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Earth Science, Twelfth Edition, consists of seven units that emphasize broad and up-to-date coverage of basic topics and principles in geology, oceanography, meteorology, and astronomy. The book is intended to be a meaningful, non-technical survey for students with little background in science. In addition to being informative and up-to-date, a major goal of Earth Science is to meet the need of beginning students for a readable and user-friendly text, a book that is a highly usable "tool" for learning basic Earth science principles and concepts.

Distinguishing Features

Readability

The language of this book is straightforward and written to be understood. Clear, readable discussions with a minimum of technical language are the rule. Frequent headings and subheadings help students follow discussions and identify the important ideas presented in each chapter. In the twelfth edition, improved readability was achieved by examining chapter organization and flow, and writing in a more personal style. Large portions of the text were substantially rewritten in an effort to make the material more understandable.

Focus on Learning

When a chapter has been completed, several useful devices help students review. First, the Chapter Summary recapitulates all of the major points. Next is a checklist of Key Terms with page references. Learning the language of Earth science helps students learn the material. This is followed by a series of Review Questions that help students examine their knowledge of significant facts and ideas. Next is a reminder for students to visit the Website for Earth Science, Twelfth Edition. It contains many excellent opportunities for review and exploration. Finally, each chapter closes with two frames from the GEODe: Earth Science DVD to remind students about this unique and interactive learning aid.

New GEODe: Earth Science, Version 3

The new version of the text's student-friendly GEODe: Earth Science included with each book is an even better and more complete learning tool than before. It reinforces key concepts using interactive exercises, animations, and practice quizzes. This dynamic, easy-to-use aid is now a DVD that has significantly broader coverage than previous versions. The GEODe: Earth Science table of contents (see pp. vii-viii) highlights these additions and changes. We continue to use a special icon that appears throughout the book whenever a test discussion has a corresponding GEODe: Earth Science activity.

Illustrations and Photographs
The Earth sciences are highly visual. Therefore, photographs and artwork are a very important part of an introductory book. Earth Science, Twelfth Edition, contains dozens of new high-quality photographs that were carefully selected to aid understanding, add realism, and heighten the interest of the reader.

There has been substantial revision and improvement of the text program. Cleaner, easier-to-understand line drawings show greater color and shading contrasts. We also added more figures that combine the use of diagrams and photos. Moreover, many new art pieces have additional labels that "narrate" the process being illustrated and/or "guide" readers as they examine the image. The result is an art program that illustrates ideas and concepts more clearly than ever before. As in previous editions, we are grateful to Dennis Tasa, a gifted artist and respected Earth science illustrator, for his outstanding work.

Focus on Basic Principles and Instructor Flexibility

Although many topical issues are treated in Earth Science, Twelfth Edition, it should be emphasized that the main focus of the book is on the major principles that recur throughout the text. The five major units stand alone; hence, they can be taught in any order the instructor deems appropriate. There has been significant revision and improvement of the book since its first edition. As in previous editions, we are grateful to Dennis Tasa, an accomplished artist and respected Earth science illustrator, for his outstanding work.

Three Important Themes

Chapter 1, "Introduction to Earth Science," presents students with three important themes that recur throughout the book: Earth as a System, People and the Environment, and Understanding Earth.
Earth as a System

An important occurrence in modern science has been the realization that Earth is a giant multidimensional system. Our planet consists of many separate but interacting parts. A change in any one part can produce changes in any or all of the other parts—often in ways that are neither obvious nor immediately apparent. Although it is not possible to study the entire system at once, it is possible to develop an awareness and appreciation for the concept and for many of the system's important interrelationships. Therefore, starting with the revised discussion of "Earth System Science" in Chapter 1, the theme of "Earth as a System" keeps recurring through all major units of the book. It is a thread that "weaves" through the chapters and helps tie them together.

Highlights of the Twelfth Edition

The twelfth edition of Earth Science represents a thorough revision. Every part of the book was examined carefully with the dual goals of keeping topics current and improving the clarity of text discussions. People familiar with preceding editions will see much that is new in the twelfth edition. The list of specifics is long. Examples include the following:

- Much of Chapter 2, "Minerals: Building Blocks of Rocks," is new, including a revamped introductory overview and a revised and expanded discussion of mineral properties.
- There is much that is new in each chapter that focuses on external processes, Chapter 4 (Box 4.2) on the landside hazards at La Conchita, California, Chapter 5 includes new material on infiltration capacity and sediment transport as well as a new case study (Box 5.1), "Coastal Wetlands are Vanishing on the Mississippi Delta." Chapter 6 contains new material on glacial Lake Missoula and Washington's Channelled Scablands.
- Chapter 8, "Earthquakes and Earth's Interior," includes an all-new examination of tsunamis. There is also a revised discussion of Earth's interior that more clearly explains how geologists probe the crust, mantle, and core.
- The section on the nature of volcanic eruptions in Chapter 10 more clearly explains eruptive mechanisms and how they do the way they do. The chapter also includes revised discussions of cinder cones and calderas.
- Chapter 12, "Earth's Evolution through Geologic Time" (formerly "Earth History: A Brief Summary"), is completely revised and rewritten. The chapter presents a clear, concise summary of Earth history that begins with an engaging introduction titled, "Is Earth Unique?" The chapter includes easy-to-follow discussions on the origin and early evolution of the planet and on the origin of continents, the atmosphere, and oceans. To allow maximum instructor flexibility, there are separate discussions of Earth's physical history and the evolution of life through geologic time.
- Unit 5, "The Global Ocean," has been thoroughly updated with the assistance of Professor Al Trujillo of Palomar College. Changes include revised discussions and new art dealing with ocean circulation, the behavior of waves, and rip currents. There is also a new special interest box on reggae waves.
- Chapter 19, "Weather Patterns and Severe Storms," has a revised discussion of tornadoes that includes updated statistics, the newly revised intensity scale, and a new box that focuses on "Surviving a Violent Tornado." The chapter also has expanded treatment of hurricanes that includes examples and images from the devastating and record-breaking 2004 and 2005 hurricane seasons.
- Chapter 20 (formerly "Climate") has a new title, "World Climates and Global Climate Change." The chapter begins with a new introduction that is followed by a strengthened presentation on climate classification and the distribution and characteristics of Earth's major climate groups. The second half of the chapter examines one of the most serious environmental issues facing humankind—global climate change. This discussion provides an excellent opportunity to explore human impact on the climate system and many interrelationships in the Earth system. It includes up-to-date information and analysis from the 2007 reports by the Intergovernmental Panel on Climate Change.
- All four chapters comprising Unit 7, Earth's Place in the Universe, have been revised, updated, and substantially rewritten with the assistance of Mark Wasyly and Teresa Trubick of Spring Hill College. This is the most complete revision of this unit ever. The subject matter is better organized and more up-to-date. Discussions progress in a manner that is easier to follow for the beginning student. Readers get an engaging perspective on the historical development of astronomy (Chapter 21) and a factual, up-to-date tour of the solar system (Chapter 22). They also learn about telescopes and are introduced to modern methods of observing the universe such as orbiting observatories (Chapter 23). The unit concludes with a clear presentation on stellar evolution and the origin of the universe (Chapter 24).

Additional Highlights

- "Students Sometimes Ask..." This popular feature has been retained and improved in the twelfth edition. Instructors and students continue to react favorably and indicated that the questions and answers that are sprinkled throughout each chapter add interest and relevance to discussions in Earth Science.
- Although there is not a significant change in the number of special interest boxes, several are totally new or substantially revised. As in the previous edition, most are intended to illustrate and reinforce the three themes of "Earth as a System," "People and the Environment," and "Understanding Earth."

The Teaching and Learning Package

The challenge is fundamental and too often overlooked in what seems to have become a weapons race of resources supplemental to the text: instructors need more time, students need more preparation. With this in mind, Pearson/Prentice Hall has produced for this edition perhaps the best set of instructor and student resources ever assembled to support an introductory Earth science textbook. Not only are they of the highest quality, they are the most useful. Please see pages xvii-xlix of this Preface for detailed description.

Acknowledgments

Writing a college textbook requires the talents and cooperation of many individuals. We value the excellent work of Mark Wasyly and Teresa Trubick of Spring Hill College. They helped to make Unit 7, "Earth's Place in the Universe," a more readable, engaging, and up-to-date introduction to astronomy. We also appreciate the aid of Alan Trujillo of Palomar College. His contributions to the cosmography unit and to the "Students Sometimes Ask..." feature remain an important part of Earth Science.

Working with Dennis Tsai, who is responsible for all of the outstanding illustrations and much of the developmental work on GEOEd: Earth Science, is always special for us. We not only value his outstanding artistic talents and imagination but his friendship. We are also grateful to Ken Pardeke at southwestern Illinois College for his important work on the text's laboratory manual, Applications and Investigations in Earth Science. Ken is an important part of our team and a valued friend as well.

Special thanks go to those colleagues who prepared in-depth reviews. Their critical comments and thoughtful input helped guide our work and clearly strengthened the text. We wish to thank:

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Edward J. Tarbuck
Frederick K. Kutzeng
The Teaching and Learning Package

Prentice Hall continues to improve the instructor resources in this edition with the goal of saving your time in preparing for your lecture needs.

Instructor's Resource Center (IRC) on DVD
The IRC puts all your lecture resources in one easy-to-reach place:
- Three PowerPoint® presentations for each chapter
- 101 animations of Earth processes
- All of the line art, tables, and photos from the text in .jpg files
- Images of Earth photo gallery
- Instructor’s Manual in Microsoft Word
- Test Item File in Microsoft Word
- TestGen test generation and management software

PowerPoints®
Found on the IRC are three PowerPoint files for each chapter. Cut down on your preparation time, no matter what your lecture needs.

1. Art and Animations—All of the line art, tables, and photos from the text, along with the animation library, pre-loaded into PowerPoint slides for easy integration into your presentation.
2. Lecture Outline—Authored by Stanley Hatfield of Southwestern Illinois College, this set averages 35 slides per chapter and includes customizable lecture outlines with supporting art.
3. Classroom Response System (CRS) Questions—Authored for use in conjunction with any of the new classroom response systems. These systems allow you to electronically poll your class for responses to questions, pop quizzes, attendance, and more.

Animations
The Prentice Hall Geoscience Animations Library includes over 100 animations illustrating the most difficult-to-visualize topics of Earth science. Created through a unique collaboration among five of the Prentice Hall’s leading geoscience authors, these animations represent a significant leap forward in lecture presentation aids. They are provided both as Flash files and, for your convenience, pre-loaded into PowerPoint slides.

"Images of Earth" Photo Gallery
Supplement your personal and test-specific slides with this amazing collection of over 300 geologic photos contributed by Marli Miller (University of Oregon) and other professionals in the field. The photos are available on the IRC on DVD.

Transparencies
Simply put: Every Dennis Tasa Illustration in Earth Science, Twelfth Edition is available as a full-color, projection enhanced transparency—175 in all. (Are illustrations central to your lecture? Check out the Student Lecture Notebook.)

Instructor's Manual with Tests
Authored by Stanley Hatfield (Southwestern Illinois College), the Instructor’s Manual contains: learning objectives, chapter outlines, answers to end-of-chapter questions and suggested, short demonstrations to spice up your lecture. The Test Item File incorporates art and averages 75 multiple-choice, true/false, short answer and critical thinking questions per chapter.

TestGen
Use this electronic version of the Test Item File to customize and manage your tests. Create multiple versions, add or edit questions, add illustrations—your customization needs are easily addressed by this powerful software.

Course Management
Prentice Hall offers instructor and student media for the 12th edition of Earth Science in formats compatible with your Blackboard and WebCT platforms. Contact your local sales representative for more information.

For the Laboratory
Applications and Investigations in Earth Science, sixth edition. Written by Ed Tarbuck, Fred Leutgens, and Ken Pinzke, this full-color laboratory manual contains 23 exercises that provide students with hands-on experience in geology, oceanography, meteorology, astronomy, and Earth science skills. The lab manual is available at a discount when purchased with the text; please contact your local Prentice Hall representative for more details.

Student Resources
The student resources to accompany Earth Science, Twelfth Edition have been further refined with the goal of focusing the students' efforts and improving their understanding of Earth science concepts.

GEODe: Earth Science
Somewhere between a text and a tutor GEODe: Earth Science version 3 DVD, included with your book, employs the unique capabilities of the computer to illuminate key concepts in Earth science. Animations, videos, photographs, text, narration, and interactive exercises are presented in a tutorial format. Do you learn better by doing? Exercises throughout the DVD get you interacting instead of just memorizing. Does your lab not always parallel your lecture? A quick review of the relevant module will help you prepare you for the lab, whether or not you have covered the topic in lecture. Look for the GEODe: Earth Science icon throughout the text. The DVD is plug-and-play—no special software or installation is necessary—so it's perfect for use in your school's computer lab (though you should probably use headphones).

Study Guide
Written by experienced educators Stanley Hatfield and Ken Pinzke (Southwestern Illinois College), the Study Guide helps students identify the important points from the text, and then provides them with review exercises, study questions, self-check exercises, and vocabulary review.

Companion Website
www.pearsonhighered.com/tarbuck Authored by Molly Bell, the Companion Website contains numerous chapter review exercises (from which students get immediate feedback). Links to other resources are also included for further study. Professors can utilize the GradeTracker to assess student progress.

Student Lecture Notebook
Illustrations are tools—use them. Illustrations are critical to understanding Earth science. They are a centerpiece of your textbook and, most likely, your instructor's lecture. In the Student Lecture Notebook you'll find all the art from the text, reproduced with space for you to take notes. In fact, you may find that these illustrations are exactly the ones you will see in class. Using the Student Lecture Notebook means more focused and more rapid note-taking, less writing in your textbook, and less to carry to class. The Student Lecture Notebook is available through your bookstore.
the number of cleavage directions and the angel(s) at which they meet (Figure 2.15).

Each cleavage surface that has a different orientation is counted as a different direction of cleavage. For example, mica, a common rock-forming mineral, exhibits cleavage, it will break into pieces that all have the same geometry. By contrast, the smooth-surfaced quartz crystals shown in Figure 2.15 (p. 30) do not have cleavage. If broken, they fracture into shapes that do not resemble one another or the original crystals.

Fracture Minerals having chemical bonds that are equally or nearly equally, strong in all directions exhibit a property called fracture. When minerals fracture, most produce uneven surfaces and are described as exhibiting irregular fracture. However, some minerals, such as quartz, break into smooth, curved surfaces resembling broken glass. Such breaks are called conchoidal fractures (Figure 2.16). Still other minerals exhibit fractures that produce splinters or fibers that are referred to as splintery and fibrous fracture, respectively.

Density and Specific Gravity
Density is an important property of matter defined as mass per unit volume usually expressed as grams per cubic centimeter. Mineralogists often use a related measure called specific gravity to describe the density of minerals. Specific gravity is a unitless number representing the ratio of a mineral’s weight to the weight of an equal volume of water.

Most common rock-forming minerals have a specific gravity between 2 and 3. For example, quartz has a specific gravity of 2.65. By contrast, some metallic minerals such as pyrite, native copper, and magnetite are more than twice as dense as quartz. Galena, which is an ore of lead, has a specific gravity of roughly 7.5, whereas the specific gravity of 24-karat gold is approximately 20.

With a little practice, you can estimate the specific gravity of a mineral by hefting it in your hand. Ask yourself, does this mineral feel about as “heavy” as similar sized rocks you have handled? If the answer is “yes,” the specific gravity of the sample will likely be between 2.5 and 3.
residual clay minerals. However, even the highly insoluble clay minerals are very slowly removed by subsurface water.

**Spheroidal Weathering**

In addition to altering the internal structure of minerals, chemical weathering causes physical changes as well. For instance, when angular rock masses are chemically weathered as water enters along joints, they tend to take on a spherical shape. Gradually the corners and edges of the angular blocks become more rounded. The corners are attacked most readily because of their greater surface area, as compared to the edges and faces. This process, called spheroidal weathering, gives the weathered rock a more rounded or spherical shape (Figure 4.8A).

Sometimes during the formation of spheroidal boulders, successive shells separate from the rock's main body (Figure 4.8B). Eventually the outer shells spall off, allowing the chemical weathering activity to penetrate deeper into the boulder. This spherical scaling results because, as the minerals in the rock weather to clay, they increase in size through the addition of water to their structure. This increased bulk exerts an outward force that causes concentric layers of rock to break loose and fall off. Hence, chemical weathering does produce forces great enough to cause mechanical weathering.

This type of spheroidal weathering, in which shells spall off, should not be confused with the phenomenon of sheeting.

**Rates of Weathering**

Sculpturing Earth’s Surface
Weathering and Soil

Several factors influence the type and rate of rock weathering. We have already seen how mechanical weathering affects the rate of weathering. By breaking rock into smaller pieces, the amount of surface area exposed to chemical weathering is increased. Other important factors examined here include rock characteristics and climate.

**Rock Characteristics**

Rock characteristics encompass all of the chemical traits of rocks, including mineral composition and solubility. In addition, any physical features, such as joints (cracks), can be important because they influence the ability of water to penetrate rock.

The variations in weathering rates, due to the mineral constituents, can be demonstrated by comparing bedrock types made from different rock types. Headstones of granite, which are composed of silicate minerals, are relatively resistant to chemical weathering. We can see this by examining the inscriptions on the headstones shown in Figure 4.9. This is not true of the marble headstone, which shows signs of extensive chemical alteration over a relatively short period. Marble is composed of calcite (calcium carbonate), which readily dissolves even in a weakly acid solution.

The silicates, the most abundant mineral group, weather in essentially the same sequence as their order of crystallization. By examining Bowen's reaction series (see Figure 3.13, p. 63), you can see that olivine crystals first and is therefore the least resistant to chemical weathering. Whereas quartz, which crystallizes last, is the most resistant.

**Climate**

Climatic factors, particularly temperature and moisture, are crucial to the rate of rock weathering. One important example from mechanical weathering is that the frequency of freeze-thaw cycles greatly affects the amount of frost wedging. Temperature and moisture also exert a strong influence on the rates of chemical weathering and on the kind and amount of vegetation present. Regions with lush vegetation generally have a thick mantle of soil rich in decayed organic matter from which chemically active fluids such as carbonic and humic acids are derived.

The optimum environment for chemical weathering is a combination of warm temperatures and abundant moisture. In polar regions chemical weathering is ineffective because frigid temperatures keep the available moisture locked up as ice, whereas in arid regions there is insufficient moisture to foster rapid chemical weathering.

Human activities can influence the composition of the atmosphere, which in turn can impact the rate of chemical weathering. One well-known example is acid rain (Figure 4.10).
TABLE 4.2 World Soil Orders

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisols</td>
<td>Moderately weathered soils that form under broadleaf deciduous forests, rich in iron and aluminum. Clay particles accumulate in a subsurface layer in response to leaching in moist environments. Fertile, productive soils, because they are neither too wet nor too dry.</td>
</tr>
<tr>
<td>Andisols</td>
<td>Young soils in which the parent material is volcanic ash and cinders, deposited by recent volcanic activity.</td>
</tr>
<tr>
<td>Andosols</td>
<td>Soils that develop in dry places; insufficient water to remove soluble minerals, may have an accumulation of calcium carbonate, pyrites, or salt in subsoil; loamy organic content.</td>
</tr>
<tr>
<td>Entisols</td>
<td>Young soils having limited development and exhibiting properties of the parent material. Productivity ranges from very high for some formed on recent river deposits to very low for those formed on shifting sand or rocky slopes.</td>
</tr>
<tr>
<td>Gelifluvis</td>
<td>Young soils with little profile development that occur in regions with perennially frozen subsoils due to latitudinal or elevational cold and where there has been little or no soil-forming processes.</td>
</tr>
<tr>
<td>Histosols</td>
<td>Organic soils with little or no climatic implications. Can be found in any climate where organic debris can accumulate to form a bog soil. Dark, partially decomposed organic material commonly referred to as peat.</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>Weakly developed young soils in which the beginning (incipient) of profile development is evident. Most common in humid climates, they exist from the Arctic to the tropics. Native vegetation is most often forest.</td>
</tr>
</tbody>
</table>

Brief descriptions of the 12 basic soil orders are provided in Table 4.2. Figure 4.18 shows the complex worldwide distribution patterns of the Soil Taxonomy's 12 soil orders. Like many classification systems, the Soil Taxonomy is not suitable for every purpose. It is especially useful for agricultural and related land-use purposes, but it is not a useful system for engineers who are preparing evaluations of potential construction sites.

Soil Erosion

Soils are just a tiny fraction of all Earth materials, yet they are a vital resource. Because soils are necessary for the growth of rooted plants, they are the very foundation of the human life-support system. Just as human ingenuity can increase the agricultural productivity of soils through fertilization and irrigation, soils can be damaged or destroyed by carelessness. Despite their basic role in providing food, fiber, and other basic materials, soils are among our most abused resources.

Perhaps this neglect and indifference has occurred because a substantial amount of soil seems to remain even where soil erosion is serious. Nevertheless, although the loss of fertile topsoil may not be obvious to the untrained eye, it is a growing problem as human activities expand and disturb more and more of Earth's surface.

How Soil Is Eroded

Soil erosion is a natural process; it is part of the constant recycling of Earth materials that we call the rock cycle. Once soil forms, erosional forces, especially water and wind, move soil components from one place to another. Every time it rains, raindrops strike the

TABLE 4.2 (continued)

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molisols</td>
<td>Soils that occur on stony land surfaces unless parent materials were strongly weathered before they were deposited. Generally found in the tropics and subtropical regions. Rich in iron and aluminum oxides, soils are heavily leached, hence are poor soils for agricultural activity (see Figure 4.15).</td>
</tr>
<tr>
<td>Spodosols</td>
<td>Soils found only in humid regions on sandy material. Common in northern coniferous forests (see Figure 4.15) and cool humid forests. Beneath the dark, upper horizon of the forest, organic material lies a light-colored horizon of leached material, the distinctive property of this soil order.</td>
</tr>
<tr>
<td>Ultisols</td>
<td>Soils that represent the products of long periods of weathering. Water percolating through the soil leaches out minerals in the lower horizons (anglic horizons). Restricted to humid climates in the temperate and tropical regions, where the growing season is long, abundant water and a long frost-free period contribute to extensive leaching, hence poorer soil quality.</td>
</tr>
<tr>
<td>Vertisols</td>
<td>Soils containing large amounts of clay, which shrink upon drying and swell with the addition of water. Found in subtropical and tropical climates, provided that adequate supplies of water are available to saturate the soil after periods of drought. Soil expansion and contraction exert stresses on human structures.</td>
</tr>
</tbody>
</table>
The Role of Water

Mass wasting is sometimes triggered when heavy rains or periods of snowmelt saturate surface materials. This was the case in December 1999 when torrential rains triggered thousands of landslides along the coast of Venezuela. Mudflows and flash floods caused severe property damage and the tragic loss of an estimated 19,000 lives. (Kimberly White/Reuters/CORBIS/Bettmann)

Mass wasting is sometimes triggered when heavy rains or periods of snowmelt or intense storms saturate surface materials. This was the case in December 1999 when torrential rains triggered thousands of landslides along the coast of Venezuela. Mudflows and flash floods caused severe property damage and the tragic loss of an estimated 19,000 lives. (Kimberly White/Reuters/CORBIS/Bettmann)

When the pores in sediment become filled with water, the cohesion among particles is destroyed, allowing them to slide past one another with relative ease. For example, when sand is slightly moist, it sticks together quite well. However, if enough water is added to fill the openings between the grains, the sand will ooze out in all directions (Figure 4.25). Thus, saturation reduces the internal resistance of materials, which are then easily set in motion by the force of gravity. When clay is wetted, it becomes very slick—another example of the "lubricating" effect of water. Water also adds considerable weight to a mass of material. The added weight in itself may be enough to cause the material to slide or flow downslope.

Oversteepened Slopes

Oversteepening of slopes is another trigger of many mass movements. There are many situations in nature where this takes place. A stream undercutting a valley wall and waves pounding against the base of a cliff are two familiar examples. Furthermore, through their activities, people often create oversteepened and unstable slopes that become prime sites for mass wasting.

Unconsolidated, granular (sand-size or coarser) particles assume a stable slope called the angle of repose (repose = to be at rest). This is the steepest angle at which material remains stable (Figure 4.26). Depending on the size and shape of the particles, the angle varies from 25 to 40 degrees. The larger, more angular particles maintain the steepest slopes if the angle is increased, the rock debris will adjust by moving downslope.

Oversteepening is important not only because it triggers movements of unconsolidated granular materials, but it also produces unstable slopes and mass movements in cohesive soils, regolith, and bedrock. The response will not be immediate, as with loose, granular materials, but sooner or later one or more mass-wasting processes will eliminate the oversteepening and restore stability to the slope.

Removal of Vegetation

Plants protect against erosion and contribute to the stability of slopes because their root systems bind soil and regolith to the ground. Where plants are lacking, mass wasting is enhanced. For example, if vegetation is removed by logging or by people (for timber, farming, or development), surface materials frequently move downslope.

In July 1994 a severe wildfire swept Storm King Mountain west of Glenwood Springs, Colorado, denuding the surface of vegetation and exposing the underlying regolith (Figure 4.27). When the rains came, the exposed soil was slaped by oversteepened slopes. The town of Carbondale, located below the steep slopes of the valley, was heavily damaged by mass wasting (Figure 4.28).

FIGURE 4.24 Aerial view of a large debris flow at Carpinteria, California, in December 1999. Heavy rains triggered thousands of debris flows and other types of mass wasting in the adjacent mountains. Once created, these moving masses of mud and rock coalesced to form giant debris flows that moved rapidly through steep, narrow canyons and engulfed the city. The result was severe property damage and the tragic loss of an estimated 10,000 lives. (Kimberly White/Reuters/CORBIS/Bettmann)

FIGURE 4.25 The effect of water on mass wasting can be great. A. When little or no water is present, friction among the closely packed soil particles on the slope holds them in place. B. When the soil is saturated, the grains are forced apart and friction is reduced, allowing the soil to move downslope.

A. Dry soil-high friction
B. Saturated soil

The deadly 2005 debris flow involved many of the town's inhabitants by surprise, such an event should not have been unexpected. Let's briefly examine the factors that contributed to the deadly debris flow at La Conchita.

The town is situated on a narrow coastal strip about 250 meters (800 feet) wide between the shoreline and a steep 80-meter (260-foot) bluff (Figure 4.18). The bluff consists of poorly sorted marine sediments and weakly cemented layers of shale, silts, and sandstone.

The deadly 2005 debris flow involved little or no newly failed materials, but rather consisted of the remobilization of a portion of a large landslide that destroyed several homes in 1995. In fact, historical accounts dating back to 1865 indicate that landslides in the immediate area have been a regular occurrence. Furthermore, geologic evidence shows that landsliding of a variety of types and scales has probably been occurring at La Conchita for thousands of years.

The most significant contributing factor to the tragic 2005 debris flow was prolonged and intense rainfall. The event occurred at the end of a span that produced near record amounts of rainfall in southern California. Wintertime rainfall at nearby Ventura totaled 49.3 centimeters (19.4 inches) as compared to an average value of just 12.2 centimeters (4.8 inches). As Figure 4.14 indicates, much of that total fell during the two weeks immediately preceding the debris flow.

This was not the first destructive landslide to strike La Conchita, nor is it likely to be the last. The town's geologic setting and history of rapid mass-wasting events clearly support this notion. When the amount and intensity of rainfall is sufficient, debris flows are to be expected.

**Note:** Based in part on material prepared by the U.S. Geological Survey.

FIGURE 4.19 The larger image is a view down the length of the 2005 La Conchita debris flow. It also depicts the setting of the small town between the ocean and a steep cliff. The arrow on the larger photo is pointing to the house shown on the inset. The flow was quite viscous and moved houses in its path rather than flowing around them. As you can see, the left side of the house was detached and moved. (Photo by Randall Jipson/U.S. Geological Survey)

FIGURE 4.10 The larger image is a view down the length of the 2005 La Conchita debris flow. It also depicts the setting of the small town between the ocean and a steep cliff. The arrow on the larger photo is pointing to the house shown on the inset. The flow was quite viscous and moved houses in its path rather than flowing around them. As you can see, the left side of the house was detached and moved. (Photo by Randall Jipson/U.S. Geological Survey)

*Box 4.2 > PEOPLE AND THE ENVIRONMENT

Landslide Hazards at La Conchita, California

Southern California lies astride a major fault boundary defined by the San Andreas Fault and numerous other related faults that spread across the region. This dynamic environment characterized by rugged mountains and steep-walled canyons. Unfortunately, this scenic landscape presents serious geologic hazards. Just as tectonic forces are steadily pushing the landscape upward, gravity is relentlessly pulling it downward. When gravity prevails, landslides occur. As you might expect, some of the region's landslides are triggered by earthquakes. Many others, however, are related to periods of prolonged and intense rainfall.

A tragic example of the latter situation occurred on January 10, 2005, when a massive debris flow (popularly called a mudslide) swept through La Conchita, California, a small town located about 80 kilometers (50 miles) northwest of Los Angeles (see chapter-opening photo).

Although the rapid torrent of mud took many of the town's inhabitants by surprise, such an event should not have been unexpected. Let's briefly examine the factors that contributed to the deadly debris flow at La Conchita.

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Students Sometimes Ask...

Are snow avalanches considered a type of mass wasting?

Sure. Sometimes these thundering downslope movements of snow and ice move large quantities of rock, soil, and trees. Of course, snow avalanches are very dangerous, especially to skiers on high mountain slopes and to buildings and roads at the bottoms of slopes in avalanche-prone regions.

About 10,000 snow avalanches occur each year in the mountainous western United States. In an average year they claim between 15 and 25 lives in the United States and Canada. They are a growing problem as more people become involved in winter sports and recreation.

Slump commonly occurs because a slope has been oversteepened. The material on the upper portion of a slope is held in place by the material at the bottom of the slope. As this anchoring material at the base is removed, the material above the slope is undercut at the base of the slope, it loses support and eventually gives way. Sometimes an earthquake is the trigger. On other occasions the slope is triggered when rain or melting snow lubricates the underlying surface to the point that friction is no longer sufficient to hold the rock unit in place. As a result, rockslides tend to be more common during the spring when heavy rains and melting snow are most prevalent.

The massive Gros Ventre slide shown in Figure 4.31 is a classic example.

FIGURE 4.31 On June 23, 1925, a massive rockslide took place in the valley of the Gros Ventre River in northwestern Wyoming following heavy spring rains and snowmelt. The volume of debris, estimated at 38 million cubic meters, created a 70-meter-high dam. Lake, the lake caused by the slide, occurred when the tilted and undercut sandstone bed could no longer maintain its position atop the saturated bed of clay. Even though the Gros Ventre rockslide occurred in 1925, the scar left on the side of Sheep Mountain is still a prominent feature.

Rockslide

FIGURE 4.32 This small, tongue-shaped earthflow occurred on a newly formed slope along a recently constructed highway. It formed in silt-rich material following a period of heavy rain. Notice the small slump at the head of the earthflow. (Photo by E. J. Tarbuck)

Earthflow

We have seen that debris flows are frequently confined to channels in semiarid regions. In contrast, earthflows most often form on hillsides in humid areas during times of heavy precipitation or snowmelt (see Figure 4.28). When water saturates the soil and regolith on a hillside, the material may become a flowing tongue of muddy water. The rate of flow therefore depends on the slope but also on the water content. When dense, debris flows are capable of carrying or pushing large boulders, trees, and even houses with relative ease.

Debris flows pose a serious hazard to development when a volcano is quiet. They take place when highly unstable layers of ash and debris become saturated with water and flow down steep volcanic slopes, generally following existing stream channels. Heavy rainfall often triggers these flows. Others are triggered when large volumes of ice and snow are suddenly melted by heat flowing to the surface from within the volcano or by the hot gases and near-melted debris emitted during a violent eruption.

In November 1985 lahars were produced when Nevado del Ruiz, a 5,300-meter (17,400-foot) volcano in the Andes Mountains of Colombia, erupted. The eruption melted much of the snow and ice that capped the uppermost 600 meters (2,000 feet) of the peak, producing torrents of hot, thick mud, ash, and debris. The lahars moved outward from the volcano, following the valleys of three rain-swollen rivers that radiate from the peak. The flow that moved down the valley of the Lagunilla River was the most destructive, devastating the town of Armero, 48 kilometers (30 miles) from the mountain. Most of the more than 25,000 deaths caused by the event occurred in this once-thriving agricultural community.

Debris Flows in Semiarid Regions

When a cloud burst or rapidly melting mountain snows create a sudden flood in a semiarid region, large quantities of soil and regolith are washed into nearby stream channels because there is usually little vegetation to anchor the surface material. The end product is a flowing tongue of well mixed mud, soil, rock, and water. Its consistency may range from that of wet concrete to a soupy mixture not much thicker than muddy water. The rate of flow therefore depends not only on the slope but also on the water content. When dense, debris flows are capable of carrying or pushing large boulders, trees, and even houses with relative ease.

Debris flows pose a serious hazard to development in dry mountainous areas such as southern California. The construction of homes on canyon hillsides and the removal of anchoring vegetation by brush fires and other means has increased the frequency of these destructive events.

Lahars

Debris flows composed mostly of volcanic materials on the flanks of volcanoes are called lahars. The word originated in Indonesia, a volcanic region that has experienced many of these often destructive events. Historically, lahars have been one of the deadliest volcanic hazards. They can occur either during an eruption or after a volcano is quiet. They take place when highly unstable layers of ash and debris become saturated with water and flow down steep volcanic slopes, generally following existing stream channels. Heavy rainfall often triggers these flows. Others are triggered when large volumes of ice and snow are suddenly melted by heat flowing to the surface from within the volcano or by the hot gases and near-melted debris emitted during a violent eruption.

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1 kilometer per hour, whereas a few rapid ones may exceed 30 kilometers per hour. Velocities are measured at gaging stations (Figure 5.5A). Along straight stretches, the highest velocities are near the center of the channel just below the surface, where friction is lowest (Figure 5.5B). But when a stream curves, its zone of maximum speed shifts toward the outer bank (Figure 5.5C).

The ability of a stream to erode and transport materials depends on its velocity. Even slight changes in velocity can lead to significant changes in the load of sediment that water can transport. Several factors determine the velocity of a stream, including (1) gradient; (2) shape, size, and roughness of the channel; and (3) discharge.

Gradient and Channel Characteristics

The slope of a stream channel expressed as the vertical drop of a stream over a specified distance is gradient. Portions of the lower Mississippi River, for example, have very low gradients of 10 centimeters per kilometer or less. By contrast, some mountain stream channels can have gradients of 400 meters per kilometer, or a gradient 40 times steeper than the low Mississippi (Figure 5.6). Gradient varies not only among different streams but also at a particular stream's length. The steeper the gradient, the more energy available for streamflow. If two streams were identical in every respect except gradient, the stream with the higher gradient would obviously have the greater velocity.

A stream's channel is a conduit that guides the flow of water but also encounters friction as it flows. The shape, size, and roughness of the channel affect the amount of friction. Larger channels have more efficient flow because a smaller proportion of water is in contact with the channel. A smooth channel promotes a more uniform flow, whereas an irregular channel filled with boulders creates enough turbulence to slow the stream significantly.

Discharge

The discharge of a stream is the volume of flow passing a certain point in a given unit of time. This is usually measured in cubic meters per second or cubic feet per second. Discharge is determined by multiplying a stream's cross-sectional area by its velocity:

\[
\text{discharge (m}^3/\text{second)} = \text{channel width (meters)} \times \text{channel depth (meters)} \times \text{velocity (meters/second)}
\]

Table 5.1 lists the world's largest rivers in terms of discharge. The largest river in North America, the Mississippi, discharges an average of 17,300 cubic meters (611,000 cubic feet) per second. Although this is a huge quantity of water, it is nevertheless dwarfed by the mighty Amazon in South America, the world's largest river. Fed by a vast rainy region that is nearly three-fourths the size of the conterminous United States, the Amazon discharges 12 times more water than the Mississippi.

The Work of Running Water

Streams are Earth's most important erosional agent. Not only do they have the ability to downcut and widen their channels, but streams also have the capacity to transport the enormous loads of sediment that they carry. The latter is especially significant in mountainous areas where the uplift is more rapid and where the sediment is made up of finer materials such as silt and clay.

Water moves downhill through various forms, including (1) ground water, (2) streams, and (3) surface water. The zone of groundwater flow is continuous but varies in thickness from place to place. The water moves at varying speeds, ranging from fractions of an inch per year to many feet per day. Streams are the most visible form of flow. They are Earth's most important erosional agents not only because of the huge loads of sediments they carry but also because of the energy available for dissection. Most streams displace energy at the base of vertical cliffs, but the energy is available to move all parts of the channel. The location of the energy source varies not only among different streams but also within a particular stream's length.
The delta of the Mississippi River in Louisiana contains about 40 percent of all coastal wetlands in the lower 48 states. Louisiana's wetlands are sheltered from the wave action of hurricanes and winter storms by levee-like offshore barrier islands. Both the wetlands and the barrier islands have formed as a result of the shifting of the Mississippi River during the past 7,000 years.

The dependence of Louisiana's coastal wetlands and offshore islands on the Mississippi River and its distributaries as a direct source of sediment leaves them vulnerable to changes in the river system. Moreover, the reliance on barrier islands for protection from storm waves leaves coastal wetlands vulnerable when these narrow offshore islands are eroded.

Today, the coastal wetlands of Louisiana are disappearing at an alarming rate. Although Louisiana contains 40 percent of the wetlands in the lower 48 states, it accounts for 80 percent of the wetland loss. According to the U.S. Geological Survey, Louisiana lost nearly 5,000 square kilometers (1,500 square miles) of coastal land between 1992 and 2000. The state continues to lose between 65 and 91 square kilometers (25 to 35 square miles) each year. At this rate another 1,500 to 4,000 square kilometers (700 to 1,500 square miles) will vanish under the Gulf of Mexico by the year 2050.* Global climate change could increase the severity of the problem because rising sea level and stronger tropical storms accelerate rates of coastal erosion.** Unfortunately, this was observed firsthand during the extraordinary 2005 hurricane season when hurricanes Katrina and Rita devastated portions of the Gulf Coast.

By nature, the delta, its wetlands, and the adjacent barrier islands are dynamic features. Over the millennia, as sediment accumulated and built the delta in one area, erosion and subsidence caused losses elsewhere. Whenever the river shifted, the zones of delta growth and destruction also shifted. However, with the arrival of people, this relative balance between formation and destruction changed—the rate at which the delta and its wetlands were destroyed accelerated and now greatly exceeds the rate of formation. Why are Louisiana's wetlands shrinking?

Before Europeans settled the delta, the Mississippi River regularly overflowed its banks in seasonal floods. The huge quantities of sediment that were deposited renewed the soil and kept the delta from sinking below sea level. However, with settlement came flood-control efforts and the desire to maintain and improve navigation on the river. Artificial levees were constructed to contain the rising river during flood stage. Over time the levees were extended all the way to the mouth of the Mississippi to keep the channel open for navigation.

The effects have been straightforward. The levees prevent sediment and fresh water from being dispersed into the wetlands. Instead, the river is forced to carry its load to the deep waters at the mouth. Meanwhile, the processes of compaction, subsidence, and wave erosion continue. Because not enough sediment is added to offset these forces, the size of the delta and the extent of its wetlands gradually shrink.

The problem has been aggravated by a decline in the sediment transported by the Mississippi, decreasing by approximately 30 percent over the past 300 years. A substantial portion of the reduction results from trapping of sediment in large reservoirs created by dams built on tributaries to the Mississippi.

Another factor contributing to wetland decline is the fact that the delta is located with 13,000 kilometers (8,000 miles) of navigation channels and canals. These artificial openings to the sea allow saltwater to flow far inland. The invasion of saltwater and tidal action causes massive "brownouts" or marsh die-offs (Figure 5.5A).

Understanding and modifying the impact of people is a necessary basis for any plan to reduce the loss of wetlands in the Mississippi delta. The U.S. Geological Survey estimates that restoring Louisiana's coast will require about $14 billion over the next 40 years. What if nothing is done? State and federal officials estimate that costs of inaction could exceed $100 billion.

**For more on this possibility, see "Worse Possible Consequences of Global Warming" in Chapter 20.
many iron-bearing silicate minerals oxidize, producing the rust-colored stain found tinting some desert landscapes.

The Role of Water

Permanent streams are normal in humid regions, but practically all desert streams are dry most of the time (Figure 6.28A). Deserts have ephemeral streams, which means that they carry water only in response to specific episodes of rainfall. A typical ephemeral stream might flow only a few days or perhaps just a few hours during the year. In some years the channel may carry no water at all.

This fact is obvious even to the casual observer who, while traveling in a dry region, notices the number of bridges with no streams beneath them or the number of dips in the road where dry channels cross. However, when the rare heavy showers do occur, so much rain falls in such a short time that all of it cannot soak in. Because the vegetative cover is sparse, runoff is common in the desert, often in well-watered mountains. Here the water supply must be great to compensate for the losses occurring in the stream as it crosses the desert (Box 6.2). For example, after the Nile leaves the lakes and mountains of central Africa and its source, it traverses almost 3,000 kilometers (nearly 1,860 miles) of the Sahara without a single tributary. By contrast, in humid regions the discharge of a river usually increases as it flows toward the sea; hence, tributaries and groundwater contribute additional water along the way.

It should be emphasized that running water, although important, constitutes only a small part of the essential work in deserts. This is contrary to a common belief that wind is the most important erosional agent sculpturing desert landscapes. Although wind erosion is indeed more significant in dry areas than elsewhere, most desert landforms are nonetheless carved by running water. As you will see shortly, the main role of wind is in the transportation and deposition of sediment, which creates and shapes the ridges and mounds we call dunes.

Basin and Range: The Evolution of a Mountainous Desert Landscape

Sculpting Earth’s Surface

Deserts and Winds

Because arid regions typically lack permanent streams, they are characterized as having interdunal drainage. This means that they have a discontinuous pattern of intermittent streams that do not flow out of the desert to the ocean. In the United States, the dry Basin and Range region provides an excellent example. The region includes southern Oregon, all of Nevada, western Utah, southeastern California, southern Arizona, and southern New Mexico. The name Basin and Range is an apt description for

The Aral Sea lies on the border between Uzbekistan and Kazakhstan in central Asia (Figure 6.2C). The setting is the Turkestan Desert, a middle-latitude desert in the rain shadow of Afghanistan’s high mountains. The region of interior drainage, two large lakes, the Aral Darya and the Syr Darya, carry water from the mountains of northern Afghanistan across the desert to the Aral Sea. Water leaves the sea by evaporation. Thus, the size of the water body depends on the balance between river inflow and evaporation.

In 1960 the Aral Sea was one of the world’s largest inland water bodies, with an area of about 67,000 square kilometers (26,000 square miles). Only the Caspian Sea, like Superior, and Lake Victoria were larger. By the year 2017 the area of the Aral Sea was less than 20 percent of its 1960 size, and its volume was reduced by 80 percent. The shrinking of this water body is depicted in Figure 6.6. By about 2050 all that will remain will be three shallow remnants.

What caused the Aral Sea to dry up over the past 40 years? The answer is that the flow of water from the mountains that supplied the sea was significantly reduced and was lost to evaporation. As recently as 2005, the Aral Sea received about 50 cubic kilometers (12 cubic miles) of fresh water per year. By the early 1980s this number fell to nearly zero. The reasons was that the waters of the Amu Darya and Syr Darya were diverted to supply a major expansion of irrigated agriculture in this dry area.

The shrinking Aral Sea has had an noticeable impact on the region’s climate. Without the moderating effect of a large water body, there are greater extremes of temperature, a shorter growing season, and reduced local precipitation. These changes have caused many flocks to switch from growing cotton to growing rice, which demands even more diverted water.

Environmental experts agree that the current situation cannot be sustained. Could this crisis be reversed if enough fresh water were to once again flow into the Aral Sea? Prospects appear grim. Experts estimate that restoring the Aral Sea to about twice its present size would require stopping all irrigation from the two major rivers for 50 years. This could not be done without reducing the economies of the countries that rely on that water.*

The decline of the Aral Sea is a major environmental disaster that sadly is of human making.


FIGURE 6.8 The shrinking Aral Sea. By the year 2017 all that will remain are three small remnants.

The intensive irrigation greatly increased agricultural productivity but without significant costs. The deltas of the two major rivers have lost their wetlands, and wildlife has disappeared. The once thriving fishing industry is dead, and the 28 species of fish that once lived in the Aral Sea are no longer there. The shoreline in ten years of kilometers from the towns that were once fishing centers (Figure 6.2).

The shrinking sea has exposed millions of acres of former seabed to sun and wind. The surface is etched with salt and with agricultural chemicals brought by the river. Strong winds routinely pick up and deposit thousands of tons of newly exposed material every year. This process has not only contributed to a significant reduction in air quality for people living in the region but has also appreciably affected crop yields due to the deposition of salt- and chemical-laden sediments on arable land.
Damaging Earthquakes East of the Rockies

When you think of San Andreas Fault, you probably think of California and Japan. However, six major earthquakes have occurred in the central and eastern United States since colonial times. Three of these have estimated Richter magnitudes of 7.3, 7.5, and 7.8, and they were centered in the Mississippian River Valley in southeastern Missouri. Over the years, investigations have shown that displacement in this area has occurred over a six-state area. The course of the Mississippi River was altered, and Tennessean’s Redfoot Lake was enlarged. The distances over which these earthquakes were felt are truly remarkable. Quake maps were proposed divided in Cincinnati, Ohio, and Richmond, Virginia, while Boston residents kept an estimated 1,700 kilometers (1,100 miles) to the northeast, felt the tremors.

Despite the history of the New Madrid, Tennessee, the largest population center in the area today, does not have adequate earthquake provisos in its building code. Furthermore, because Memphis is located on an unconsolidated floodplain deposit, buildings are more susceptible to damage than similar structures located on bedrock. It has been estimated that if an earthquake the size of the 1811-1812 Missouri event were to strike in the next decade, it would result in casualties in the thousands and damages in tens of billions of dollars.

Damaging earthquakes that occurred in Arizona, Illinois (1905), and Virginia, Texas (1907), remind us that other areas in the central and eastern United States are vulnerable to earthquake damage.

Earthquakes in the central and eastern United States occur less frequently than in California. Yet history indicates that the central and eastern United States is older and more rigid. As a result, seismic waves are able to travel greater distances with lesser weakening than in the western United States. It is estimated that for earthquakes of similar magnitude, the region of maximum ground motion in the East may be up to 10 times larger than in the West. Consequently, the higher estimated rate of earthquake occurrence in the central and eastern United States is balanced somewhat by the fact that central and eastern U.S. quakes are relatively less damaging.

San Andreas Fault: An Active Earthquake Zone

The San Andreas Fault is undoubtedly the most studied fault system in the world (Figure 8.6). Over the years, investigations have shown that displacement occurs along discrete segments that are 100 to 200 kilometers long. Furthermore, each fault segment exhibits a different pattern of behavior compared to other fault segments. Some portions of the San Andreas exhibit a slow, gradual displacement known as fault creep, which occurs relatively smoothly and with little noticeable seismic activity. Other segments regularly slip, producing small earthquakes. Still other segments remain locked and store elastic energy for hundreds of years before rupturing in great earthquakes. The latter process is described as stick-slip motion, because the fault exhibits alternating periods of locked behavior followed by a major slip event. It is estimated that great earthquakes should occur about every 50 to 300 years along these sections of the San Andreas Fault that exhibit stick-slip motion. This knowledge is useful when assigning a potential earthquake risk to a specific segment of the fault zone.

The tectonic forces along the San Andreas Fault that were responsible for the 1906 San Francisco earthquake are still active. Currently, laser beams are used to measure the relative motion between the opposite sides of this fault. These measurements reveal a displacement of 2.0 centimeters (+1 mm) per year. Although this seems slow, it produces substantial movement over millions of years.

To illustrate, in 30 million years this rate of displacement would slide the western portion of California northward so that Los Angeles, on the Pacific plate, would be adjacent to San Francisco. On the North American plate, more important in the short term, a displacement of just 2 centimeters per year produces 2 meters of offset every 100 years. Consequently, the four meters of displacement predicted during the 1906 San Francisco earthquake should occur at least every 250 years along this segment of the fault zone. This fact lies behind California's concern for making buildings earthquake-resistant in anticipation of the inevitable "Big One."

Seismology: The Study of Earthquake Waves

The study of earthquake waves, seismology (seismos = shake, graph = write) dates back to the Chinese almost 3,000 years ago to determine the direction of the source of each earthquake. Modern seismographs are instruments that record earthquake waves. Their principal is simple: A weight is freely suspended from a support that is attached to a bedrock (Figure 8.8). When an earthquake occurs, the instrument, the inertia of the weight keeps it stationary, while Earth and the support vibrate. The movement of Earth in relation to the stationary object is recorded by a rotating drum. (Inertia is the tendency of a stationary object to remain still, or a moving object to stay in motion.)

Modern seismographers amplify and record ground motion, producing a trace as shown in Figure 8.8. These records, called seismograms (seismos = shake, graph = write), reveal that seismic waves are elastic energy. This energy radiates outward in all directions from the source, as you saw in Figure 8.2. The transmission of this energy can be compared to the shaking of a galvanometer that is jarred. Seismograms reveal that two main types of seismic waves are generated by the slippage of a rock mass. Some travel along Earth's outer layer and are called surface waves. Others travel within Earth's interior and are called body waves.

Body waves are further divided into primary waves (P waves) and secondary waves (S waves). P waves are push-pull waves—they push (compress) and pull (expand) rocks in the direction the wave is traveling (Figure 8.9A). Imagine holding someone by the shoulders and shaking them. This push-pull movement is how P waves move through Earth. This wave motion is analogous to that generated by human vocal cords as they move air to create
Measuring the Size of Earthquakes

Seismologists have employed a variety of methods to obtain two fundamentally different measures that describe the size of an earthquake: intensity and magnitude. The first of these to be used was intensity—measure of the degree of earthquake shaking at a given locale based on the amount of damage. With the development of seismographs, it became clear that a quantitative measure of earthquake shaking at a given locale based on the amount of the energy released at the source of the earthquake was needed. This measure was used to estimate the relative sizes of earthquakes. As shown in Table 8.2, the Richter scale is based on the amplitude of the largest seismic wave (P, or surface wave) recorded on a seismograph. Because seismic waves weaken as the distance between the earthquake focus and the seismograph increases (in a manner similar to light), Richter developed a method that accounted for the decrease in wave amplitude with increased distance. Theoretically, as long as the same, or equivalent, instruments were used, monitoring stations at various locations would obtain the same Richter magnitude for every recorded earthquake. (Richter selected the Wood-Anderson seismograph as the standard recording device.)

Although the Richter scale has no upper limit, the largest magnitude recorded on a Wood-Anderson seismograph was 8.9. These great shocks release approximately 10^23 ergs of energy—roughly equivalent to the detonation of 1 million tons of TNT. Conversely, earthquakes with a Richter magnitude of less than 2.0 are not felt by humans. With the development of more sensitive instruments, tremors of a magnitude of minus 2 were recorded. Table 8.2 shows how Richter magnitudes and their effects are related.

**Modified Mercalli Intensity Scale**

<table>
<thead>
<tr>
<th>No.</th>
<th>Effect</th>
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<tr>
<td>I</td>
<td>Little felt except by a very few under especially favorable circumstances.</td>
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<td>II</td>
<td>Felt by a few only at rest, especially on upper floors of buildings.</td>
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<tr>
<td>III</td>
<td>Felt by many, especially by individuals in motion; sleep disturbed; rain or sleet heard outdoors.</td>
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<tr>
<td>IV</td>
<td>Felt by many, but not everyone; objects slightly moved; minor damage in well-built wooden structures.</td>
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<tr>
<td>V</td>
<td>Felt by nearly everyone; many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed.</td>
</tr>
<tr>
<td>VI</td>
<td>Felt by all; many frightened and run outdoors. Some heavy furniture moved; few instances of fallen plaster or damaged chimneys.</td>
</tr>
<tr>
<td>VII</td>
<td>Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built structures; minor damage in blocks of solid masonry buildings.</td>
</tr>
<tr>
<td>VIII</td>
<td>Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures; major damage in structures made of durable materials; ground badly cracked.</td>
</tr>
<tr>
<td>IX</td>
<td>Damage considerable in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures; major damage in structures made of durable materials; ground badly cracked.</td>
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<tr>
<td>X</td>
<td>Damage considerable in specially designed structures; considerable in ordinary substantial buildings with partial collapse; major damage in structures made of durable materials; ground badly cracked.</td>
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Earthquakes vary enormously in strength, and great earthquakes produce wave amplitudes that are thousands of times larger than those generated by weak tremors. To accommodate this wide variation, Richter used a logarithmic scale to express magnitude, where a tenfold increase in wave amplitude corresponds to an increase of 1 on the magnitude scale. Thus, the amount of ground shaking for a 5.5-magnitude earthquake is 30 times greater than that produced by an earthquake having a Richter magnitude of 4.

In addition, each unit of Richter magnitude equates to roughly a 30-fold energy increase. Thus, an earthquake with a magnitude of 6.5 releases 32 times more energy than one with a magnitude of 5.5, and roughly 1,000 times more energy than a 4.5-magnitude quake. A major earthquake with a magnitude of 8.5 releases millions of times more energy than the smallest earthquakes felt by humans.

Richter’s original goal was modest in that he only attempted to rank the earthquakes of southern California (shallow-focus earthquakes) into groups of large, medium, and small magnitude. Hence, Richter magnitude was designed to study nearby (or local) earthquakes and is denoted by the symbol (Ms), where M is for magnitude and s for local.

The convenience of describing the size of an earthquake by a single number that could be calculated quickly from seismograms makes the Richter scale a powerful tool. Furthermore, unlike intensity scales that could only be applied to populated areas of the globe, Richter magnitudes could be designed to more remote regions and even to events that occurred in the ocean basins. As a result, the method devised by Richter was adapted to a number of different seismographs located throughout the world. In time, seismologists modified Richter’s work and developed new magnitude scales.

**Magnitude:** Seismologists have recently been employing a more precise measure called moment magnitude (Mw), which can be calculated using several techniques. In one method, the moment magnitude is calculated from field studies using a combination of factors that include the average amount of displacement along the fault, the area of rupture surface, and the shear strength of the fault rock—a measure of how much energy a rock can store before it suddenly slips and releases this energy in the form of an earthquake (and heat).

The moment magnitude can also be readily calculated from seismograms by examining very long period seismic waves. The values obtained have been calibrated so that they are roughly equivalent to Richter magnitudes. However, moment magnitudes are much better for describing very large earthquakes. For example, on the moment magnitude scale, the 1906 San Francisco earthquake, which had a Richter magnitude of 8.3, would be denoted as 7.9 on the moment magnitude scale, whereas the 1964 Alaskan earthquake with an 8.3 Richter magnitude would be increased to 9.2. The strongest earthquake ever recorded is the 1960 Chilean earthquake with a moment magnitude of 9.5.

**Moment magnitude has gained widespread acceptance among seismologists and engineers because:** (1) it is the only magnitude scale that estimates adequately the size of very large earthquakes; (2) it is a measure that can be derived mathematically from the size of the rupture surface and the amount of displacement and it better reflects the total energy released during an earthquake; and (3) it can be verified by two independent methods—field studies that are based on measurements of fault displacement and seismographic methods using long-period waves.

### Destruction from Earthquakes

The most violent earthquake to jar North America in the early 1960s—the Good Friday Alaskan Earthquake—occurred in 1964. Felt throughout the state, the quake had a moment magnitude of 9.2 and reportedly lasted 3–4 minutes. The initial shock was recorded as far as 3,000 miles away, destroying 113,000 buildings, killing 129 people, and leaving thousands homeless. The myth that larger earthquakes are less destructive than smaller ones is quickly dispelled by the 1964 Alaskan earthquake, which had a moment magnitude of 8.7 and released energy equivalent to 1,000 Hiroshima bombs.

**Damage from Seismic Vibrations**

The 1964 Alaskan earthquake provided geologists with new insights into the role of ground shaking as a destructive force. As the energy released by an earthquake travels along Earth’s surface, it causes the ground to vibrate in a complex manner by moving up and down as well as from side to side. The amount of structural...
Fire

The 1906 San Francisco earthquake reminds us of the formidable forces of fire. The central city contained mostly large, older wooden structures and brick-clad buildings that were mostly destroyed by fires that started when gas and electrical lines were severed. The fires raged uncontrollably for three days and devastated over 500 city blocks (see Figure 8.3). The problem was compounded by the initial ground shaking, which broke the city's water lines into hundreds of unconnected pieces.

The fire was finally contained when buildings were dynamited along a wide boulevard to create a fire break, the same strategy used in fighting a forest fire. Although only a few deaths were attributed to the fires, such is not always the case. A 1923 earthquake in Japan (their worst quake prior to the 1995 Kobe tremor) triggered an estimated 350 fires, which devastated the city of Yokohama and destroyed more than half the homes in Tokyo. More than 100,000 deaths were attributed to the fires, which were driven by unusually high winds.

Can Earthquakes be Predicted?

The vibrations that shook Northridge, California, in 1994 inflicted 37 deaths and about $60 billion in damage (Figure 8.23). This was from a brief earthquake (about 40 seconds) of moderate rating (Ms 6.7). Seismologists warn that earthquakes of comparable or greater strength will occur along the San Andreas Fault, which cuts a 1,300-kilometer (800-mile) path through the state. The obvious question is, can earthquakes be predicted?

Short-Range Predictions

The goal of short-range earthquake prediction is to provide a warning of the location and magnitude of a large earthquake within a narrow time frame. Substantial efforts to achieve this objective are being put forth in Japan, the United States, China, and Russia—countries where earthquake risks are high (Table 8.3). This research has concentrated on producing possible precursors—phenomena that precede and thus provide a warning of a forthcoming earthquake. In California, for example, some seismologists are studying unexplained fluctuations in the tides and in the rocks near active faults. Some Japanese scientists are studying peculiar animal behavior that may precede a quake.

One claim of a successful short-range prediction was made by Chinese seismologists after the February 4, 1975, earthquake in Liaoning Province. According to reports, very few people were killed, although more than 1 million lived near the epicenter, because the earthquake was predicted and the population was evacuated. Recently, some Western seismologists have questioned this claim and suggest instead that an intense swarm of foreshocks that began 24 hours before the main earthquake may have caused many people to evacuate spontaneously. Furthermore, an official Chinese government report issued 10 years later stated that 1,328 people died and 16,358 injuries resulted from this earthquake.

One year after the Lecce earthquake at least 24,000 people died in the Tangshan, China, earthquake, which was not predicted. The Chinese have also issued false alarms in a province near Hong Kong, people reportedly left their dwellings for over a month, but no earthquake followed. Clearly, whatever method the Chinese employ for short-range predictions, it is not reliable.

For a short-range prediction scheme to warrant general acceptance, it must be both accurate and reliable. Thus, it must have a small range of uncertainty as regards to location and timing, and it must produce no false alarms. For example, one can imagine a debate that would precede an order to evacuate a large city in the United States, such as Los Angeles or San Francisco. The cost of evacuating millions of people, arranging for their lack of work time and wages would be staggering.

Long-Range Forecasts

In contrast to short-range predictions, which aim to predict earthquakes within a time frame of hours or at most days, long-range forecasts give the probability of a certain magnitude earthquake occurring on a time scale of 30 to 100 years or more. Stated another way, these forecasts give statistical estimates of the expected intensity of ground motion for a given area over a specified time frame. Although long-range forecasts may not be as informative as we might wish, the data are important for updating the Uniform Building Code, which contains nationwide standards for designing earthquake-resistant structures.

Long-range forecasts are based on the premise that earthquakes are repetitive or cyclical, like the weather. In other words, as soon as one earthquake occurs, the continuing motions of Earth’s plates begin to build strain in the rocks again, until they fail once more. This has led seismologists to study historical records of earthquakes to see if there are any discernible patterns so that the probability of recurrence might be established.

One study conducted by the U.S. Geological Survey gives the probability of a rupture occurring along various segments of the San Andreas Fault for the 30 years between 1988 and 2018 (Figure 8.24). From this investigation, the Santa Cruz Mountains area was given a 39 percent probability of producing a 6.5-magnitude earthquake during this time period. In fact, it produced the Loma Prieta quake in 1989, of 7.1 magnitude.

The region along the San Andreas Fault given the highest probability (50 percent) of generating a quake is the Parkfield section. This area has been called the “Old Faithful” of earthquakes.
BOX 9.1 PEOPLE AND THE ENVIRONMENT

Eruption of Vesuvius A.D. 79

In addition to producing some of the most violent volcanic activity, composite cones can erupt unexpectedly. One of the best documented of these events was the A.D. 79 eruption of the Italian volcano we now call Vesuvius. Prior to this eruption, Vesuvius had been dormant for centuries and had vineyards adorning its sunny slopes. On August 24, however, the tranquility ended, and in less than 2 hours the city of Pompeii (near Naples), and more than 2,000 of its 20,000 residents, perished. Most were entombed beneath a layer of pumice nearly 3 meters (10 feet) thick. They remained this way for nearly 17 centuries, until the city was partially excavated, giving archaeologists a superbly detailed picture of ancient Roman life (Figure 9.8a).

By reconciling historical records with detailed scientific studies of the region, volcanologists have pieced together the chronology of the destruction of Pompeii. The eruption may have begun as steam discharges on the morning of August 24. By early afternoon fine ash and pumice fragments formed a fall eruption cloud emanating from Vesuvius. Shortly thereafter, debris from this cloud began to shower Pompeii, located 9 kilometers (6 miles) downhill from the volcano. Undoubtedly, many people died during this early phase of the eruption.

For the next several hours pumice fragments as large as 8 centimeters (3 inches) fell on Pompeii. One historical record of this eruption states that people looked twice as distantly than Pompeii hed pumice in their heads in order to fend off the flying fragments.

The pumice fall continued for several hours, accumulating at the rate of 12-15 centimeters (5-6 inches) per hour. Most of the roofs in Pompeii eventually gave way. Then suddenly and unexpectedly a cloud of scalding hot dust and ash swept rapidly down the flanks of Vesuvius. This blast killed an estimated 2,000 people who had somehow managed to survive the pumice fall. Some may have been killed by flying debris but most died of suffocation as a result of inhaling ash-laden gases. Their remains were quickly buried by the falling ash, which rain-

Fissure Eruptions and Lava Plateaus

We think of volcanic eruptions as building a cone or shield from a central vent. But by far the greatest volume of volcanic material is extruded from fissures in the crust called fissures (fissure = to split). Rather than building a cone, these low-angle cracks may emit a low-viscosity basaltic lava, blanketing a wide area.

The extensive Columbia Plateau in the northwestern United States was formed this way (Figure 9.22). Here numerous fissure eruptions extruded very fluid basaltic lava. Successive flows, some 80 meters (260 feet) thick, buried the existing landscape as they built a plateau nearly a mile thick. The fluid nature of the lava is evident, because some remained molten long enough to flow 150 kilometers (90 miles) from its source. The term flood basalt appropriately describes these flows. Massive accumulations of basaltic lava, similar to those of the Columbia Plateau, occur worldwide. One of the largest is the Deccan Traps, a thick sequence of flood-lava flows covering nearly 500,000 square kilometers (195,000 square miles) of west-central India. When the Deccan Traps formed about 66 million years ago, nearly 2 million cubic kilometers of lava were extruded in less than 1 million years. Another huge deposit of flood basalt, called the Ontong Java Plateau, is found in the floor of the Pacific Ocean.

Volcanic Pipes and Necks

Volcanoes are fed magma through short conduits, called pipes, that connect a magma chamber to the surface. In rare circumstances, pipes may extend tubelike to depths exceeding 30 kilometers (125 miles). When this occurs, the ultramafic magma that migrates up these structures produces rocks that are thought to be samples of the mantle that have undergone very little alteration during their ascent. Geologists consider these unusually deep conduits to be "windows" into Earth, for they allow us to view rocks normally found only at great depth.

The best-known volcanic pipes are the diamond-bearing structures of South Africa. Here, the rocks filling the pipes originated at depths of at least 150 kilometers (90 miles), where pressure is high enough to generate diamonds and other high-pressure minerals. The task of transporting essentially unaltered magma (along with diamond inclusions) through 500 kilometers of solid rock is exceptional. This fact accounts for the scarcity of natural diamonds.

Volcanoes on land are continually being lowered by weathering and erosion. Cinder cones are easily eroded, because they are composed of unconsolidated materials. However, all volcanoes will eventually succumb to relentless erosion over geologic time. As erosion progresses, the rock occupying the volcanic pipe is often more resistant and may remain stand-
Can Volcanoes Change Earth's Climate?

The idea that explosive volcanic eruptions might alter Earth's climate was first proposed many years ago. It is still regarded as a plausible explanation for some aspects of climate variability. Exploding eruptions emit large quantities of gases and fine-grained debris high into the atmosphere, where it spreads around the globe and remains for many months or even years (Figure 9.8).

The Baseline

The basic premise is that this suspended volcanic material will filter out a portion of the incoming solar radiation, in turn, will drop temperatures in the lowest layers of the atmosphere. More than 200 years ago Benjamin Franklin used this idea to argue that material from the eruption of a large Icelandic volcano could have reflected sunlight back to space and therefore might have been responsible for the unusually cold winter of 1783-1784.

Perhaps the most notable cool period linked to a volcanic event is the "year without a summer" that followed the 1815 eruption of Mount Tambora in Indonesia. The eruption of Tambora is the largest in modern times. During May-June 1815, this nearly 10,000-foot-high (3,000 meter) volcano violently expelled more than 100 cubic kilometers (24 cubic miles) of volcanic debris. The impact of the volcanic aerosols on climate is believed to have been widespread in move away from each other and new sea floor is created, and (3) areas within the plates proper that are not associated with any plate boundary.

Igneous Activity at Convergent Plate Boundaries

Recall that at convergent plate boundaries, slabs of oceanic crust are bent as they descend into the mantle, generating an oceanic trench. As a slab sinks deeper into the mantle, the increase in temperature and pressure drives volatiles (water, H2O) from the oceanic crust. These mobile fluids migrate upward into the wedge-shaped piece of mantle located between the subducting slab and overlying plate (see Figure 9.32).

Once the sliding slab reaches a depth of about 100 to 150 kilometers, these water-rich fluids reduce the melting point of mantle rock sufficiently to trigger some melting. The partial melting of mantle rock generates magma with a basaltic composition. After a sufficient quantity of magma has accumulated, it slowly migrates upward. Volcanism at a convergent plate margin results in the development of a linear or slightly curved chain of volcanoes called a volcanic arc. These volcanic chains develop roughly parallel to the associated trench—distances of 200-300 kilometers (125-186 miles). Volcanic arcs can be constructed on oceanic or continental lithosphere. Those that develop within the ocean and grow large enough for their tops to rise above the surface are labeled as subduction zones; most active are the oceanic crust. Geologists prefer to classify these subduction zones.

more descriptive term volcanic island arcs, or simply island arcs (Figure 9.34, left). Several young volcanic island arcs of this type border the western Pacific basin, including the Aleutian Islands, the Tonga, and the Marianas Trenches, and the Mariana trench. An eruption in the Marianas trench can lead to the formation of a large volcanic island arc. The Marianas Trench is the deepest part of the ocean and is found in the western Pacific Ocean.

Volcanism associated with convergent plate boundaries may also develop where slabs at oceanic lithosphere are subducted under continental lithosphere to produce a continental volcanic arc (Figure 9.34, lower left). These volcanic arcs may form along the western edge of South America, the Marianas Trench, and the western edge of South America. The volcanic chain of the Andes Mountains is one of the best examples of this kind of arc. The volcanic chain of the Andes Mountains is perhaps the best example of a mature continental volcanic arc. Since the Pacific basin is essentially bordered by convergent plate boundaries and associated subduction zones, it is easy to see why the irregular belt of volcanic arcs we call the Ring of Fire is formed in this region. The volcanoes of the Cascade Range in the northwestern United States, including Mt. Hood, Mt. Rainier, and Mount St. Helens, are included in this group (Figure 9.35).
Intraplate Igneous Activity

We know why igneous activity is along plate boundaries, but why do hot spots occur in the interior of Hawaii's hot spot is considered the most active volcano, yet it is situated in the middle of the active volcanic chain of islands. Some mantle plumes are thought to be responsible for the outpouring of basaltic lava, while others may be associated with hot spots, such as the Hawaiian Hot Spot. However, the cause of the volcanic activity on the island of Hawaii is still hotly debated. Many people appear to form deep basaltic magma at the core-mantle boundary, then rise up through the mantle, eroding them together. This activity continues as flows on the ocean floor. The magma eventually migrates upward along fractures in the crust and erupts at hot spots, forming new volcanic islands. This process generates large quantities of magma that may be responsible for the creation of new oceanic crust and the formation of new volcanic islands.

Intraplate Igneous Activity

Partial melting of mantle rock at spreading centers produces basaltic magma. Because this newly formed basaltic magma is less dense than the mantle rock from which it was derived, it migrates upward. Collecting in reservoirs located just beneath the ridge crests, about 10 percent of this molten material eventually migrates upward along fissures to escape as flows on the ocean floor. This activity continuously adds new rock to the plate margins, transforming them together to form new oceanic crust.

Volcanic Hazards

About 10 percent of Earth's population lives in the vicinity of an active volcano. In fact, several major cities including Seattle, Washington; Mexico City; Tokyo, Japan; Naples, Italy; and Quito, Ecuador, are located on or near a volcano.

Until recently, the dominant view of Western society was that humans possess the wherewithal to subdue volcanoes and other types of catastrophic natural hazards. It is now becoming increasingly apparent that volcanoes are not only very destructive but unpredictable as well. Despite this realization, the new focus is on how to live with volcanoes.

Living with Volcanoes

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Living with volcanoes.
The recent discovery of ground-based three-dimensional radar images shows that some volcanoes are detectable using radars at a wavelength of 0.3 m to 180 m. As a result, many volcanoes are now visible from space. This includes those that are too small to be detected by satellites, and (2) expansion of a near-surface magma chamber, which leads to inflation of the volcano; (3) changes in the amount and size of gas that escape from the volcano's vent, which include ash, pumice, lapilli, clinker, blocks, and bombs; (4) an increase in ground temperature caused by the emergence of hot water and steam.

The overlying goal of all monitoring techniques is to discover precursors that warn of an imminent eruption. This is accomplished by monitoring the conditions of a volcano and then using the baseline data to predict its future behavior. A method of monitoring volcanoes is to detect changes in the amount and size of gas that escape from the volcano's vent, which include ash, pumice, lapilli, clinker, blocks, and bombs.

Successive eruptions of lava from a central vent result in the formation of a single, large, nearly symmetrical structure built of interbedded pyroclastic deposits. Composite cones produce the largest calderas formed by the discharge of magma. The walls of the caldera collapse, forming a large, nearly circular depression called a caldera.

The roof of a volcano may rise all new magma accumulates at the base of the volcano. This is caused by the expansion of a near-surface magma chamber, which leads to inflation of the volcano. As the magma rises, it forces the overlying strata upward. This upward movement is called the volcanic bulge.

The materials associated with a volcanic eruption include magma and its products. Magma is the fluid, hot, and volatile part of the Earth's mantle that rises to the surface through volcanic vents. It consists of a mixture of gases, water, and solid minerals. Magma can be classified as basaltic, andesitic, or rhyolitic, based on its silica content. Basaltic magma is rich in iron and magnesium and is very fluid. Andesitic magma is intermediate in composition and is more viscous than basaltic magma. Rhyolitic magma is silica-rich and is very viscous and sticky.

In summary, the primary factors that determine the nature of volcanic eruptions include the magma's composition, the amount of dissolved gas it contains, and the amount of water it contains. As the magma rises, it begins to cool and solidify, and as it cools, its viscosity increases, its mobility decreases. The viscosity of magma is directly related to its silica content. Rhyolitic lava, which has a high silica content, is very viscous and forms short, thick flows. Basaltic lava, with a lower silica content, is more fluid and may travel long distances before being consumed. Dissolved gases provide the force that propels molten rock from the vent of a volcano.

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Moreover, stream courses follow. The rectangular drainage pattern developed rocks is controlled by the presence of the San Andreas Fault. When the fault is thought to contain its northwesterly trend, eventually joining the Mendocino fracture zone. In the second section, the San Andreas is relatively straight and parallel. However, at its two intersections, several branches spread out from the main trace, so that in some areas the fault zone exceeds 100 meters (300 feet) in width.

Over much of its extent, a linear trough formed by the presence of the San Andreas Fault. When the fault is thought to contain its northwesterly trend, eventually joining the Mendocino fracture zone. In the second section, the San Andreas is relatively straight and parallel. However, at its two intersections, several branches spread out from the main trace, so that in some areas the fault zone exceeds 100 meters (300 feet) in width.

Many rocks are broken by two or three sets of intersecting joints that slice the rock into numerous regularly shaped blocks. These joint sets often exert a strong influence on other geologic processes. For example, chemical weathering tends to be concentrated along joints, and in many areas groundwater movement and the resulting dissolution in soluble rocks is controlled by the joint pattern (Figure 10.12). Moreover, a system of joints can influence the direction that stream courses follow. The rectangular drainage pattern described in Chapter 8 is such a case.

Mountain Building

Mountain Building

TABLE 10.1 Major Earthquakes on the San Andreas Fault System

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Magnitude</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1812</td>
<td>Wrightwood, CA</td>
<td>7</td>
<td>Church at San Juan Capistrano collapsed, killing 40 worshipers.</td>
</tr>
<tr>
<td>1857</td>
<td>San Francisco peninsula</td>
<td>5.2</td>
<td>At least 10 people were killed by the earthquake.</td>
</tr>
<tr>
<td>1868</td>
<td>Fort Tejon, CA</td>
<td>7.5</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
<tr>
<td>1892</td>
<td>San Andreas, CA</td>
<td>7.8</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
<tr>
<td>1906</td>
<td>Imperial Valley</td>
<td>8.2</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
<tr>
<td>1906</td>
<td>Kern County</td>
<td>7.0</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
<tr>
<td>1964</td>
<td>San Fernando Valley</td>
<td>7.0</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
<tr>
<td>1964</td>
<td>Santa Cruz Mountains</td>
<td>7.5</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
<tr>
<td>1964</td>
<td>Northridge, Los Angeles</td>
<td>6.9</td>
<td>Largest earthquake in California since 1857.</td>
</tr>
</tbody>
</table>
BOX 14.1 PEOPLE AND THE ENVIRONMENT

Desalination of Seawater—Fresh Water from the Sea

Earth's growing population uses fresh water in greater volumes each year. As fresh water becomes increasingly scarce, several countries have begun using the ocean as a source of water. The removal of salts and other chemicals to extract low-salinity (“fresh”) water from seawater is termed desalination.

Worldwide, there are more than 12,500 desalination plants (Figure 14.4), with the majority located in water deficit regions of the Middle East, Caribbean, and Mediterranean. The United States produces only about 10 percent of the world's desalted water, primarily in Florida. To date, only a limited number of desalination plants have been built along the California coast, primarily because the cost of desalination is generally higher than the costs of other water supplies. However, as drought conditions occur and concern over water availability increases, desalination projects are being proposed at numerous locations in the state.

Because desalinated water is expensive to produce, most desalination plants are small-scale operations. In fact, desalination plants provide only about 1 percent of the world's drinking water.

In desalination, seawater is evaporated, and the resulting saltwater vapor is condensed and cooled to produce fresh water. This simple procedure is very efficient at purifying seawater. For instance, distillation of 35% seawater produces fresh water with a salinity of only 0.003%, which is about 10 times fresher than bottled water.

Density Variation with Depth

By extensively sampling ocean waters, oceanographers have learned that temperature and salinity—and the water's resulting density—vary with depth. Figure 14.4 shows two graphs of density versus depth: one for high-latitude regions and one for low-latitude regions. Not surprisingly, the curves in Figure 14.4 are a mirror image of the temperature curves in Figure 14.4. This similarity demonstrates that temperature is the most important factor affecting seawater density and that temperature is inversely proportional with density.

Ocean Density Variation

The ocean, like Earth's interior, is layered according to density. Low-density water exists near the surface, and high-density water occurs below. Except for some shallow inlets, with a high rate of evaporation, the highest-density water in the world is found at the greatest ocean depths. Oceanographers generally recognize a three-layered structure in most parts of the open ocean: a shallow surface mixed zone, a transition zone, and a deep zone (Figure 14.7).

Because solar energy is received at the ocean surface, it is here that water temperatures are warmest. The mixing of these waters by waves as well as the turbulence from currents and tides creates a rapid vertical heat transfer. Hence, the surface mixed zone has nearly uniform temperatures. The thickness and temperature of this layer vary, depending on latitude and season. The zone usually extends to about 30 meters (98 feet) but may attain a thickness of 450 meters (1,480 feet). The surface mixed zone accounts for about 2 percent of ocean water.

Below the sun-warmed mixing layer, the temperature falls abruptly with depth (see Figure 14.4). Here, a distinct layer called the transition zone exists between the warm surface layer above and the deep cold water below. The transition zone includes a prominent thermocline and accounts for about 18 percent of ocean water.

Below the transition zone is the deep zone, where sunlight never reaches and water temperatures are just a few degrees above freezing. As a result, deep water remains dense and high. Remarkably, the deep zone includes about 80 percent of ocean water, indicating the immense depth of the ocean (the average depth of the ocean is 3,792 meters, or 12,434 feet).

In high latitudes, the three-layer structure of ocean layers does not exist because the water column is isothermal and isopycnal, which means that there is no rapid change in water properties with depth. Consequently, good vertical mixing between surface and deep waters can occur in high-latitude regions. Here, cold high-density water forms at the surface, sinks, and initiates deep-ocean currents, which are discussed in Chapter 15.

FIGURE 14.4 Variations in ocean water density with depth for low- and high-latitude regions. The layer of rapidly changing density, called the pycnocline, is present in the low latitudes but absent in the high latitudes.

FIGURE 14.7 Oceanographers recognize three main layers in the ocean based on water density: the surface mixed zone, the transition zone, and the deep zone. The deep zone is characterized by uniform temperature and density.

FIGURE 14.8 Density curves for low latitudes (left) and high latitudes (right). The high-latitude curve in Figure 14.8 begins at the surface with low density (related to high surface water temperatures) and increases rapidly with depth because the water temperature is getting colder. At a depth of about 1,000 meters (3,300 feet), seawater density reaches a maximum value related to the water's low temperature. Pycnocline is the ocean floor, density remains constant and high. The layer of ocean water between about 300 meters (980 feet) and 1,000 meters (3,300 feet) is where there's a rapid change in density with depth, called the pycnocline (pycnocline = density = slope). A pycnocline has a high gravitational stability and prevents a significant barrier to mixing between low-density water above and high-density water below. The high-latitude curve in Figure 14.8 is also related to the transition zone, where a prominent thermocline and accounts for about 18 percent of ocean water.

FIGURE 14.9 Temperature and salinity profiles for a mid-latitude ocean. The surface mixed zone is characterized by uniform temperature and density.
increase in size. When the maximum fetch and duration are reached for a given wind velocity, the waves are said to be "fully developed." The reason that waves can grow so further is that they are losing as much energy through the breaking of whitecaps as they are receiving energy from the wind.

When the wind stops or changes direction, or if the waves leave the storm area where they were created, they continue on without relation to local winds. The waves also undergo a gradual change to swell, a term that describes any wave that has traveled out of its area of origination. Swells are lower in height and longer in length and may carry a storm's energy to distant shores. Because many independent wave systems exist at the same time, the sea surface acquires a complex and irregular pattern, sometimes producing very large waves (see Box 15.2). The sea waves that are seen from shore are usually a mixture of swells from faraway storms and waves created by local winds.

**Circular Orbital Motion**

Waves can travel great distances across ocean basins. In one study, waves generated near Antarctica were tracked as they traveled through the Pacific Ocean basin. After more than 10,000 kilometers (over 6,000 miles), the waves finally expended their energy a week later along the shoreline of the Aleutian Islands of Alaska. The water itself doesn't travel the entire distance, but the waves from there. As the wave travels, the water rides the energy along by moving in a circle. This motion is called circular orbital motion.

Observation of an object floating in waves shows that it moves not only up and down but also slightly forward and backward with each successive wave. Figure 15.13 shows that a floating object moves up and downward with the crest approaches, up and forward as the crest passes, down and forward after the crest, down and backward as the trough approaches, and rises and moves backward again as the next crest advances. When the movement of the floating toy boat shown in Figure 15.13 is traced as a wave passes, it can be seen that the boat moves in a circle and it returns to essentially the same place. Circular orbital motion allows a waveform (the wave's shape) to move forward through the water while the individual water particles transmit the wave move around in a circle. Wind moving across a field of wheat causes

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**FIGURE 15.12** Diagrammatic view of an idealized non-breaking crest wave showing the basic concepts of a wave as well as the movement of water particles at depth. Negligible water movement occurs below a depth equal to one half the wavelength (lower dashed line).

**FIGURE 15.13** The movement of the toy boat shows that the wave moves forward, but the water does not advance appreciably from its original position. In this sequence, the wave moves from left to right as the boat rides the water in which it is floating relative to an imaginary circle.

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**BOX 15.2 PEOPLE AND THE ENVIRONMENT**

**Rogue Waves—Ships Beware!**

Rogue waves are massive, solitary waves that can form under extraordinary conditions and create enormous heights and are often called freak waves. For example, a 28-meter (92-foot) rogue wave may suddenly appear, without any warning, on the horizon. These waves are generated near Antarctica were tracked as they traveled to the Atlantic and encountered a rogue wave that did considerable damage to the ship's superstructure. In 1960, for example, the luxury liner Andrea Doria, which was carrying 2,500 people, was caught in a storm in the North Atlantic and encountered a rogue wave that did considerable damage to the ship's superstructure. In 1966, a 36-meter (120-foot) wave struck the Andrea Doria during a North Atlantic storm. In 1960, a large ship was caught in a storm in the North Atlantic and encountered a rogue wave that did considerable damage to the ship's superstructure. In 1966, a 36-meter (120-foot) wave struck the Andrea Doria during a North Atlantic storm. In 1960, a large ship was caught in a storm in the North Atlantic and encountered a rogue wave that did considerable damage to the ship's superstructure.

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**Waves in the Surf Zone**

As long as a wave is in deep water, it is unaffected by water depth (Figure 15.14, left). However, when a wave approaches the shore, the water becomes shallower and influences wave behavior. The wave begins to "feel bottom" at a water depth equal to its wave base. Such depths interfere with water movement at the base of the wave and slow its advance (Figure 15.14, center). As a wave advances toward the shore, the slightly faster waves faster to the front of the wave, decreasing the wavelength.
Many coastal scientists and planners are calling for a policy shift from defending and rebuilding beaches and coastal property in high hazard areas to relocating storm-damaged or at-risk buildings and letting nature reclaim the beach. This approach is similar to that adopted by the federal government for river floodplains following the devastating 1993

Mississippi River floods in which vulnerable structures were abandoned and relocated on higher, safer ground.

Such proposals, of course, are controversial. People with significant shoreline investments shoulder the threat of not rebuilding and defending coastal development from the annual wrath of the sea. Others, however, argue that

LEVEL RISING, THE IMPACT OF COASTAL STORMS WILL ONLY GET WORSE IN THE DECADES TO COME. THIS GROUP ADVOCATES THAT DAMAGED STRUCTURES BE ABANDONED OR TRANSFORMED TO IMPROVE SAFETY AND REDUCE COSTS. SUCH IDEAS WILL NO DOUBT BE THE FOCUS OF MUCH STUDY AND DISCUSSION AS STATES AND COMMUNITIES EVALUATE AND REVISE COASTAL LAND-USE POLICIES.

Erosion Problems Along U.S. Coasts

The shoreline along the Pacific Coast of the United States is markedly different from that characterizing the Atlantic and Gulf Coast regions. Some of the differences are related to plate tectonics. The West Coast represents a boundary of the North American plate, and because of this, it has experienced much greater vertical movement and deformation. By contrast, the East Coast is a tectonically quiet region that is far from any active plate margin. Because of this basic geologic difference, the nature of shoreline erosion problems along America's opposite coasts is different.

Atlantic and Gulf Coasts

Much of the coastal development along the Atlantic and Gulf coasts has occurred on barrier islands. Typically, barrier islands consist of a wide beach that is backed by dunes and separated from the mainland by marshy bays. The broad expanse of sand and exposure to the ocean have made barrier islands exceedingly attractive sites for development. Unfortunately, development has taken place much too rapidly than has our understanding of barrier island dynamics.

Because barrier islands face the open ocean, they receive the full force of major storms that strike the coast. When a storm occurs, the barriers absorb the energy of the waves primarily through the movement of sand (Figure 15.29). This process and the dilemma that results have been described as follows:

Waves may move sand from the beach to offshore areas or, conversely, into the dunes; they may erode the dunes, deposit sand onto the beach or carry it out to sea; or they may carry sand from the beach and the dunes into the breakers behind the barrier, a process known as overwash.

The common factor is movement. Just as a flexible reed may survive a wind that destroys an oak tree, so the barriers survive hurricanes and nor'easters not through unyielding strength but by giving before the storm.

The picture changes when a barrier is developed for homes or a resort. Storm waves that previously rushed harmlessly through gaps between the dunes now encounter buildings and embayments. Moreover, since the dynamic nature of the barrier is readily perceived only during storms, homeowners tend to attribute damage to a particular storm, rather than to the basic mobility of coastal barriers. With these losses or investments at stake, local residents are more likely to seek to hold the sand in place and the waves at bay than to admit that development was improperly placed to begin with.

The West Coast, like the East Coast, has many narrow beaches that are backed by cliffs.

Although the retreat of the cliffs provides material to reconstitute the beach from the mountains, the increase in runoff, which is not controlled, can result in serious bluff erosion. Watershed runoff and gases release significant quantities of water to the slope. This water percolates downward toward the base of the cliff,

FIGURE 16.28 Miami Beach: A. Before beach nourishment; B. After beach nourishment. (Courtesy of the U.S. Army Corps of Engineers, Vicksburg District)

Erosion Problems Along U.S. Coasts

In contrast to the broad, gently sloping coastal plains of the Atlantic and Gulf coasts, much of the Pacific Coast is characterized by relatively narrow beaches that are backed by steep cliffs and mountain ranges. Recall that America's western margin is a more rugged and tectonically active region than the eastern margin. Because uplift continues, the rate of sea level rise in the West is not so readily apparent. Nevertheless, like the shoreline erosion problems facing the East's barrier islands, West Coast difficulties also stem largely from the alteration of natural systems by people.

A major problem facing the Pacific shoreline—particularly along southern California—isa significant narrowing of many beaches. The bulk of the sand on many of these beaches is supplied by rivers that transport it from the mountainous regions to the coast. Over the years this natural flow of material to the coast has been interrupted by dams built for irrigation and flood control. The reservoirs effectively trap the sand that would otherwise nourish the beach environment. When the beaches were wider, they served to protect the cliffs behind them from the force of storm waves. Now, however, the waves move across the narrowed beaches without losing much energy and cause more rapid erosion of the sea cliffs.

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FIGURE 15.29 When the lighthouse at Cape Hatteras, North Carolina, was built in 1797, it stood 457 meters (1,500 feet) from the shoreline. By 1970, waves began to lap just 37 meters (120 feet) from its base. In order to save the historic structure, it was moved 468 meters (1,500 feet) back from the shore. At the current rate of shoreline retreat, the lighthouse should be safe for another 50 years. (Photo by Reuters/ Stringer/Getty Images, Inc.—Hulton Archive Photos)
Students Sometimes Ask... 

Who provides all of the data needed to prepare a weather forecast?

Data from every part of the globe are needed to produce accurate weather forecasts. The World Meteorological Organization (WMO) is established by the United Nations to coordinate scientific activity related to weather and climate. It consists of 193 countries and territories representing all parts of the globe. In addition to the standards and regulations developed, the WMO provides up-to-the-minute standardized observations through its network of meteorological observation systems. This global system involves 10,000 land-based stations and 7,000 ship stations, as well as hundreds of automated data采集ers and thousands of aircraft.

Thus, if you were planning a vacation trip to an unfamiliar place, you would want to know what kind of weather to expect. Such information would help as you select clothes to pack and could influence decisions regarding activities you might engage in during your stay. Unfortunately, weather forecasts that go beyond a few days are not very dependable. Thus, it would not be possible to get a reliable weather report about the conditions you are likely to encounter during your stay.

Instead, you might ask someone who is familiar with the area about what kind of weather to expect. "Are thunderstorms common?" "Does it get cold at night?" "Are the afternoons sunny?" "What are storms common?" "Does it get cold at night?" "Are the afternoons sunny?" What you are seeking is information that is common to that place. Another useful source of such information is the great variety of climate tables, maps, and graphs that are available. For example, the graph in Figure 16.3 shows average daily high and low temperatures for each month, as well as extremes for New York City.

Such information could not doubt help as you planned your trip. But it is important to realize that climate data cannot predict the weather. Although the place may usually (climatically) be warm, sunny, and dry during the time of your planned vacation, you may actually experience cool, overcast, and rainy weather. There is a well-known saying that summarizes this idea: "Climate is what you expect, but weather is what you get."

The nature of weather and climate is expressed in terms of the same basic elements, those quantities or properties that are measured regularly. The most important are (1) air temperature, (2) humidity, (3) type and amount of cloudiness, (4) type and amount of precipitation, (5) air pressure, and (6) the speed and direction of the wind. These elements are the major variables from which weather patterns and climates are depicted. Although you will study these elements separately at first, keep in mind that they are very much interrelated. A change in any one of the elements will often bring about changes in the others.

Composition of the Atmosphere

introduction to the atmosphere

Air is not a unique element or compound. Rather, air is a mixture of many discrete gases, each with its own physical properties, in which varying quantities of tiny solid and liquid particles are suspended.

Major Components

The composition of air is not constant. It varies from time in time and from place to place (Box 16.1). If the water vapor, dust, and other variable components are removed from the atmosphere, we would find that its makeup is very stable worldwide up to an altitude of about 80 kilometers (50 miles).
Ozone Depletion—A Global Issue

The loss of ozone high in the atmosphere as a consequence of human activities is a serious global-scale environmental problem (Figure 16.1). For nearly a billion years Earth's ozone layer has protected life on the planet. However, over the past half century, people have unintentionally placed the ozone layer in jeopardy by polluting the atmosphere. The most significant of the polluting chemicals are known as chlorofluorocarbons (CFCs for short). They are versatile compounds that are chemically stable, odourless, non-toxic, and inexpensive to produce. Over the decades many uses were developed for CFCs, including as coolants for air-conditioning and refrigeration equipment, cleaning solvents for electronic components, propellants for aerosol sprays, and the production of certain plastic foams.

No one worried about how CFCs might affect the atmosphere until three scientists—Paul Crutzen, F. Sherwood Rowland, and Mario Molina—stated the relationship. In 1974 they alerted the world when they reported that CFCs were probably reducing the average concentration of ozone in the atmosphere. In 1995 these scientists were awarded the Nobel Prize in chemistry for their pioneering work.

They discovered that because CFCs are practically inert (i.e., not chemically active) in the lower atmosphere, a portion of these gases gradually makes its way to the ozone layer, where sunlight separates the chemical into its constituent atoms. The chlorine atoms released this way, through a complicated series of reactions, harm the net effect of removing some of the ozone.

Because ozone filters out most of the ultraviolet (UV) radiation from the Sun, a decrease in its concentration permits more of these harmful wavelengths to reach Earth's surface. The most serious threat to human health is an increased risk of skin cancer. An increase in damaging UV radiation also can impair the human immune system as well as promote cataracts, a clouding of the eye lens that reduces vision and may cause blindness if not treated.

Realizing that the risks of not curbing CFC emissions were difficult to ignore, an international agreement known as Montreal Protocol on Substances That Deplete the Ozone Layer was concluded under auspices of the United Nations. More than 180 nations eventually ratified the treaty. Although relatively strong action was taken, CFC levels in the atmosphere will drop rapidly. Once in the atmosphere, CFC molecules can take many years to reach the ozone layer and once there, they can remain active for decades. This does not provide near-term reprieve for the ozone layer.

The Montreal Protocol represents a positive international response to a global environmental problem. As a result of the action, the total abundance of ozone-depleting gases in the atmosphere is expected to decrease in recent years. If the actions of the world continue to follow the provisions of the protocol, the decrease is expected to continue through the twenty-first century. Some scientists think climate change may affect the abundance of ozone-depleting gases, but the overall trend is expected to be downward.

Students Sometimes Ask...

Isn't ozone some sort of pollutant?

Yes, you're right. Although the naturally occurring ozone in the stratosphere is critical to life on Earth, it is regarded as a pollutant when produced at ground level because it can damage vegetation and be harmful to human health. Ozone is a major component in a noxious mixture of gases and particles called photochemical smog. It forms as a result of reactions triggered by sunlight that occur among pollutants emitted by motor vehicles and industries.

Height and Structure of the Atmosphere

Earth's Dynamic Atmosphere

To say that the atmosphere begins at Earth's surface and extends upward is obvious. However, where does the atmosphere end and outer space begin? There is no sharp boundary: the atmosphere rapidly thins as you travel away from Earth, until there are too few gas molecules to detect.

Pressure Changes

To understand the vertical extent of the atmosphere, let us examine the changes in the atmospheric pressure with height. Atmospheric pressure is simply the weight of the air above. At sea level, the average pressure is slightly more than 1,000 millibars. This corresponds to a weight of slightly more than 1 kilogram per square centimeter (14.7 pounds per square inch). Obviously the pressure at higher altitudes is less (Figure 16.6).

One half of the atmosphere lies below an altitude of 5.6 kilometers (3.5 miles). At about 16 kilometers (10 miles), 80 percent of the atmosphere has been traversed, and above 80 kilometers (50 miles), only 0.00001 percent of all the gases making up the atmosphere remains. Even so, traces of our atmosphere extend far beyond this altitude, gradually merging with the emptiness of space.

Temperature Changes

By the early twentieth century, much had been learned about the lower atmosphere. The upper atmosphere was largely known from indirect methods. Data from balloons and kites had revealed that the air temperature dropped with increasing height above Earth's surface. This phenomenon is felt by anyone who has climbed a high mountain or mountain top and found the air temperature drastically lower than at sea level. The cold air causes the body to shiver and the skin to become numb. 

The thickness of the atmosphere is not the same everywhere. It varies with latitude and the season. On the average, the temperature drop continues to a height of about 12 kilometers (7.4 miles). The outer boundary of the atmosphere is called the stratosphere.

Stratosphere Beyond the troposphere is the stratosphere. In this stratosphere, the temperature remains constant to a height of about 20 kilometers (12 miles) and then begins a gradual
Atmospheric Stability and Air Pollution

Air quality is not just a function of the quantity and types of pollutants emitted into the air, but it is also closely linked to the atmosphere's ability to disperse these noxious substances. Perhaps you have heard the well-known phrase: "The solution to pollution is dilution." At a significant degree this is true. If the air in which the pollution is released is not dispersed, the air will become more toxic. Two of the most important atmospheric conditions affecting the dispersion of pollutants are the strength of the wind and the stability of the air. These factors are critical because they determine how rapidly pollutants are diluted by mixing with the surrounding air after leaving the source.

The way in which wind speed influences the concentration of pollutants is straightforward. When winds are weak or calm, the concentration of pollutants is higher than when winds are strong. High wind speeds mix pollutants into a greater volume of surrounding air and therefore cause the pollution to be more diluted. When winds are light, there is less turbulence and mixing, so the concentration of pollutants is higher.

Whereas wind speed governs the amount of air into which pollutants are initially mixed, atmospheric stability determines the extent to which vertical motions will mix the pollutants with cleaner air above. The distance between Earth's surface and the height to which vertical air movements extend is termed the mixing depth. Generally, the greater the mixing depth, the better the air quality. When the mixing depth is several kilometers, pollutants are mixed through a large volume of cleaner air and diluted rapidly. When the mixing depth is small, pollutants are confined to a much smaller volume of air and concentrations can reach unhealthy levels. When air is stable vertical motions are suppressed and mixing depths are small. Conversely, unstable atmosphere promotes vertical air movements and greater mixing depths. Because heating of Earth's surface by the Sun enhances convective movements, mixing depths are usually greater during the afternoon hours. For the same reason, mixing depths during the summer months are typically greater than during the winter months.

Temperature inversion represents a situation in which the atmosphere is very stable, and the mixing depth is significantly affected. Warm air overlying cooler air acts as a lid and prevents upward movements of the pollutants trapped in a relatively narrow zone near the ground level. Inversions are generally classified as one of two categories - those that form at the ground and those that form aloft. Atmospheric inversions develop when hot air is forced aloft, such as during a day with high temperatures. On the other hand, during a day with low temperatures, inversions develop when cold air is forced down.

Stability and Daily Weather

From the previous discussion, we can conclude that stable air resists vertical movement, whereas unstable air ascends freely because of its own buoyancy. But how do these facts manifest themselves in our daily weather?

Because stable air resists upward movement, we might conclude that clouds will not form when stable conditions prevail in the atmosphere. Although this seems reasonable, recall that processes exist that force air aloft. These include orographic lifting, frontal wedging, and convergence. When stable air is forced aloft, the clouds that form are widespread and have little vertical development compared to their horizontal dimension, and precipitation, if any, is light to moderate.

By contrast, clouds associated with the lifting of unstable air are towering and often generate thunderstorms and occasionally even a tornado. For this reason, we can conclude that on a sunny, overcast day with light drizzle, stable air has been forced aloft. On the other hand, during a day with cold, snow-covered clouds appearing to be growing in the absence of any lifting it is possible that the ascending air is unstable.

In summary, stability plays an important role in determining our daily weather. To a large degree, stability determines the type of clouds that develop and whether precipitation occurs as a gentle shower or a heavy downpour.

Condensation and Cloud Formation

To review briefly, condensation occurs when water vapor in the air changes to a liquid. The result of this process may be fog, dew, or clouds. For any of these forms of condensate to occur, the air must be saturated. Saturation occurs when air is cooled to its dew point or when water vapor is added to the air.

In the formation of a cloud consisting of millions upon millions of tiny water droplets, all so fine that they remain suspended in the air. When cloud formation occurs, the air becomes saturated, and tiny ice crystals form. This cloud might consist of water droplets, ice crystals, or both.

The slow growth of cloud droplets by additional condensation and the immense size difference between cloud droplets and raindrops suggests that condensation alone is not sufficient for the formation of drops large enough to fall as rain. We first examine clouds and then turn to the mechanisms of how precipitation forms.

Types of Clouds

Clouds are among the most conspicuous and observable aspects of the atmosphere and its weather. Clouds are a form of condensation best described as visible aggregates of minute droplets of water or tiny crystals of ice. In addition to being
Science and Serendipity

Serendipity is defined by Nobel Laureate Irving Langmuir as "the art of profiting from unexpected occurrences." In other words, if you are observing something and the entirely unexpected happens, and if you see this in a new and meaningful discovery, then you have experienced serendipity. Most scientists, some scientists, and, alas, many teachers are not aware that many of the great discoveries in science were serendipitous.

An excellent example of serendipity in science occurred when Tor Bergeron, the great Swedish meteorologist, discovered the importance of ice crystals in the initiation of precipitation in supercooled clouds. Bergeron's discovery occurred when he spent several weeks at a beach in southern California, generally becoming bored in the atmosphere and not generally become active until the temperature reaches -10°C (-14°F) or less.

**FIGURE 17.2** Distribution of fog when the temperature is above freezing and when the temperature falls to -10°C.

Bergeron immediately concluded that temperatures below about -5°C the branches of the trees acted as freezing nuclei upon which some of the supercooled droplets crystallized. Once the ice crystals developed, they grew rapidly at the expense of the remaining water droplets (see Figure 17.3). The result was the growth of ice crystals (white) on the branches of the frosty tree. The temperature at which this occurs is known as the "freezing point" or "freezing temperature." The process of condensation is illustrated in Figure 17.3.

**Supercooling** When air is saturated (100 percent relative humidity) with respect to water, it is supercooled (relative humidity is greater than 100 percent) with respect to ice. Table 17.3 shows that at -10°C (14°F), when the relative humidity is 100 percent with respect to water, the relative humidity with respect to ice is nearly 90 percent. Thus, ice crystals cannot exist with water droplets, because the air always appears supercooled with respect to ice. Hence, the ice crystals begin to consume the "excess" water vapor, which lowers the relative humidity near the surrounding droplets. In turn, the water droplets evaporate to replenish the diminishing water vapor, thereby providing a continual source of vapor for the growth of the ice crystals (Figure 17.2).

Because the level of supercooling with respect to ice can be quite high, the growth of ice crystals is generally rapid enough to generate clouds large enough to fall. During their descent, these ice crystals enlarge as they intercept cloud droplets, which freeze upon them. Air movement will sometimes break up these delicate crystals and the fragments will serve as freezing nuclei. A chain reaction develops, producing many ice crystals, which, by accretion form into large crystals called snowflakes.

In summary, the Bergeron process can produce precipitation throughout the year in the middle latitudes, provided that the upper portions of clouds are cold enough to generate ice crystals. The type of precipitation (snow, sleet, rain, or freezing rain) that reaches the ground depends on the temperature profile in the lower few kilometers of the atmosphere. When the surface temperature is above 0°C (32°F), ice nuclei are unlikely to form before reaching the ground and continue their descent as rain. Even on a hot summer day, a heavy downpour may have begun as a snowstorm high in the clouds overhead.

**TABLE 17.3** Relative Humidity with Respect to Ice When Relative Humidity with Respect to Water is 100 Percent

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Relative Humidity with Respect to Water (%)</th>
<th>Relative Humidity with Respect to Ice (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>100</td>
<td>121</td>
</tr>
<tr>
<td>-15</td>
<td>100</td>
<td>116</td>
</tr>
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<td>100</td>
<td>111</td>
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<td>100</td>
<td>83</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>78</td>
</tr>
</tbody>
</table>

**FIGURE 17.2** The Bergeron process: Ice crystals grow at the expense of cloud droplets until they are large enough to fall. The size of these particles has been greatly exaggerated.

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**Students Sometimes Ask...**

What is the snowiest city in the United States?

According to National Weather Service records, Rochester, New York, averages nearly 239 centimeters (94 inches) of snow annually, the snowiest city in the United States. However, Boulder, Colorado, has a close run-off.

Only at temperatures well below freezing will ice crystals begin to form in clouds, and even then, it will be far and few between. Once ice crystals form, they are in competition with the supercooled droplets for the available water vapor.

Research has shown that clouds composed entirely of liquid droplets must contain some droplets larger than 20 micrometers (0.02 millimeters) if precipitation is to form. These large droplets form when "giant" condensation nuclei are present, or when hygroscopic particles such as sea salt exist. Hygroscopic particles begin to remove water vapor from the air at relative humidities under 100 percent and can grow quite large. Because the rate at which drops fall is size-dependent, these "giant" droplets fall most rapidly. As they plummet, they collide with smaller, slower droplets and coalesce. Growing larger in the process, they fall even more rap-
Wind Energy—An Alternative with Potential

Air has mass, and when it moves (i.e., when the wind blows), it contains the energy of that motion—kinetic energy. A portion of that energy can be converted into other forms—mechanical force or electricity—that we can use to perform work (Figure 18.1).

Mechanical energy from wind is commonly used for pumping water in rural or remote places. The "windmill," still a familiar site in many rural areas, is an example. Mechanical energy converted from wind can also be used for other purposes, such as generating logos, grinding grain, and propelling sailboats. By contrast, wind-powered electricity generates electricity for homes, businesses, and for sale to utilities.

Approximately 0.25 percent (or about 4 percent of the solar energy) reaches the lower atmosphere in the form of wind. Although it is just a small fraction of the available solar energy, wind energy is enormous. According to one estimate, North Dakota alone is technically capable of producing enough wind-generated power to meet more than one-third of its electricity demand. Wind speed is an essential element in determining whether a particular site is suitable for installing a wind-electricity facility. Generally a minimum average wind speed of 21 kilometers (13 miles) per hour is necessary for a utility-scale wind power plant.

The power available in the wind is proportional to the cube of its speed. Thus a turbine operating at a site with an average wind speed of 12 meters per second could in theory generate about 33 percent more electricity than an identical turbine operating at 11 meters per second. In the real world, this potential difference would not be realized because of factors such as terrain that affect the wind speed. The important thing to remember is that a difference in wind speed can mean a large difference in the available energy and in electricity produced, and therefore a large difference in the cost of the electricity generated. Also, the less the wind blows, the less the electricity produced.

### Local Winds

Having examined Earth's large-scale circulation, let us turn briefly to winds that influence much smaller areas. Remember that all winds are produced for the same reasons—pressure differences that arise because of temperature differences that are caused by unequal heating of Earth's surface. Local winds are simply small-scale winds produced by a locally generated pressure gradient. Those described here are caused either by topographic effects or variations in surface composition in the immediate area.

#### Land and Sea Breezes

In coastal areas during the warm summer months, the land surface is heated more intensely during the day than the adjacent body of water (see the section "Land and Water" in Chapter 16). As a result, the air above the land surface heats, expands, and rises, creating an area of lower pressure. A sea breeze then develops, because cools in the water (higher pressure) moves toward the warmer land (lower pressure) [Figure 18.1A]. The sea breeze begins to develop shortly after noon and generally reaches its greatest intensity during the mid- to late afternoon. These relatively cool winds can be a significant moderating influence on afternoon temperatures in coastal areas.

At night, the reverse may take place. The land cools more rapidly than the sea, and the land breeze develops [Figure 18.1B]. Small-scale sea breezes and land breezes can also develop along the shores of large lakes. People who live in a city near a large lake, such as Chicago, recognize this land breeze, especially in the summer. They are reminded daily by weather reports...
Students Sometimes Ask...

Some tornado watches may include people who have been living through a tornado warning for several hours, and some tornado warnings may be issued for areas that are already under a tornado watch. These watches and warnings are both critical to the safety of the public, and they are issued by the National Weather Service (NWS) in cooperation with local, state, and federal agencies.

Tornadoes are small, rotating columns of air that are in contact with the ground. They are often associated with severe thunderstorms and can cause significant damage to property and infrastructure. The National Weather Service uses a scale to rate the intensity of tornadoes, with categories ranging from F0 (very weak) to F5 (extremely strong).

Tornadoes can be very dangerous, but there are ways to prepare for them. The best way to prepare is to have a plan in place and to stay informed about the weather. If a tornado is expected in your area, make sure you know where to go and what to do. If you are in a building, go to an interior room on the lowest level, away from windows and external doors. If you are outside, seek shelter in a vehicle or lie in a low, sturdy ditch with your hands over your head.

Tornadoes can strike suddenly, so it's important to be prepared. Have a plan in place and know what to do in case of a tornado. Stay informed and be ready to take action to protect yourself and your loved ones.