locations in the process of **erosion**. Sediments are laid down by the process of **deposition**. **Hydraulic action** is the erosive work of water caused by hydraulic squeeze-and-release action to loosen and lift rocks and sediment. As this debris moves along, it mechanically erodes the streambed further through a process of **abrasion**. Streams may deepen their valley by channel incision, they may lengthen in the process of headward erosion, or they may erode a valley laterally in the process of meandering.

When stream energy is high, particles move downstream in the process of **sediment transport**. The sedi-

▼ ***Critical Thinking*** activities integrated throughout chapter sections give students an opportunity to stop, check, and apply their understanding.

CRITICAL**thinking 12.1**

**Locate Your Drainage Basin**

Determine the name of the drainage basin within which your campus is located. Where are its headwaters? Where is the river's mouth? If you are in the United States or Canada, use Figure 12.3 to locate the larger drainage basins and divides for your region, and then take a look at this region on Google Earth™. Does any regulatory organization oversee planning and coordination for the drainage basin you identified? Can you find topographic maps online that cover this region?

CRITICAL**thinking 12.2**

**Identifying Drainage Patterns**

Examine the photograph in **Figure CT 12.2.1**, where you see two distinct drainage patterns. Of the seven types illustrated in Figure 12.5, which two patterns are most like those in the aerial photo? Looking back to Figure 12.1a, which drainage pattern is prevalent in the area around Mount Mismi in Brazil? Explain your answer. The next time you fly in an airplane, look out the window to observe the various drainage patterns across the landscape.

**▲Figure CT 12.2.1 Two drainage patterns dominate this scene from central Montana, in response to rock structure and local relief.** [Bobbé Christopherson.]

MasteringGeography™

# Continuous learning before, during, & after class

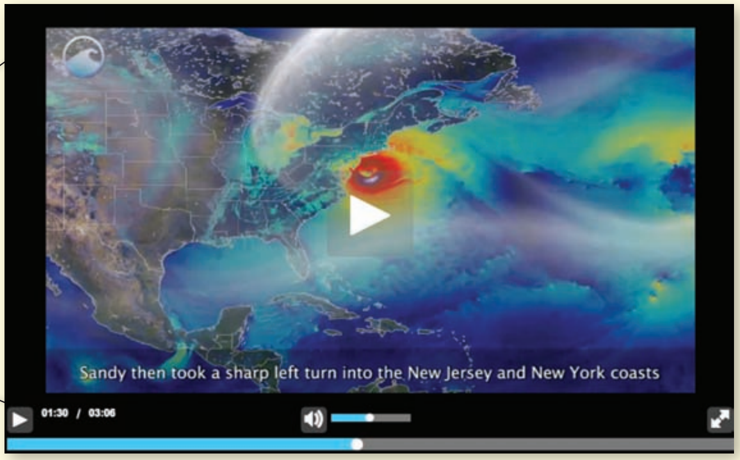
MasteringGeography™ delivers engaging, dynamic learning opportunities—focusing on course objectives and responsive to each student's progress—that are proven to help students absorb geography course material and understand challenging physical processes and geographic concepts.

## BEFORE CLASS

### Pre-Class Assignments Provide Students with a Preview of What's to Come

▼ **NEW! *Mobile-Enabled Media*** Quick Response (QR) Codes integrated throughout each chapter empower students to use their mobile devices to learn as they read, providing instant access to over 80 Animations and Videos of real-world physical geography phenomena and visualizations of key physical processes. All media can be assigned with quizzes in MasteringGeography.

**Video** MG
Superstorm Sandy
http://goo.gl/k6HaNa

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- Now available on smartphones and tablets.
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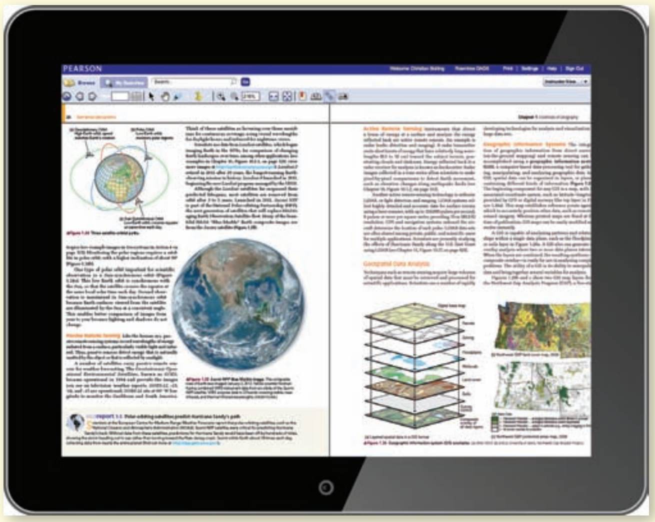

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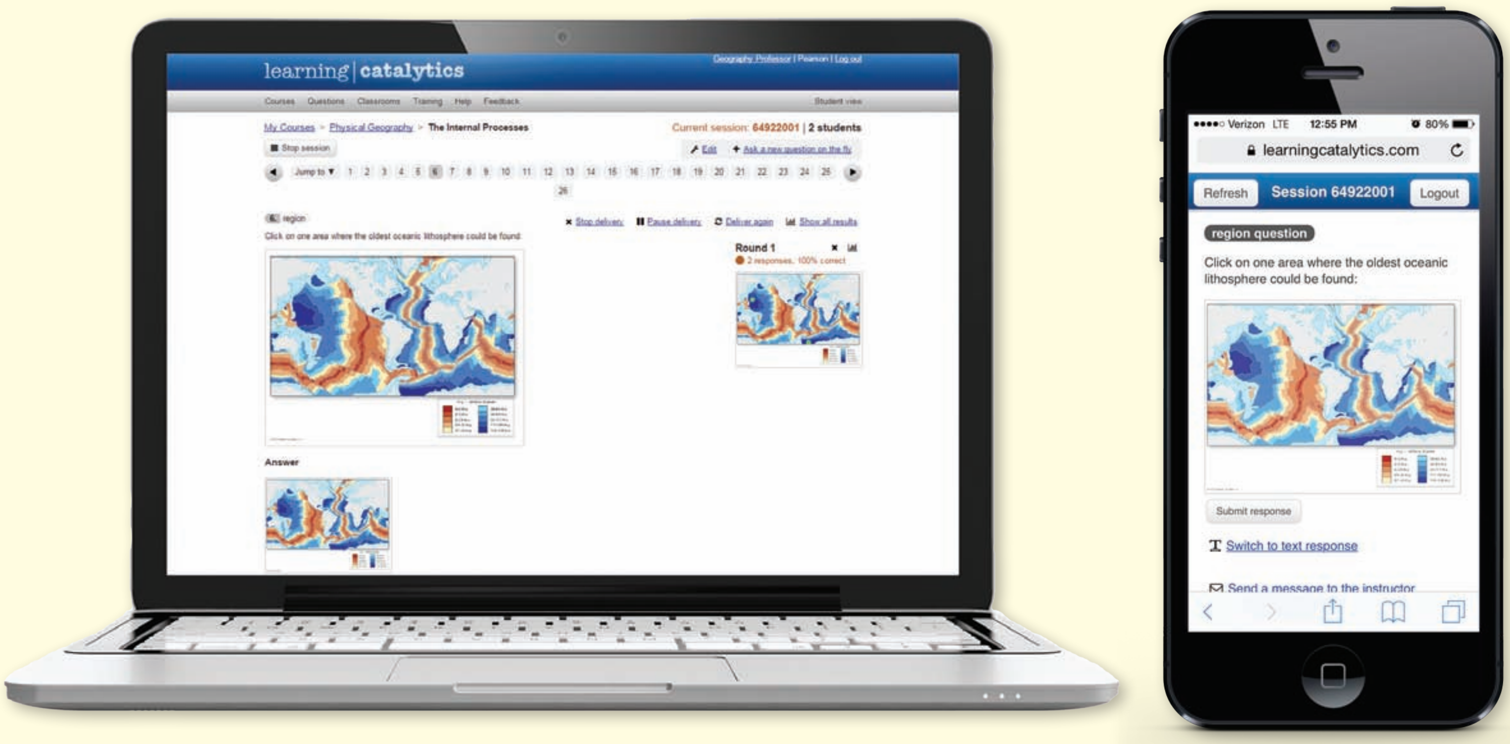
**NEW! *Reading Quiz Questions*** in MasteringGeography ensure that students complete the assigned reading before class and stay on track with reading assignments. Reading Quizzes are 100% mobile ready and can be completed by students on their mobile devices.

# DURING CLASS
# Learning Catalytics

*"My students are so busy and engaged answering Learning Catalytics questions during lecture that they don't have time for Facebook."* (Declan De Paor, Old Dominion University)

What has teachers and students excited? Learning Catalytics, a "bring your own device" student engagement, assessment, and classroom intelligence system, allows students to use their smartphone, tablet, or laptop to respond to questions in class. With Learning Catalytics, teachers can:

- Assess students in real-time using open-ended question formats to uncover student misconceptions and adjust lecture accordingly.
- Automatically create groups for peer instruction based on student response patterns to optimize discussion productivity.




## Enrich Lecture with Dynamic Media

Teachers can incorporate dynamic media into lecture, such as Geoscience Animations, Videos, and MapMaster Interactive Maps.

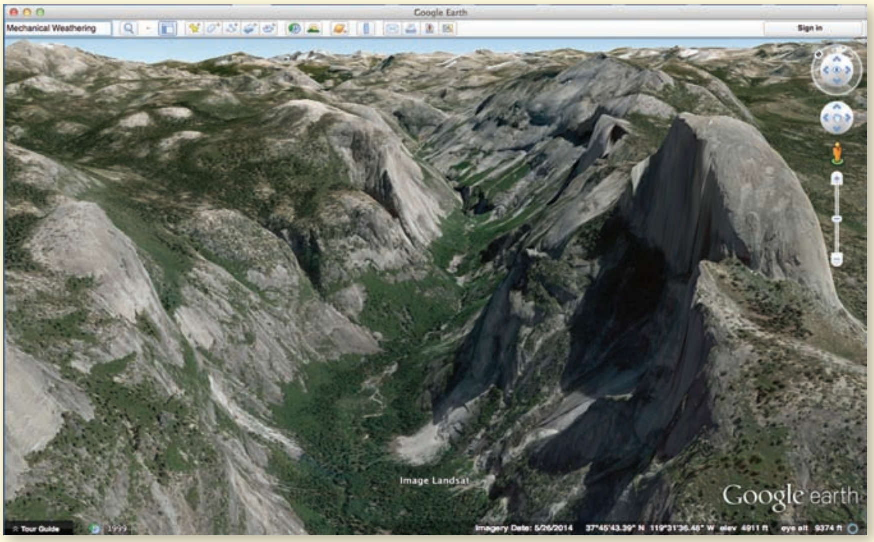
# MasteringGeography™

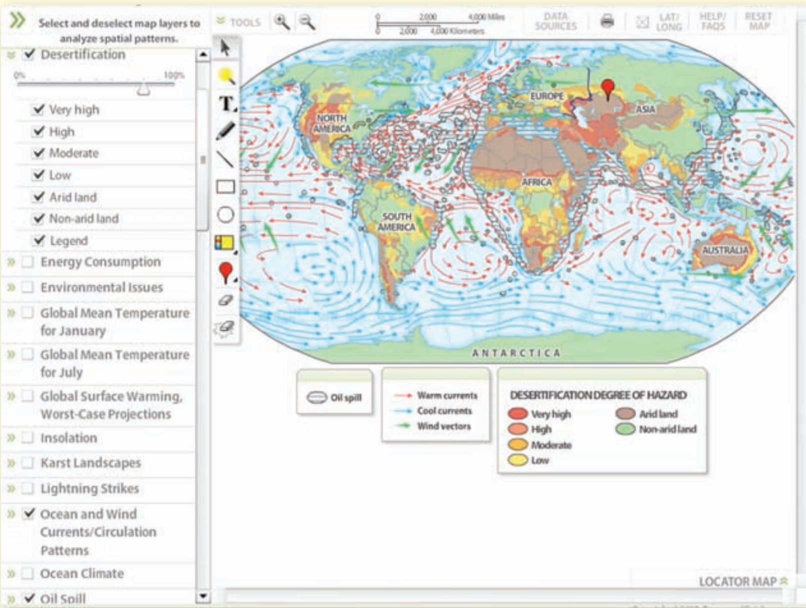
## AFTER CLASS

### Easy-to-Assign, Customizable, Media-Rich, and Automatically-Graded Assignments

The breadth and depth of media content available in MasteringGeography are unparalleled, allowing teachers to quickly and easily assign homework to reinforce key concepts.

► **Encounter Activities** provide rich, interactive Google Earth explorations of physical geography concepts to visualize and explore Earth's landscape and physical processes. Available with multiple-choice and short answer questions. All Explorations include corresponding Google Earth KMZ media files, and questions include hints and specific wrong-answer feedback to help coach students toward mastery of the concepts.



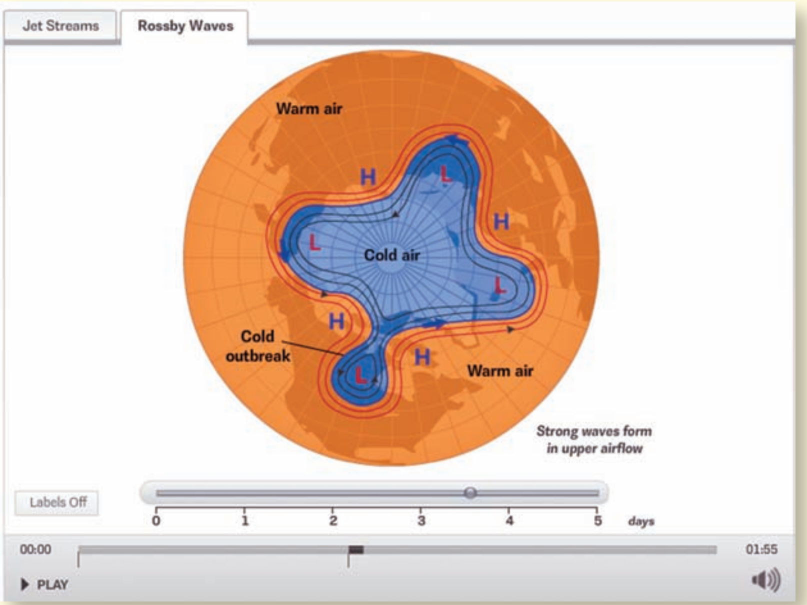

◄ **MapMaster Interactive Map Activities** are inspired by GIS, allowing students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. This tool includes zoom and annotation functionality, with hundreds of map layers leveraging recent data from sources such as NOAA, NASA, USGS, United Nations, and the CIA.

**Student Study Area Resources** in MasteringGeography include:

- Animations, Videos, MapMaster™ interactive maps
- Practice quizzes, Glossary flashcards
- "In the News" RSS feeds
- Optional Pearson eText and more

► **Geoscience Animations** help students visualize the most challenging physical processes in the physical geosciences with schematic animations that include audio narration.

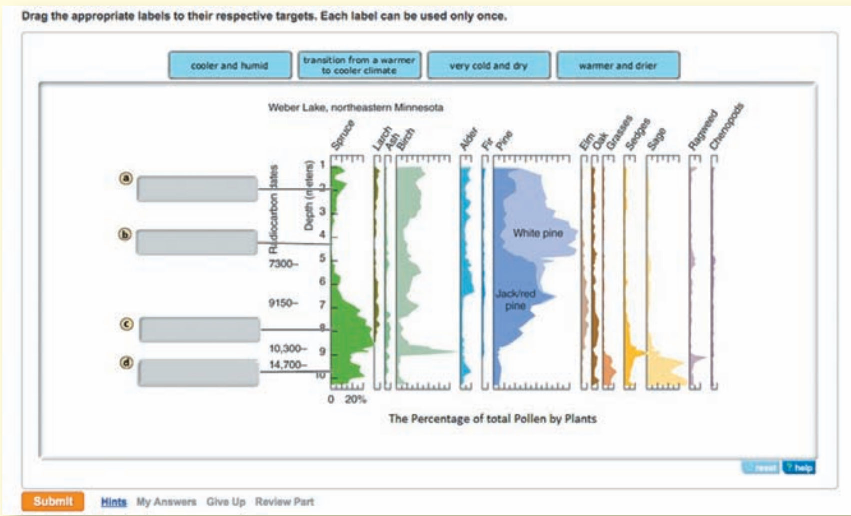
Animations include assignable multiple-choice quizzes with specific wrong-answer feedback to help guide students toward mastery of these core physical process concepts.

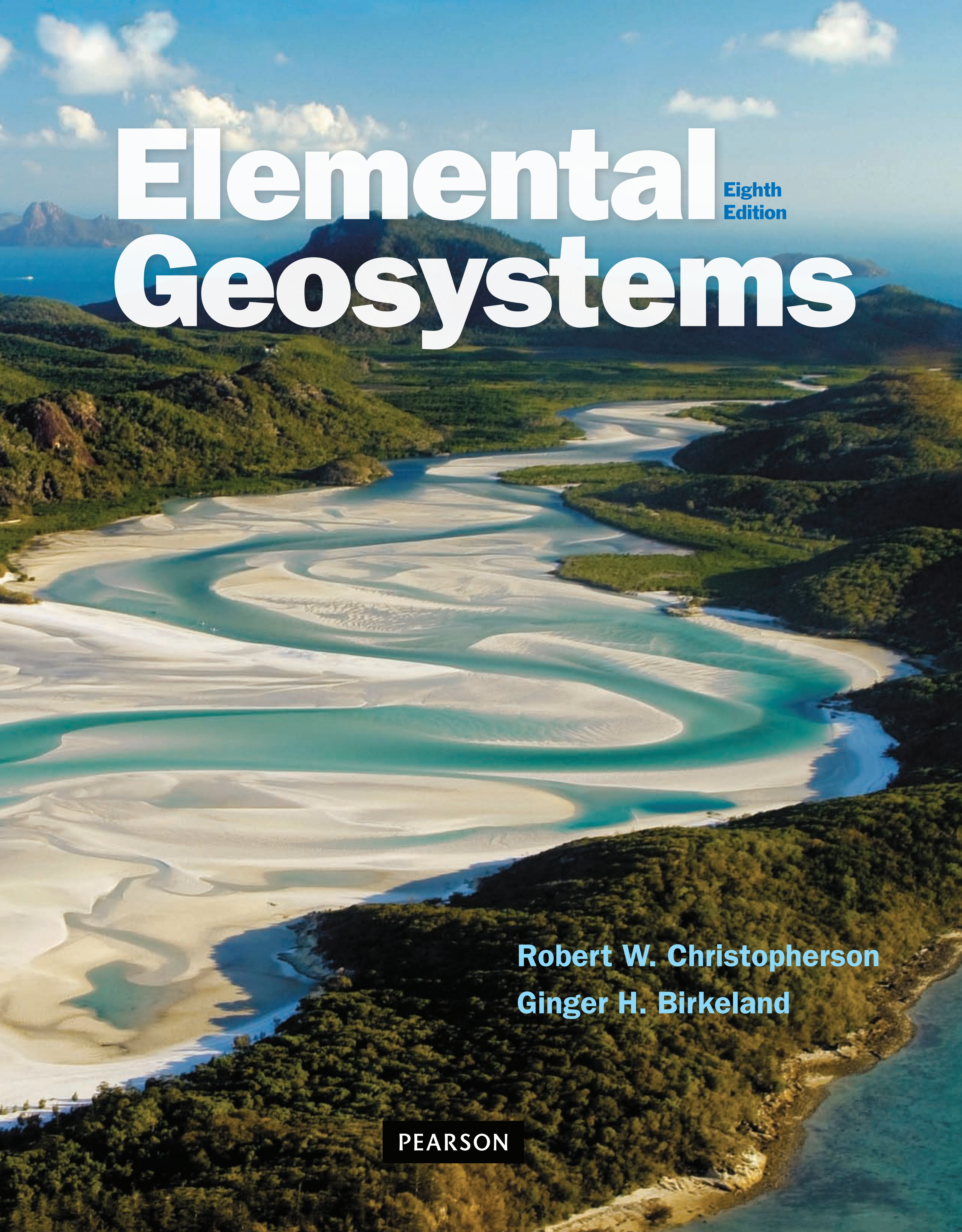




◄ **NEW! Videos** from such sources as the BBC and the *Financial Times* are now included in addition to the videos from Television for the Environment's *Life and Earth Report* series in MasteringGeography. These videos provide students with applied real-world examples of physical geography in action, a sense of place, and allow them to explore a range of locations and topics.

► **GeoTutor Coaching Activities** help students master the toughest physical geoscience concepts with highly visual, kinesthetic activities focused on critical thinking and application of core geoscience concepts.





# Elemental Geosystems

Eighth Edition

Robert W. Christopherson
Ginger H. Birkeland

PEARSON

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## dedication

To the students and teachers of Earth, and to all the children and grandchildren, for it is their future and home planet.

---

*The land still provides our genesis, however we might like to forget that our food comes from dank, muddy Earth, that the oxygen in our lungs was recently inside a leaf, and that every newspaper or book we may pick up is made from the hearts of trees that died for the sake of our imagined lives. What you hold in your hands right now, beneath these words, is consecrated air and time and sunlight.*

—Barbara Kingsolver

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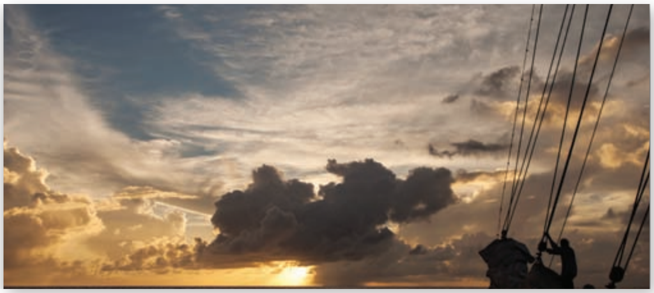

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# MasteringGeography™
# Mobile-Ready Animations & Videos

*Elemental Geosystems, 8th edition* includes Quick Response links to over 80 mobile-ready animations and videos, which students can access using mobile devices. These media are also available in the Study Area of MasteringGeography.

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**Geoscience Animation**
- Map Projections

## 2 Solar Energy, Seasons, and the Atmosphere

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# Preface

Welcome to the Eighth Edition of *Elemental Geosystems*. This edition marks the addition of Dr. Ginger Birkeland as a coauthor to Robert Christopherson. This Eighth Edition features significant revision, with a new chapter on climate change, new features, updated content, and many new photos and illustrations. We continue to build on the success of the first seven editions, as well as the companion texts, *Geosystems*, now in its ninth edition, and *Geosystems, Canadian Edition*, Third Edition. Students and teachers appreciate the systems organization, scientific accuracy, integration of figures and text, clarity of the summary and review sections, and overall relevancy to what is happening to Earth systems in real time. *Elemental Geosystems* continues to tell Earth's story in student-friendly language.

The goal of physical geography is to explain the spatial dimension of Earth's dynamic systems—its energy, air, water, weather, climate, tectonics, landforms, rocks, soils, plants, ecosystems, and biomes. Understanding human–Earth relations is part of physical geography as it seeks to understand and link the planet and its inhabitants. Welcome to physical geography!

## New to the Eighth Edition

Nearly every page of *Elemental Geosystems*, Eighth Edition, presents updated material, new content in text and figures, and new features. A sampling of new features includes:

- A **new chapter on climate change**. Although climate change science affects all systems and is discussed to some extent in every chapter of *Elemental Geosystems*, we now present a stand-alone chapter covering this topic—Chapter 8, Climate Change. This chapter covers paleoclimatology and mechanisms for past climatic change (expanding on topics covered in Chapter 13 in previous editions), climate feedbacks and the global carbon budget, the evidence and causes of present climate change, climate models and projections, and actions that we can take to moderate Earth's changing climate. This new Chapter 8 expands on the climate change discussion that was formerly part of Chapter 7, Climate Systems and Climate Change, in previous editions.
- A new ***Geosystems in Action*** feature focusing on key topics, processes, systems, or human–Earth connections. In every chapter, *Geosystems in Action* is a one- to two-page highly visual presentation of a topic central to the chapter, with active learning questions and links to media in *MasteringGeography*™, as well as a GeoQuiz to aid student learning. Throughout each part of the *Geosystems in Action* figure, students are asked to analyze, explain, infer, or predict based on the information presented. Topics include Earth–Sun Relations (Chapter 2), Earth–Atmosphere Energy Balance (Chapter 3), The Global Carbon Budget (Chapter 8), Glaciers as Dynamic Systems (Chapter 14), and Biological Activity in Soils (Chapter 15).
- A new feature, ***The Human Denominator***, linking chapter topics to human examples and applications. At the end of Chapters 2 through 17, this new feature includes maps, photos, graphs, and other diagrams to provide visual examples of many human–Earth interactions. This feature replaces and expands on the content of Chapter 17 in previous *Elemental Geosystems* editions, called Earth and the Human Denominator.
- **New and revised illustrations and maps** to improve student learning. More than 250 new photos and images bring real-world scenes into the classroom. Our photo and remote sensing program, updated for this edition, exceeds 500 items, integrated throughout the text.
- **New integrated mobile media**, where students use mobile devices to scan Quick Response (QR) codes throughout the book to view over 100 animations and videos.
- **Learning Catalytics**, a "bring your own device" student engagement, assessment, and classroom intelligence system, integrated with *MasteringGeography*™.

## Continuing in the Eighth Edition

- Fifteen *Focus Studies*, with either updated or new content, explore relevant applied topics in greater depth and are a popular feature of the *Elemental Geosystems* texts. In the Eighth Edition, these features are grouped by topic into five categories: Pollution, Climate Change, Natural Hazards, Sustainable Resources, and Environmental Restoration. Nine new Focus Study topics include:
    - Hurricanes Katrina and Sandy: Development, Effects, and Links to Climate Change (Chapter 5)
    - Global Climate Feedback Mechanisms (Chapter 8)
    - Earthquakes in Haiti, Chile, and Japan: A Comparative Analysis (Chapter 10)
    - Human-Caused Mass Movement at the Kingston Steam Plant, Tennessee (Chapter 11)
    - Stream Restoration: Merging Science and Practice (Chapter 12)
    - The 2011 Japan Tsunami (Chapter 13)
    - Thawing Methane Hydrates—Another Arctic Methane Concern (Chapter 14)

- Wildfire and Fire Ecology (Chapter 16)
- Global Conservation Strategies (Chapter 17)

- The chapter-opening *Geosystems Now* case study feature presents current issues in geography and Earth systems science. These original, unique applications, updated for the Eighth Edition, immediately draw readers into the chapter with relevant, real-world examples of physical geography. New *Geosystems Now* topics in the Eighth Edition include shale gas as an energy resource in the United States (Chapter 1), California's Santa Ana winds (Chapter 4), the Oso, Washington, landslide (Chapter 11), the effects of proposed dams on rivers in China (Chapter 12), and coastal erosion caused by Hurricane Sandy (Chapter 13). Many of these features emphasize linkages across chapters and Earth systems, exemplifying the *Elemental Geosystems* approach.
- *GeoReports* continue to describe timely and relevant events or facts related to the discussion in the chapter, provide student action items, and offer new sources of information. The 26 *GeoReports* in the Eighth Edition, placed along the bottom of pages, are updated, with many new to this edition. Example topics include:
    - Did light refraction sink the Titanic? (Chapter 3)
    - Satellite *GRACE* enables groundwater measurements (Chapter 6)
    - Tropical climate zones advance to higher latitudes (Chapter 7)
    - Surprise waves flood a cruise ship (Chapter 13)
    - Will species adapt to climate change? (Chapter 16)
    - Overgrazing effects on Argentina's grasslands (Chapter 17)
- *Critical Thinking* exercises are integrated throughout the chapters. These carefully crafted action items bridge students to the next level of learning, placing students in charge of further inquiry. Example topics include:
    - Applying Energy-Balance Principles to a Solar Cooker
    - What Causes the North Australian Monsoon?
    - Identify Two Kinds of Fog
    - Consider Your Carbon Footprint
    - Compare Two Mass-Movement Events
    - Tropical Forests: A Global or Local Resource?
- *Key Learning Concepts* appear at the outset of each chapter, many rewritten for clarity. Each chapter concludes with *Key Learning Concepts Review*, which summarizes the chapter using the opening objectives.
- *Elemental Geosystems* continues to embed Internet URLs within the text. More than 150 appear in this edition. These allow students to pursue topics of interest to greater depth, or to obtain the latest information about weather and climate, tectonic events, floods, and the myriad other subjects covered in the book.
- The *MasteringGeography*™ online homework and tutoring system delivers self-paced tutorials that provide individualized coaching, focus on course objectives, and are responsive to each student's progress. Instructors can assign activities built around Geoscience Animations, *Encounter* Google Earth™ activities, MapMaster™ interactive maps, *Thinking Spatially and Data Analysis* activities, new *GeoTutors* on the most challenging topics in the physical geosciences, end-of-chapter questions, Test Bank questions, and more. Students now have access to new *Dynamic Study Modules* that provide each student with a customized learning experience. Students also have access to a text-specific Study Area with study resources, including a Pearson eText version of *Elemental Geosystems*, Geoscience Animations, MapMaster™ interactive maps, new videos, additional content to support materials for the text, photo galleries, *In the News* readings, web links, career links, physical geography case studies, flashcard glossary, quizzes, and more—all at **www.masteringgeography.com**.

## Author Acknowledgments

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As you read this book, you will learn from more than 300 content-specific, beautiful photographs made by my wife, nature photographer Bobbé Christopherson. Her contribution to the success of the *Geosystems* texts is obvious. Please visit the photo galleries at *MasteringGeography*™ and learn more from her camera work. Bobbé is my expedition partner, colleague, wife, and best friend.

**From Ginger:** Many thanks to my husband, Karl Birkeland, for his ongoing patience, support, and inspiration throughout the many hours of work on this book. I also thank my daughters, Erika and Kelsey, for their sense of humor and understanding in enduring my frequent absences from family activities. The love, laughs, and lively discussions shared by our family help me see the world through their eyes and know that the future is bright. My gratitude also goes to the many river guides and scientists who taught me about rivers and the Grand Canyon and inspired my love of all things related to physical geography.

Most importantly, I offer special thanks to Robert Christopherson, who took a leap of faith to bring me on this *Geosystems* journey. I am honored to work with him, and I hope our raft runs smoothly and stays upright on the voyage ahead!

**From us both:** Physical geography teaches us a holistic view of the intricate supporting web that is Earth's environment and our place in it. Dramatic global change is under way in human–Earth relations as we alter physical, chemical, and biological systems. Our attention to climate change science and applied topics is in response to the impacts we are experiencing and the future we are shaping. All things considered, this is a critical time for you to be enrolled in a physical geography course! The best to you in your studies—and ***carpe diem!***

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# Digital & Print Resources

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***Television for the Environment Earth Report Geography Videos*, DVD** (0321662989). This three-DVD set helps students visualize how human decisions and behavior have affected the environment and how individuals are taking steps toward recovery. With topics ranging from the poor land management promoting the devastation of river systems in Central America to the struggles for electricity in China and Africa, these 13 videos from Television for the Environment's global *Earth Report* series recognize the efforts of individuals around the world to unite and protect the planet.

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***Teaching College Geography: A Practical Guide for Graduate Students and Early Career Faculty*** by Association of American Geographers (0136054471). This two-part resource provides a starting point for becoming an effective geography teacher from the very first day of class. Part One addresses "nuts-and-bolts" teaching issues. Part Two explores being an effective teacher in the field, supporting criticalthinking with GIS and mapping technologies, engaging learners in large geography classes, and promoting awareness of international perspectives and geographic issues.

***Aspiring Academics: A Resource Book for Graduate Students and Early Career Faculty*** by Association of American Geographers (0136048919). Drawing on several years of research, this set of essays is designed to help graduate students and early career faculty start their careers in geography and related social and environmental sciences. *Aspiring Academics* stresses the interdependence of teaching, research, and service—and the importance of achieving a healthy balance of professional and personal life—while doing faculty work. Each chapter provides accessible, forward-looking advice on topics that often cause the most stress in the first years of a college or university appointment.

## For Students

***Applied Physical Geography—Geosystems in the Laboratory*, Ninth Edition** by Charlie Thomsen and Robert Christopherson (0321987284). A variety of exercises provides flexibility in lab assignments. Each exercise includes key terms and learning concepts linked to *Geosystems*. The Ninth Edition includes new exercises on climate change, soils, and rock identification, a fully updated exercise on basic GIS using ArcGIS online, and more integrated media, including Google Earth™ and Quick Response (QR) codes linking to Pre-Lab videos. Supported by a website with media resources needed for exercises, as well as a downloadable Solutions Manual for teachers.

**Companion website for *Applied Physical Geography: Geosystems in the Laboratory*.** The website for the lab manual provides online worksheets as well as KMZ files for all of the Google Earth™ exercises found in the lab manual. www.mygeoscienceplace.com

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- *Encounter Physical Geography* by Jess C. Porter and Stephen O'Connell (0321672526)
- *Encounter World Regional Geography* by Jess C. Porter (0321681754)
- *Encounter Human Geography* by Jess C. Porter (0321682203)

***Dire Predictions: Understanding Global Climate Change* 2nd Edition** by Michael Mann, Lee R. Kump (0133909778). Periodic reports from the Intergovernmental Panel on Climate Change (IPCC) evaluate the risk of climate change brought on by humans. But the sheer volume of scientific data remains inscrutable to the general public, particularly to those who may still question the validity of climate change. In just over 200 pages, this practical text presents and expands upon the essential findings of the *IPCC's 5th Assessment Report* in a visually stunning and undeniably powerful way to the lay reader. Scientific findings that provide validity to the implications of climate change are presented in clear-cut graphic elements, striking images, and understandable analogies.

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***Instructor Resource DVD*** (0321992679). The *Instructor Resource DVD* provides a collection of resources to help teachers make efficient and effective use of their time. All digital resources can be found in one well-organized, easy-to-access place. The IRDVD includes:

- All textbook images as JPEGs, PDFs, and PowerPoint™ Presentations
- Pre-authored Lecture Outline PowerPoint® Presentations which outline the concepts of each chapter with embedded art and can be customized to fit teachers' lecture requirements
- CRS "Clicker" Questions in PowerPoint™
- The TestGen software, *Test Bank* questions, and answers for both Macs and PCs
- Electronic files of the *Instructor Resource Manual* and *Test Bank*

This *Instructor Resource* content is also available online via the Instructor Resources section of *MasteringGeography*™ and www.pearsonhighered.com/irc.

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# 1 Essentials of Geography

The Vista House observatory, built in 1918 as a rest stop for travelers and a memorial to the Oregon pioneers, sits on a dramatic promontory overlooking the Columbia River Gorge. Rivers serve as corridors of movement and transportation, physical and political boundaries, sites for recreation, and sources of hydropower. The ongoing interaction of humans with their environment is one of the essential themes in geographic science, discussed in Chapter 1. [Erik Harrison/Shutterstock.]

## KEYLEARNING**concepts**

*After reading the chapter, you should be able to:*

- *Define* geography in general and physical geography in particular.
- *Discuss* human activities and human population growth as they relate to geographic science and *summarize* the scientific process.
- *Describe* systems analysis, open and closed systems, and feedback information and *relate* these concepts to Earth systems.
- *Explain* Earth's reference grid: latitude and longitude and latitudinal geographic zones and time.
- *Define* cartography and mapping basics: map scale and map projections.
- *Describe* modern geoscience techniques—the Global Positioning System (GPS), remote sensing, and geographic information systems (GIS)—and *explain* how these tools are used in geographic analysis.

GEO**SYSTEMS**now

# Shale Gas: An Energy Resource for the Future?

In an area stretching 965 km (600 mi) from Ohio to western New York, methane lies deeply buried in a sedimentary rock deposit, the Marcellus Shale. Methane is the primary constituent of natural gas, and scientists suggest that this ancient rock layer, underlying 60% of Pennsylvania, may be one of the most significant reservoirs of natural gas in the world. Pennsylvania alone is dotted with nearly 6000 shale gas wells extracting pressurized methane (**Figure GN 1.1**).

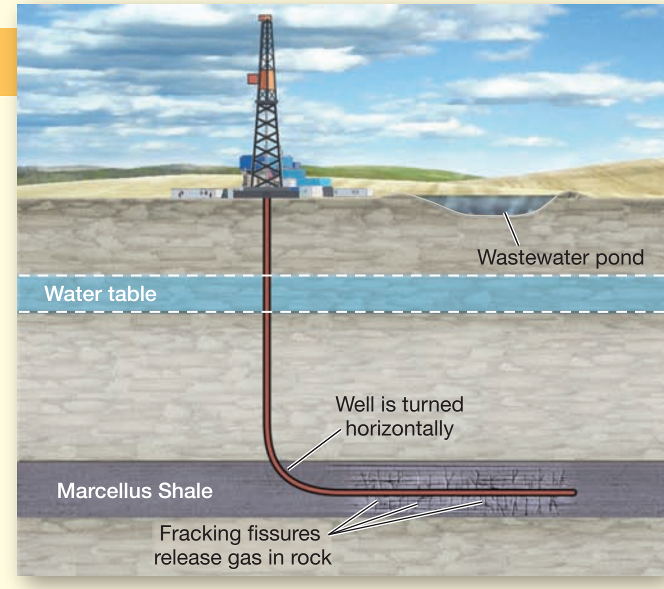
**Sources of Methane** Methane is a chemical compound with the formula $CH_4$ and is a by-product of several natural processes: digestive activity of animals (cattle, sheep, bison) and termites; burning associated with wildfires; melting of arctic permafrost; and bacterial activity in bogs, swamps, and wetlands. Nearly 60% of the methane in our atmosphere comes from human sources, including natural gas production, beef and dairy production, rice cultivation, coal and oil extraction and burning, landfills, and wastewater treatment. In the United States, the natural gas industry makes up the largest percentage of methane emissions.

**Drilling for Methane** To release methane trapped within shale layers, the rock must be broken up so that gas diffuses into the cracks and flows upward. Over the past 20 years, advances in horizontal drilling techniques, combined with the process of hydraulic fracturing, or "fracking," opened access to large amounts of natural gas previously deemed too expensive or difficult to tap. A typical shale gas well descends vertically 2.4 km (1.5 mi), turns, and then extends horizontally into the rock strata. Horizontal drilling exposes a greater area of the rock, allowing more of it to be broken up and more gas to be released (**Figure GN 1.2**).

A pressurized fluid is pumped into the well to break up the rock. This fluid is 90% water, 9% sand or glass beads that prop open the fissures, and 1% chemical additives that act as lubricants. The specific chemicals used are as yet undisclosed by the industry. This use of an injected fluid to fracture the shale is the process of fracking. Gas then flows up the well to be collected at the surface.

Fracking uses massive quantities of water: approximately 15 million L (4 million gal) for each well system, flowing at a rate of 16,000 L (4200 gal) per minute—far more than could be provided by a public water system. In some regions, such intensive water use for energy extraction may deplete natural water sources, affecting stream or lake ecosystems, or redirect water from other uses.

The U.S. Energy Information Administration (EIA) projects a boom in shale gas extraction and production from fracking over the next 20 years, with U.S. production rising from 34% of all natural gas production in 2011 to 50% in 2040.




▲**Figure GN 1.2 Horizontal drilling for hydraulic fracturing (fracking) and shale gas extraction.**

▼**Figure GN 1.1 Shale deposits and areas of exploration for natural gas extraction, United States and Canada.** [U.S. Energy Information Administration.]


**Environmental Effects** As with other resource-extraction techniques, fracking leaves hazardous by-products. It produces large amounts of toxic wastewater, often held in wells or containment ponds. Any leak or failure of pond retaining walls spills pollutants into surface water supplies and groundwater.

Methane gas may leak around well casings, which tend to crack during the fracking process. Leaks can cause buildup of methane in groundwater, leading to contaminated drinking water wells, flammable tap water, methane accumulation in barns and homes, and possible explosions.

Methane adds to air pollution as a constituent in smog and is a potent greenhouse gas, absorbing heat from the Sun near Earth's surface and contributing to global climate change. In addition, scientific evidence links the injection of fluid into wastewater wells to earthquake activity and ground instability in Oklahoma, Texas, Ohio, West Virginia, and parts of the Midwest.

This rapidly expanding energy resource has varied impacts on air, water, land, and living Earth systems. However, many of the environmental effects of shale gas extraction remain unknown; further scientific study is critical.

**Shale Gas and *Elemental Geosystems*** Resource location and distribution and human–environment interactions are important issues associated with shale gas extraction; these issues are also at the heart of geographic science. In this chapter, you work with several "Essentials of Geography": spatial concepts, the scientific process, human–Earth connections, Earth systems thinking, and mapping. Throughout *Elemental Geosystems*, we expand the story of shale gas and its potential effects on global climate, surface water and groundwater resources, earthquake hazards, and ecosystem functions.

**QUESTION AND EXPLORE** To work with an interactive diagram called "Breaking Fuel from the Rock," go to http://ngm.nationalgeographic.com/2012/12/methane/lavelle-text. For another perspective, go to http://www.energyfromshale.org/shale-extraction-process. Should the United States and other countries expand shale gas as an energy resource for the future? MG

Welcome to the Eighth Edition of *Elemental Geosystems* and the study of physical geography! In this text, we examine the powerful Earth systems that influence our lives and the many ways humans impact those systems. Physical geography involves the study of Earth's environments, including the systems that form the landscapes, seascapes, atmosphere, and ecosystems on which humans depend. In this second decade of the 21st century, our natural world is changing, and the scientific study of Earth and its environments is more crucial than ever.

Physical geography uses a spatial perspective to examine processes and events happening at specific locations and follow their effects across the globe.

Consider as examples the following events and the questions they raise for the study of Earth's systems and physical geography. This text provides tools for answering these questions and addressing the underlying issues.

- In October 2012, Hurricane Sandy made landfall along the U.S. East Coast, hitting New York and New Jersey at high tide with hurricane-force winds and record storm surges. The storm cost 110 human lives and over $42 billion in New York State alone, approaching $100 billion in damages overall. What atmospheric processes explain the formation and movement of this storm? Why the unprecedented size and intensity? How does this storm relate to record air and ocean temperatures?
- In March 2011, a magnitude 9.0 earthquake and resultant 10- to 20-m (33- to 66-ft) tsunami devastated Honshu Island, Japan—at US$309 billion, Earth's most expensive natural disaster so far. Why do earthquakes occur in particular locations across the globe? What produces tsunami, and how far and fast do they travel? How have prevailing winds and ocean currents dispersed tsunami debris across the Pacific?
- In 2014, the U.S. National Park Service finished the deconstruction of two dams on the Elwha River in Washington—the largest dam removals in the world to date. The project will restore a free-flowing river for fisheries and associated ecosystems. How do dams change river environments? Can rivers be restored after dam removal?
- In 2011, the world released 2.4 million pounds of carbon dioxide ($CO_2$) into the atmosphere every second, mainly from the burning of fossil fuels. This "greenhouse gas" contributes to climate change by trapping heat near Earth's surface. Each year atmospheric $CO_2$ levels rise to a new record, altering Earth's climate. What are the effects on Earth systems?

Physical geography uses a *spatial* perspective to examine processes and events happening at specific locations and follow their effects across the globe. Why does the environment vary from equator to midlatitudes and between tropical and polar regions? What produces the patterns of wind, weather, and ocean currents? How does solar energy influence the distribution of trees, soils, climates, and human populations? In this book, we explore those questions, and more, through geography's unique perspective.

Perhaps more than any other issue, climate change has become an overriding focus of the study of Earth systems. The past decade experienced the highest air temperatures over land and water in the instrumental record. In response, the extent of sea ice in the Arctic Ocean continues to decline to record lows. At the same time, melting of the Greenland and Antarctica Ice Sheets is accelerating; together, they now lose more than three times the ice they lost annually 20 years ago. As sea ice and ice sheets melt, sea level is rising. Elsewhere, intense weather events, drought, and flooding continue to increase. In presenting the state of the planet, *Elemental Geosystems* surveys climate change evidence and considers its implications. In every chapter, we present up-to-date science and information to help you understand our dynamic Earth systems. Welcome to an exploration of physical geography!

**In this chapter**: We begin with a look at the science of physical geography, which uses an integrative spatial approach, guided by the scientific process, to study Earth systems. The role of humans is an increasingly important focus of physical geography, as are questions of global sustainability as Earth's population grows.

Physical geographers study the environment by analyzing air, water, land, and living systems. Therefore, we discuss systems and the feedback mechanisms that influence system operations. We then consider location on Earth as determined by the coordinated grid system of latitude and longitude, and the determination of world time zones. Next, we examine maps as critical tools that geographers use to display physical and cultural information. This chapter concludes with an overview of technologies that are adding exciting new dimensions to geographic science: the Global Positioning System, remote sensing from space, and geographic information systems.

# The Science of Geography

Geographic science is concerned with much more than place names. **Geography** (from *geo*, "Earth," and *graphein*, "to write") is the science that studies the relationships among natural systems, geographic areas, and human society and culture, and the interdependence of all of these, *over space.* These last two words are key, for geography is a science that is in part defined by its method—a special way of analyzing phenomena over space. In geography, the term **spatial** refers to the nature and character of physical space, its measurement, and the distribution of things within it.

Geographic concepts pertain to distributions and movement across Earth and how these processes interact with human actions. Given this spatial perspective, the concerns of geographic science are traditionally divided into five themes: **location**, **region**, **human–Earth relationships**, **movement**, and **place**, each illustrated and defined in Figure 1.1. These themes provide a framework


▲**Figure 1.1 Five themes of geographic science.** Drawing from your own experience, can you think of examples of each theme? This satellite image shows New Zealand's South Island. [Photos by Karl Birkeland, except Movement by Ian Dagnall/Alamy. *Terra* MODIS image, NASA/GSFC.]

for understanding geographic concepts and asking geographic questions. How does solar energy influence the distribution of climates, soils, and living organisms in particular places and across regions? How do natural systems affect human populations, and, in turn, what impact are humans having on natural systems?

Although geography is not limited to place names, maps and location are central to the discipline and are important tools for conveying geographic data. Evolving technologies such as geographic information systems and the Global Positioning System are widely used for scientific applications and in today's society as hundreds of millions of people access maps and locational information every day on computers and mobile devices.

In response to increasing globalization and environmental change, the geography education guidelines—updated by the National Council for Geographic Education (NCGE)—have now redefined the essential elements (or themes) of geography, expanding their number to six: *the spatial world*, *places and regions*, *physical systems*, *human systems*, *environment and society*, and *uses of geography in today's society*. These categories emphasize the spatial and environmental perspectives within the discipline and reflect the growing importance of human–environment interactions.

## The Geographic Continuum

Because many subjects can be examined geographically, geography is an eclectic science that integrates subject matter from a wide range of disciplines. Even so, it splits broadly into two primary fields: *physical geography*, comprising specialty areas that draw largely on the physical and life sciences; and *human geography*, comprising specialty areas that draw largely on the social and cultural sciences (**Figure 1.2**). The growing complexity of the human–Earth relationship in the 21st century has shifted the study of geographic processes even farther toward the center of the continuum, resulting ultimately in a more balanced, more holistic perspective—such is the thrust of *Elemental Geosystems*.

Within physical geography, research now emphasizes human influences on natural systems in all specialty areas, effectively moving this end of the continuum closer to the middle. For example, physical geographers monitor air pollution, examine the vulnerability of human populations to climate change, study impacts of human activities on forest health and the movement of invasive species, study changes in river systems caused by dams and dam removal, and examine the response of glacial ice to changing climate.

## Geographic Analysis

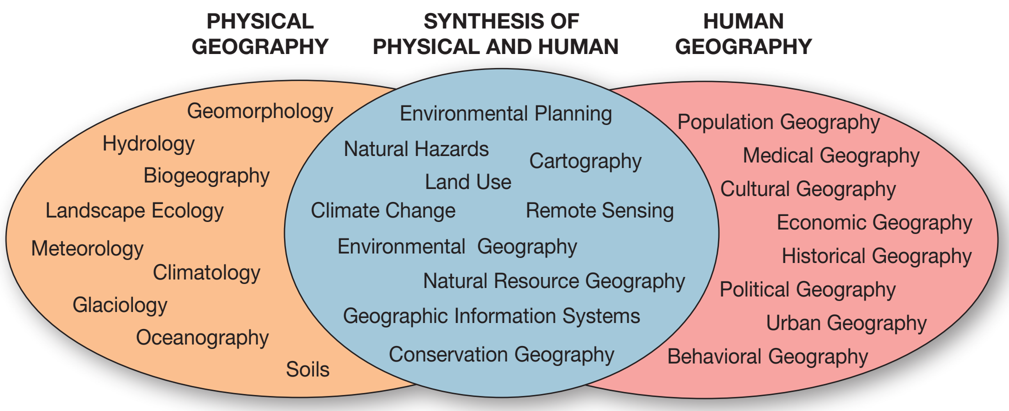
As mentioned earlier, the science of geography is unified more by its method than by a specific body of knowledge. The method is **spatial analysis**. Geographers view phenomena as occurring across spaces, areas, and locations. The language of geography—territory, zone, pattern, distribution, place, location, region, sphere, province, and distance—reflects this spatial view. Geographers analyze the differences and similarities between places.

**Process**, a set of actions or mechanisms that operate in some special order, is a central concept of geographic analysis. Among the examples you encounter in *Elemental Geosystems* are the numerous processes involved in Earth's vast water–atmosphere–weather system, in continental crust movements and earthquake occurrences, in ecosystem functions, and in river channel dynamics. Geographers use spatial analysis to examine how Earth's processes interact through space or over areas.

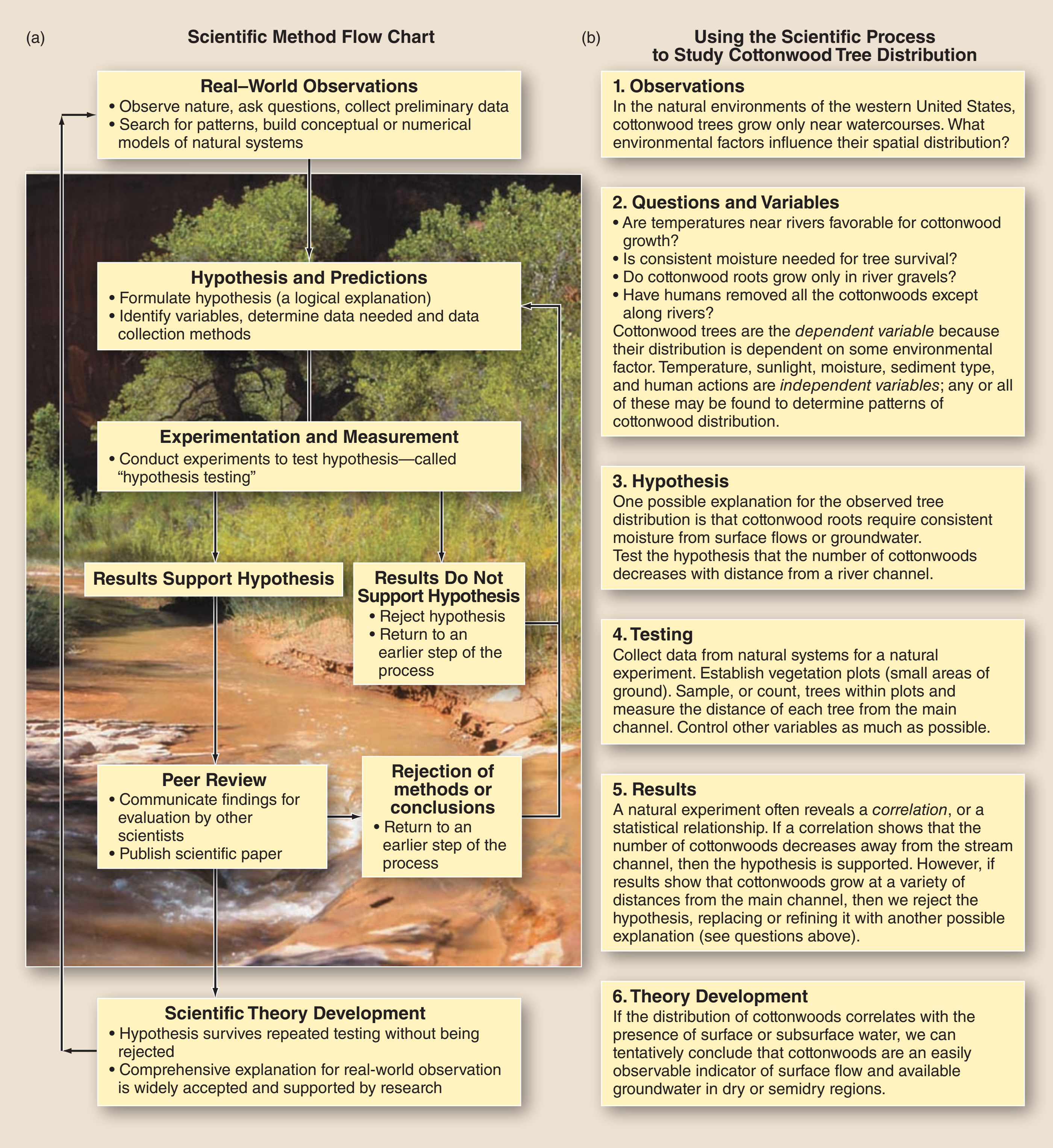
Therefore, **physical geography** is the spatial analysis of all the physical elements, processes, and systems that make up the environment: energy, air, water, weather, climate, landforms, soils, animals, plants, microorganisms, and Earth itself. Today, in addition to its place in the geographic continuum, physical geography encompasses the field of **Earth systems science**, the area of study that seeks to understand Earth as a complete entity, an interacting set of physical, chemical, and biological systems. With these definitions in mind, we now discuss the general process and methods used by scientists, including geographers.

## The Scientific Process

The process of science consists of observing, questioning, testing, and understanding elements of the natural world. The **scientific method** is the traditional recipe of a scientific investigation; it can be thought of as simple, organized steps leading toward concrete, objective conclusions (**Figure 1.3**). There is no single, definitive method for scientific




◀**Figure 1.2 The geographic continuum.** Geography combines Earth topics and human topics, blending ideas from many different sciences. This book focuses on physical geography, but integrates pertinent human and cultural content for a whole-Earth perspective.




▲**Figure 1.3 Scientific method flow chart and example application.** [Ginger Birkeland.]

inquiry; scientists in different fields and even in different subfields of physical geography may approach their scientific testing in different ways. However, the end result must be a conclusion that is reproducible by other scientists, and that can be tested repeatedly and possibly shown as true or as false. Without this characteristic, it is not science.

**Using the Scientific Method** Scientists who study the physical environment begin with the clues they see in nature, followed by an exploration of the relevant published scientific literature on their topic. Brainstorming with others, continued observation, and preliminary data collection may occur at this stage.

In the next step, scientists use questions and observations to identify variables, which are the conditions that change in an experiment or model. They often seek to reduce the number of variables when formulating a *hypothesis*—a tentative explanation for the phenomena observed. Since natural systems are complex, controlling or eliminating variables helps simplify research questions and predictions.

Scientists test hypotheses using experimental studies in laboratories or natural settings. The methods used for these studies must be reproducible so that repeat testing can occur. Results may support or disprove the hypothesis, or predictions made according to the hypothesis may prove accurate or inaccurate. If the results disprove the hypothesis, the researcher will need to adjust data-collection methods or refine the hypothesis statement. If the results support the hypothesis, repeated testing and verification may lead to its elevation to the status of a *theory*.

Reporting research results is also part of the scientific method. For scientific work to reach other scientists and eventually the public at large, it should be described in a scientific paper and published in one of the many scientific journals. When a scientist submits a paper to a scientific journal, that journal sends it out for *peer review*. During this critical process, other members of the scientific or professional community critique the methods and interpretation of results set out in the paper. This process also helps detect any personal or political bias on the part of the scientist. The reviewers may recommend rejecting the paper or accepting and revising it for publication. Once a number of papers are published with similar results and conclusions, the building of a theory begins.

A scientific *theory* is an explanation constructed on the basis of several extensively tested hypotheses and can be reevaluated or expanded according to new evidence. Thus, a scientific theory is not absolute truth; the possibility always exists that the theory could be proved wrong. However, theories can be expanded to represent truly broad general principles—unifying concepts that tie together the laws that govern nature. Examples include plate tectonics theory and the theory of evolution, discussed in Chapters 9 and 16. The value of a scientific theory is that it stimulates continued observation, testing, understanding, and pursuit of knowledge within scientific fields.

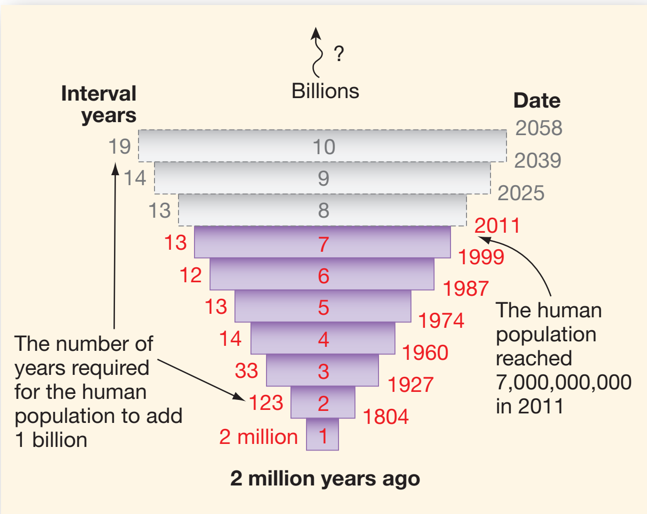
While the scientific method is of fundamental importance in guiding scientific investigation, the real process of science is more dynamic and less linear, leaving room for questioning and thinking "out of the box." Flexibility and creativity are essential to the scientific process, which may not always follow the same sequence of steps or use the same methods for each experiment or research project.

**Applying Scientific Results** Scientific studies described as "basic" are designed largely to help advance knowledge and build scientific theories. Other research is designed to produce "applied" results tied directly to real-world problem solving. Applied scientific research may advance new technologies, affect natural resource policy, or directly impact management strategies. Scientists share the results of both basic and applied research at conferences as well as in published papers, and they may take leadership roles in developing policy and planning. For example, the awareness that human activity is producing global climate change places increasing pressure on scientists to participate in decision making. Numerous editorials in scientific journals have called for such practical scientific involvement.

Science is objective by nature and does not make value judgments. Instead, pure science provides people and their institutions with objective information on which to base their own value judgments. Social and political judgments about the applications of science are increasingly important as Earth's natural systems respond to the impacts of modern civilization.

## Human–Earth Interactions in the 21st Century

Issues surrounding the growing influence of humans on Earth systems are central concerns of physical geography; we discuss them in every chapter of *Elemental Geosystems*. Human influence on Earth is now pervasive. The global human population passed 6 billion in August 1999 and continued to grow at the rate of 82 million per year, adding another billion by 2011, when the 7 billionth human was born. More people are alive today than at any previous moment in the planet's long history, unevenly distributed among 193 countries and numerous colonies. Virtually all new population growth is in the less-developed countries (LDCs), which now possess 81% (about 5.75 billion) of the total population. Over the span of human history, billion-mark milestones occurred at ever closer intervals through the sixth-billion milestone; the interval is now slightly increasing (**Figure 1.4**).




▲**Figure 1.4 Human population growth.** Note the population forecasts through 2058.

**The Human Denominator** We consider the totality of human impact on Earth to be the *human denominator*. Just as the denominator in a fraction tells how many parts a whole is divided into, so the growing human population and its increasing demand for resources and rising planetary impact suggest the stresses on the whole Earth system that must support us. Yet Earth's resource base—the numerator in this fraction—remains relatively fixed.

The population in just two countries makes up 37% of Earth's human count: 19.1% live in China and 17.9% in India—2.63 billion people combined. Considered overall, the planetary population is young, with some 26% still under the age of 15 years.*

Population in most of the more-developed countries (MDCs) is no longer increasing. In fact, some European countries are actually declining in growth or are near replacement levels. However, people in these developed countries have a greater impact on the planet per person and therefore constitute a population impact crisis. The United States and Canada, with about 5% of the world's population, produce about 25% ($16.2 trillion and $1.8 trillion in 2012, respectively) of the world's gross domestic product (GDP). These two countries use more than 2 times the energy per capita of Europeans, more than 7 times that of Latin Americans, 10 times that of Asians, and 20 times that of Africans. Therefore, the impact of this 5% on the state of Earth systems, natural resources, and sustainability of current practices in the MDCs is critical.

**Global Sustainability** Recently, **sustainability science** emerged as a new, integrative discipline, broadly based on concepts of sustainable development related to functioning Earth systems. Geographic concepts are fundamental to this new science, with its emphasis on human well-being, Earth systems, and human–environment interactions.

Dr. Carol Harden, past president of the Association of American Geographers, pointed out the important role of geographical concepts in sustainability science in 2009. She wrote that the idea of a human "footprint," representing the human impact on Earth systems, relates to sustainability and geography. When the human population of over 7 billion is taken into account, the human footprint on Earth is enormous in terms of both its spatial extent and the strength of its influence. Shrinking this footprint ties to sustainability science in all of its forms—for example, sustainable development, sustainable resources, sustainable energy, and sustainable agriculture. Geographers are now part of the effort to articulate this emerging field, which seeks to directly link science and technology with sustainability.

If we consider some of the key issues for this century, many of them fall beneath the umbrella of sustainability science, such as global food supply, energy supplies and demands, climate change, loss of biodiversity, and air and water pollution. These are issues that should be addressed in new ways if we are to achieve sustainability for both human and Earth systems. Understanding Earth's physical geography and geographic science informs your thinking on these issues.

*Data for 2013 from the Population Reference Bureau (**http://www.prb.org**) and the U.S. Census Bureau's *POPClock Projection* (**http://www.census.gov/popclock**).

# Earth Systems Concepts

The word *system* is in our lives daily: "Check the car's cooling system"; "A weather system is approaching." *Systems analysis* techniques in science began with studies of energy and temperature (thermodynamics) in the 19th century. Today, systems methodology is an important analytical tool. In this book's 4 parts and 17 chapters, the content is organized along logical flow paths consistent with systems thinking.

## Systems Theory

Simply stated, a **system** is any set of ordered, interrelated components and their attributes, linked by flows of energy and matter, as distinct from the surrounding environment outside the system. The elements within a system

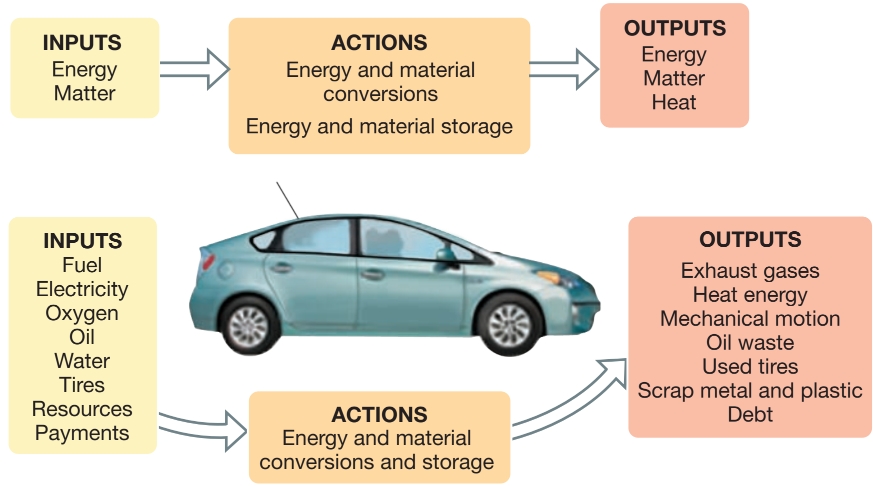
**CRITICALthinking 1.1**

**What Is Your Footprint?**

The concept of an individual's "footprint" has become popular—ecological footprint, carbon footprint, lifestyle footprint. The term has come to represent the costs of affluence and modern technology to our planetary systems. Footprint assessments are gross simplifications, but they can give you an idea of your impact and even an estimate of how many planets it would take to sustain that lifestyle and economy if everyone lived like you. Calculate your carbon footprint online at **http://www.epa.gov/climatechange/ghgemissions/ind-calculator.html**, one of many such websites, for housing, transportation, or food consumption. How can you reduce your footprint at home, at school, at work, or on the road? How does your footprint compare to the U.S. and worldwide average footprints?

**GEOreport 1.1** Welcome to the Anthropocene

The human population on Earth reached 7 billion in 2011. Many scientists now agree that the *Anthropocene*, a term coined by Nobel Prize–winning scientist Paul Crutzen, is an appropriate name for the most recent years of geologic history, when humans have influenced Earth's climate and ecosystems. Some scientists mark the beginning of agriculture, about 5000 years ago, as the start of the Anthropocene; others place the start at the dawn of the Industrial Revolution, in the 18th century. To see a video charting the growth of humans as a planetary force, go to **http://www.anthropocene.info**.




▲**Figure 1.5 An open system.** In an open system, inputs of energy and matter undergo conversions and are stored or released as the system operates. Outputs include energy, matter, and heat energy (waste). After considering how the various inputs and outputs listed here are related to the operation of the car, expand your thinking to the entire system of auto production, from raw materials to assembly to sales to car accidents to junkyards. Can you identify other open systems that you encounter in your daily life?

may be arranged in a series or intermingled. A system may comprise any number of subsystems. Within Earth's systems, both matter and energy are stored and retrieved, and energy is transformed from one type to another. (*Matter* is mass that assumes a physical shape and occupies space; *energy* is a capacity to change the motion of, or to do work on, matter.)

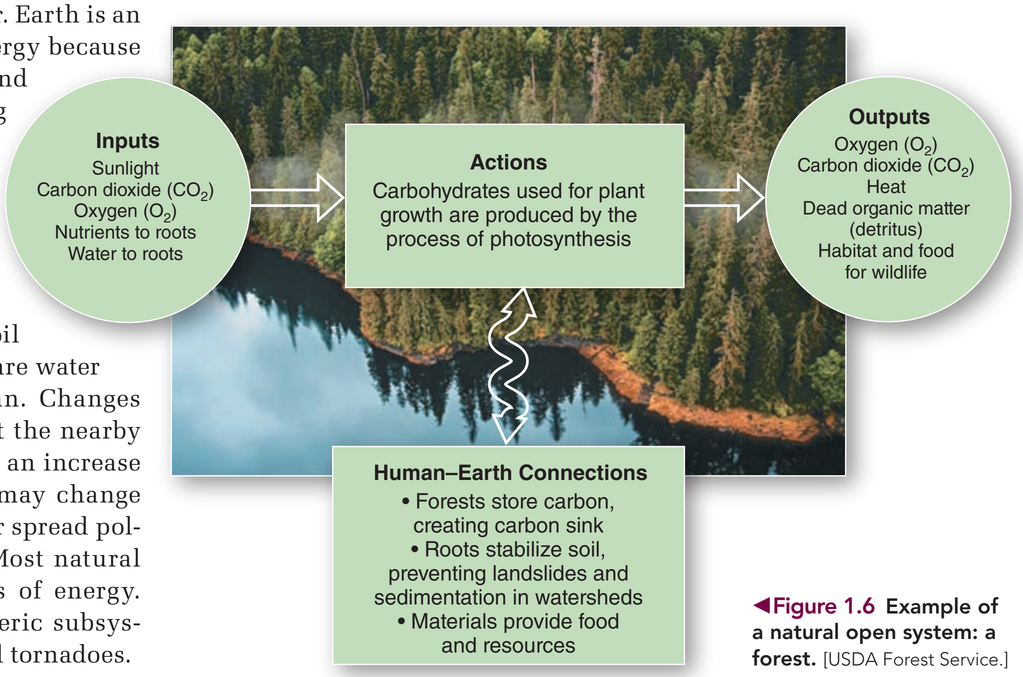
**Open Systems** Systems in nature are generally not self-contained: Inputs of energy and matter flow into the system, and outputs of energy and matter flow from the system. Such a system is an **open system** (Figure 1.5). Within a system, the parts function in an interrelated manner, acting together in a way that gives each system its operational character. Earth is an open system in terms of energy because solar energy enters freely and heat energy leaves, going back into space.

Within the Earth system, many subsystems are interconnected. Free-flowing rivers are open systems: Inputs consist of solar energy, precipitation, and soil and rock particles; outputs are water and sediments to the ocean. Changes to a river system may affect the nearby coastal system; for example, an increase in a river's sediment load may change the shape of a river mouth or spread pollutants along a coastline. Most natural systems are open in terms of energy. Examples of open atmospheric subsystems include hurricanes and tornadoes.

Earth systems are dynamic—active and energetic— because of the tremendous infusion of radiant energy from the Sun. As this energy passes through the outermost edge of Earth's atmosphere, it is transformed into various kinds of energy that power terrestrial systems, such as kinetic energy (of motion), potential energy (of position), and chemical or mechanical energy—setting the fluid atmosphere and ocean in motion. Eventually, Earth radiates this energy back to space as heat energy.

**Closed Systems** A system that is shut off from the surrounding environment so that it is self-contained is a **closed system**. Although such closed systems are rarely found in nature, Earth is essentially a closed system in terms of physical matter and resources—air, water, and material resources. The only exceptions are the slow escape of lightweight gases (such as hydrogen) from the atmosphere into space and the input of frequent, but tiny, meteors and cosmic dust. The fact that Earth is a closed material system makes recycling efforts inevitable if we want a sustainable global economy.

**Natural System Example** A forest is an example of an open system (Figure 1.6). Through the process of photosynthesis, trees and other plants use sunlight as an energy input and water, nutrients, and carbon dioxide as material inputs. The photosynthetic process converts these inputs to stored chemical energy in the form of plant

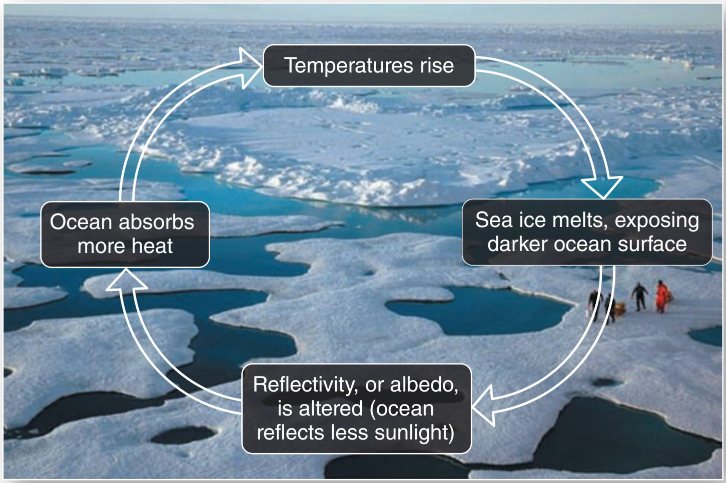



◀**Figure 1.6 Example of a natural open system: a forest.** [USDA Forest Service.]

sugars (carbohydrates). The process also releases an output from the forest system: the oxygen that we breathe.

Forest outputs also include products and activities that link to other broad-scale Earth systems. For example, forests store carbon and are thus referred to as "carbon sinks." A 2011 study found that forests absorb about one-third of the carbon dioxide released through the burning of fossil fuels, making them a critical part of the climate system as global carbon dioxide levels rise. Forest roots stabilize soil on hillslopes and stream banks, connecting them to land and water systems. Finally, the food and habitat resources provided by forests link them closely to other living systems, including humans. (Chapters 11, 16, and 17 discuss these processes and interactions.)

The connection of human activities to inputs, actions, and outputs of forest systems is indicated by the double-headed arrow in Figure 1.6. This interaction has two causal directions, since forest processes affect humans and humans influence forests. Forests affect humans through the outputs of carbon storage (which mitigates climate change), soil stabilization (which prevents erosion and sedimentation into source areas for drinking water), and food and resources. Human influences on forests include direct impacts such as logging for wood resources, burning to make way for agriculture, and clearing for development as well as indirect impacts from human-caused climate change, which may enhance the spread of disease and insects, and pollution, which affects tree health.




▲**Figure 1.7 The Arctic sea ice–albedo positive feedback loop.** Average ice thickness in the Arctic summer has dropped dramatically, leaving thinner ice that melts more easily. Since 2000, 70% of the September ice volume has disappeared. If this rate of loss continues, the first ice-free Arctic September might happen before 2017. [NOAA.]

**System Feedback** As a system operates, it generates outputs that influence its own operations. These outputs function as "information" that returns to various points in the system via pathways called **feedback loops**. Feedback information can guide, and sometimes control, further system operations.

If the feedback information discourages change in the system, it is **negative feedback**. Further production of such feedback opposes system changes and leads to stability. Such negative feedback causes self-regulation in a natural system. Negative feedback loops are common in nature. In a forest, for example, healthy trees produce roots that stabilize hillslopes and inhibit erosion, providing a negative feedback. If the forest is damaged or removed, perhaps by fire or logging practices, the hillslope may become unstable and subject to landslides or mudslides. This instability affects nearby systems as sediment is deposited into streams, along coastlines, or into developed areas.

If feedback information encourages change in the system, it is **positive feedback**. Further production of positive feedback stimulates system changes. Unchecked positive feedback in a system can create a runaway ("snowballing") condition. In natural systems, such unchecked system changes can reach a critical limit, leading to instability, disruption, or death of organisms.

Global climate change creates an example of positive feedback as summer sea ice melts in the Arctic (discussed in Chapters 3, 8, and 14). As arctic temperatures rise, summer sea ice and glacial melting accelerate. This causes light-colored snow and sea-ice surfaces, which reflect sunlight and so remain cooler, to be replaced by darker-colored open ocean surfaces, which absorb sunlight and become warmer. As a result, the ocean absorbs more solar energy, which raises the temperature, which, in turn, melts more ice, and so forth (**Figure 1.7**). This is a positive feedback loop, further enhancing the effects of higher temperatures and warming trends.

**System Equilibrium** Most systems maintain structure and character over time. An energy and material system that remains balanced over time, in which conditions are constant or recur, is in a *steady-state condition.* When the rates of inputs and outputs in the system are equal and the amounts of energy and matter in storage within the system are constant (or, more realistically, fluctuate around a stable average), the system is in **steady-state equilibrium**. For example, river channels commonly adjust their form in response to inputs of water and sediment; these inputs may change in amount from year to year, but the channel form represents a stable average—a steady-state condition.

However, a steady-state system may demonstrate a changing trend over time, a condition described as **dynamic equilibrium**. These changing trends may appear gradually and are compensated for by the system. A river may tend toward channel widening as it adjusts to greater inputs of sediment over some time scale, but the overall system will adjust to this new condition and thus maintain a dynamic equilibrium. **Figure 1.8** illustrates the steady-state and dynamic equilibrium conditions.

Note that systems in equilibrium tend to maintain their functional operations and resist abrupt change.