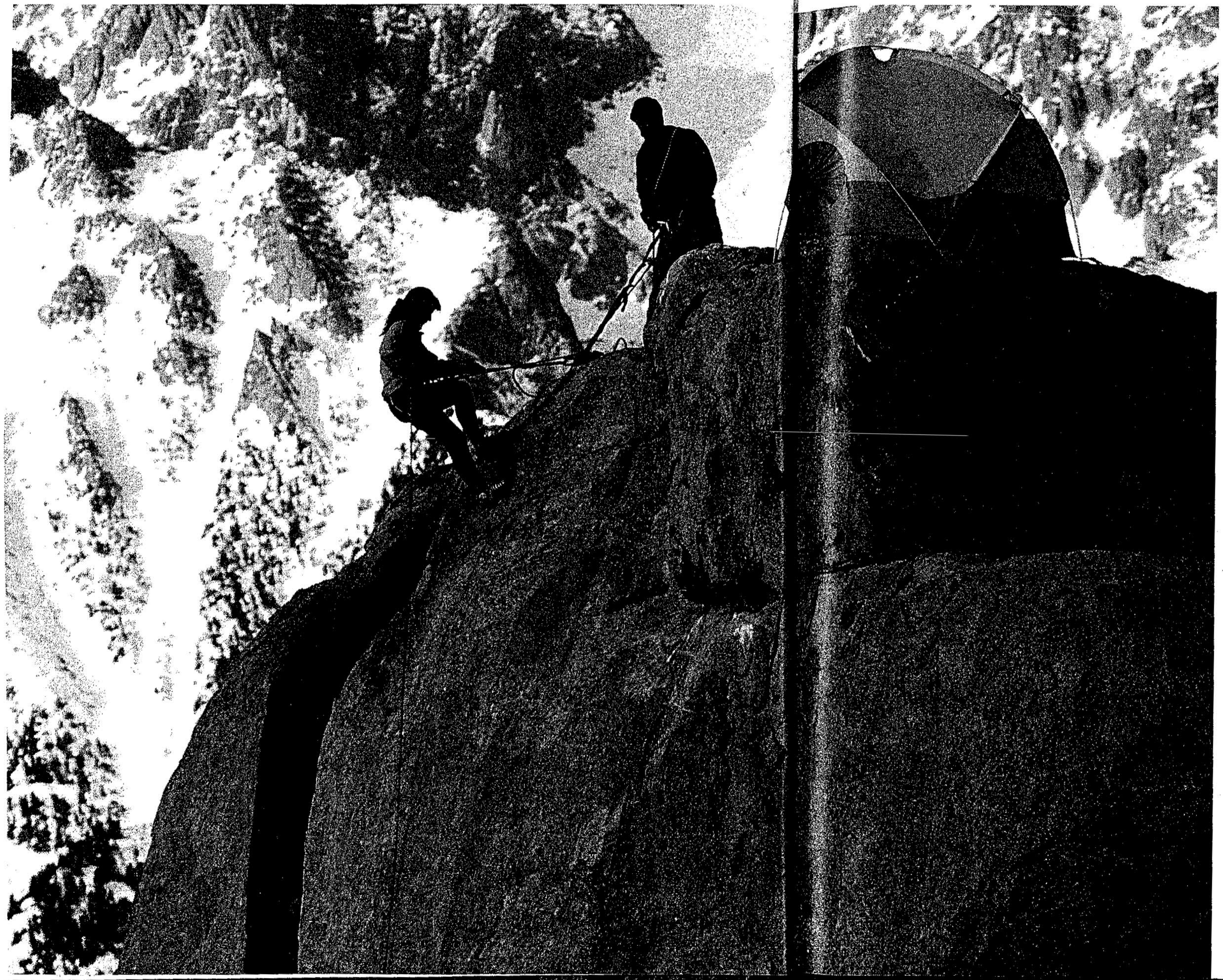

TWELFTH EDITION

EARTH SCIENCE

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Illustrated by

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GEODe: Earth Science v.3

A copy of *GEODe: Earth Science*, v.3 is packaged with each copy of ***Earth Science***, Twelth Edition.
This dynamic learning aid reinforces key concepts by using tutorials, animations, and interactive exercises.

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A. **Minerals**
  1. Introduction to Minerals
  2. Mineral Groups
  3. Physical Properties of Minerals
  4. Quiz: Minerals

B. **Rock Cycle**

C. **Igneous Rocks**
  1. Introduction to Igneous rocks
  2. Igneous Textures
  3. Igneous Compositions
  4. Naming Igneous Rocks
  5. Quiz: Igneous Rocks

D. **Sedimentary Rocks**
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  2. Types of Sedimentary Rocks
  3. Sedimentary Environments
  4. Quiz: Sedimentary Rocks

E. **Metamorphic Rocks**
  1. Introduction to Metamorphic Rocks
  2. Agents of Metamorphism
  3. Textural and Mineralogical Changes
  4. Common Metamorphic Rocks
  5. Quiz: Metamorphic Rocks

Unit 2: Sculpturing Earth's Surface

A. **Weathering and Soil** ***ALL NEW***
  1. Earth's External Processes
  2. Types of Weathering
  3. Mechanical Weathering
  4. Chemical Weathering
  5. Rates of Weathering
  6. Quiz: Weathering and Soil

B. **Mass Wasting: The Work of Gravity** ***ALL NEW***
  1. Controls and Triggers of Mass Wasting
  2. Mass-Wasting Processes
  3. Quiz: Mass Wasting

C. **Running Water**
  1. Hydrologic Cycle
  2. Stream Characteristics
  3. Reviewing Valleys and Stream-Related Features ***NEW SECTION***
  4. Quiz: Running Water

D. **Groundwater**
  1. Importance and Distribution
  2. Springs and Wells
  3. Quiz: Groundwater

E. **Glaciers and Glaciation**
  1. Introduction
  2. Budget of a Glacier
  3. Reviewing Glacial Features ***NEW SECTION***
  4. Quiz: Glaciers and Glaciation

F. **Deserts and Winds**
  1. Distribution and Causes of Dry Lands
  2. Common Misconceptions About Deserts
  3. Reviewing Landforms and landscapes ***NEW SECTION***
  4. Quiz: Deserts and Winds

Unit 3: Forces Within

A. **Plate Tectonics** ***EXPANDED AND REVISED***
  1. Introduction to Plate Tectonics
  2. Divergent Boundaries
  3. Convergent Boundaries
  4. Transform fault boundaries
  5. Formation and Breakup of Pangaea
  6. Plate Tectonics Quiz

B. **Earthquakes**
  1. What is an Earthquake?
  2. Seismology
  3. Locating the Source of an Earthquake
  4. Earthquakes at Plate Boundaries
  5. Earthquake Quiz

C. **Earth's Interior** ***ALL NEW***
  a. Earth's Layered Structure
  b. Earth's Interior Quiz

D. **Volcanoes and Other Igneous Activity**
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  b. Materials extruded During an Eruption
  c. Volcanic Structures and Eruptive Styles
  d. Volcanoes Quiz

E. **Mountain Building** ***ALL NEW***
  a. Deformation
  b. Folds

- c. Faults and Fractures
- d. Continental Collisions
- e. Crustal Fragments and Mountain Building
- f. Mountain Building Quiz

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- B. Relative Dating—Key Principles
- C. Dating With Radioactivity
- D. Quiz: Geologic Time

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  - 2. Features of the Ocean Floor
  - 3. Quiz: Ocean Floor
- B. Coastal Processes
  - 1. Waves and Beaches
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- A. Introduction to the Atmosphere *ALL NEW*
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  - 2. Weather and Climate
  - 3. Composition of the Atmosphere
  - 4. Extent of the Atmosphere
  - 5. Temperature Structure of the Atmosphere
  - 6. Quiz: Introduction to the Atmosphere
  - 7. In The Lab: Reading Weather maps
- B. Heating Earth's Surface and Atmosphere
  - 1. Understanding Seasons, Part 1 *NEW SECTION*
  - 2. Understanding Seasons, Part 2 *NEW SECTION*
  - 3. Solar Radiation
  - 4. What happens to Incoming Solar Radiation
  - 5. The Greenhouse Effect
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- C. Temperature Data and the Controls of Temperature
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  - 5. The Critical Weathermaker: Atmospheric Stability *NEW SECTION*
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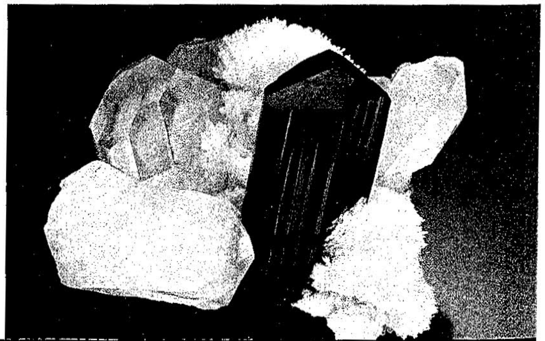

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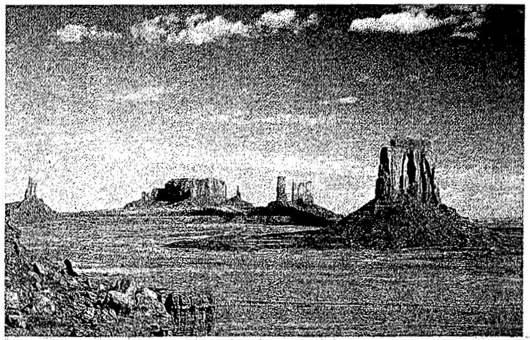

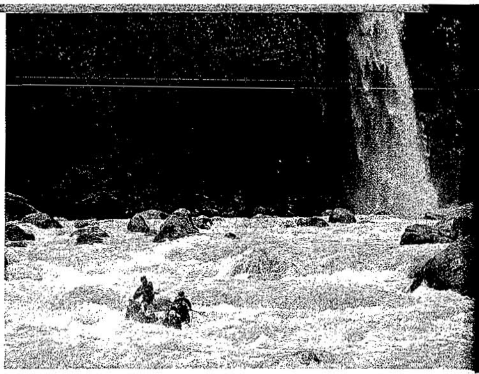

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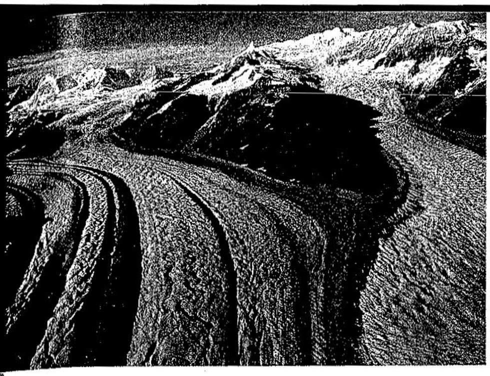

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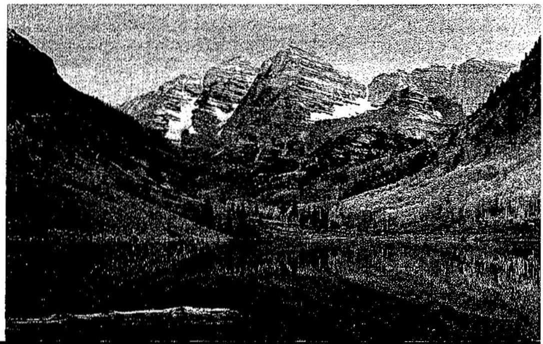

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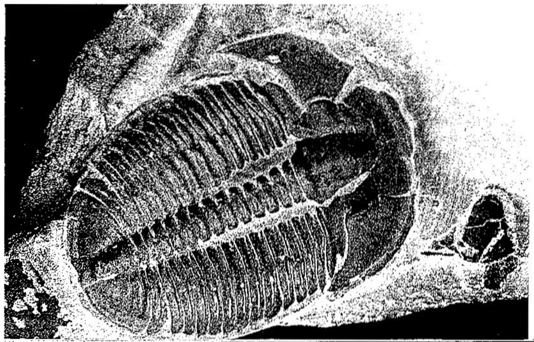

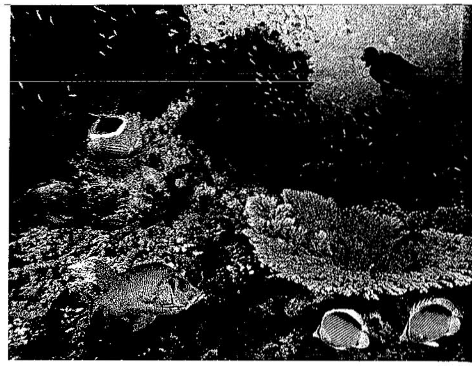

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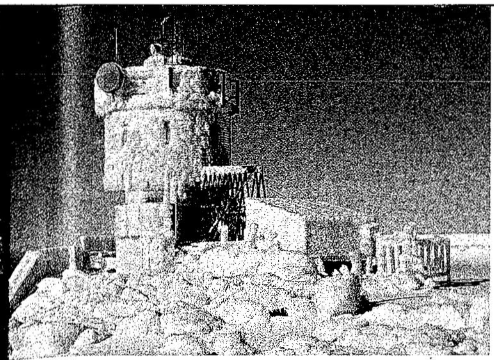

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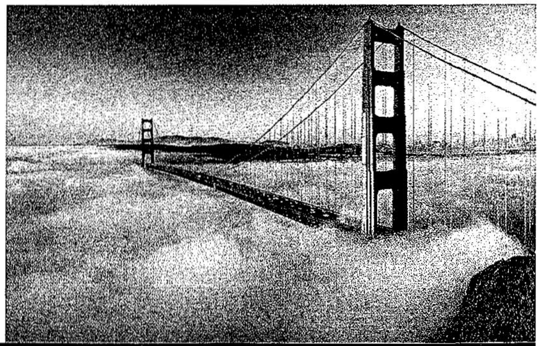

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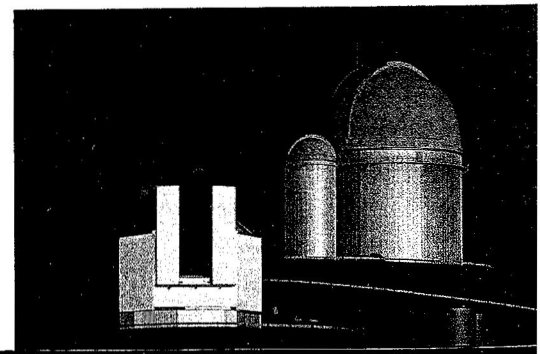

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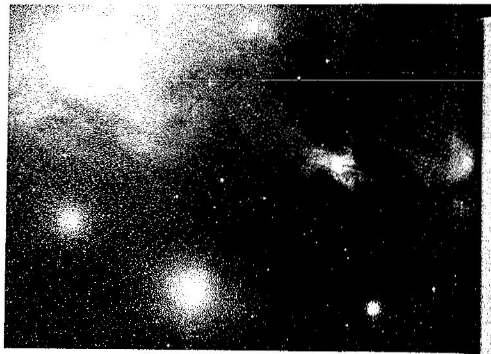

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Preface

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, nontechnical 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** recaps 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 **Review Questions** that help students examine their knowledge of significant facts and ideas. Next is a reminder 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 effective 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 text 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 art program. Clearer, 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 this new edition remains the same as its predecessors—to foster student understanding of basic Earth science principles. Whereas student use of the text is a primary concern, the book's adaptability to the needs and desires of the instructor is equally important. Realizing the broad diversity of Earth science courses in both content and approach, we have continued to use a relatively nonintegrated format to allow maximum flexibility for the instructor. Each of the major units stands alone; hence, they can be taught in any order. A unit can be omitted entirely without appreciable loss of continuity, and portions of some chapters may be interchanged or excluded at the instructor's discretion.

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. Several new and revised special interest boxes relate to *Earth as a system*. In addition, each chapter concludes with a section on *Examining the Earth System*. The questions and problems found here are intended to develop an awareness and appreciation for some of the Earth system's many interrelationships.

People and the Environment

Because knowledge about our planet and how it works is necessary to our survival and well-being, the treatment of environmental issues has always been an important part of *Earth Science*. Such discussions serve to illustrate the relevance and application of Earth science knowledge. With each new edition this focus has been given greater emphasis. This is certainly the case with the twelfth edition. The text integrates a great deal of information about the relationship between people and the natural environment and explores the application of the Earth sciences to understanding and solving problems that arise from these interactions. In addition to many basic text discussions, many of the text's special interest boxes involve the "People and the Environment" theme.

Understanding Earth

As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Developing an understanding of how science is done and how scientists work is a third important theme that appears throughout this book, beginning with the section on "The Nature of Scientific Inquiry" in Chapter 1. Students will examine some of the difficulties encountered by scientists as they attempt to acquire reliable data about our planet and some of the ingenious methods that have been developed to overcome these difficulties. Students will also explore many examples of how hypotheses are formulated and tested as well as learn about the evolution and development of some major scientific theories. Many basic text discussions as well as a number of the special interest boxes on "Understanding Earth" provide the reader with a sense of the observational techniques and reasoning processes involved in developing scientific knowledge. The emphasis is not just on what scientists know, but how they figured it out.

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 the chapters that focus on external processes. Chapter 4 has a new case study (Box 4.2) on the landslide 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), "Costal Wetlands are Vanishing on the Mississippi Delta." Chapter 6 contains new material on proglacial lakes and a new case study (Box 6.1) that focuses on glacial Lake Missoula and Washington's Channeled Scablands.
- Chapter 8, "Earthquakes and Earth's Interior," includes an all-new examination of tsunami. 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 why volcanoes erupt and behave 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 birth 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 line art dealing with ocean circulation, the behavior of waves, and rip currents. There is also a new special interest box on rogue 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 Watry and Teresa Tarbuck 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.
- 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 as a credo, 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 xxii-xxiii of this Preface for detailed descriptions.

Acknowledgments

Writing a college textbook requires the talents and cooperation of many individuals. We value the excellent work of Mark Watry and Teresa Tarbuck 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 oceanography unit and to the "Students Sometimes Ask . . ." feature remain an important part of *Earth Science*.

Working with Dennis Tasa, who is responsible for all of the outstanding illustrations and much of the developmental work on *GEODe: 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 Pinzke 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 goes 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. Lutgens

The Teaching and Learning Package

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

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 (Are illustrations central to your lecture? Check out the *Student Lecture Notebook*.)

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. Theses 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 text-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 Lutgens, 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.

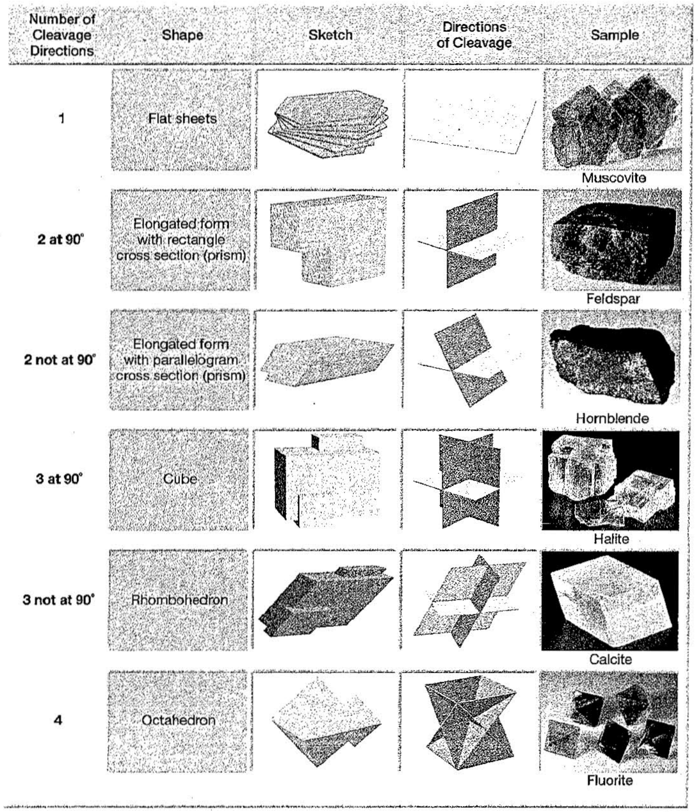
Companion Website

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 asses 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 notetaking, less writing in your textbook, and less to carry to class. The *Student Lecture Notebook* is available through your bookstore.



Number of Cleavage Directions	Shape	Sketch	Directions of Cleavage	Sample
1	Flat sheets			Muscovite
2 at 90°	Elongated form with rectangle cross section (prism)			Feldspar
2 not at 90°	Elongated form with parallelogram cross section (prism)			Hornblende
3 at 90°	Cube			Halite
3 not at 90°	Rhombohedron			Calcite
4	Octahedron			Fluorite

FIGURE 2.15 Common cleavage directions exhibited by minerals. (Photos by Dennis Tasa and E. J. Tarbuck)

the number of cleavage directions and the angle(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, some minerals cleave to form six-sided cubes. Because cubes are defined by three different sets of parallel planes that intersect at 90-degree angles, cleavage is described as *three directions of cleavage that meet at 90 degrees.*

Do not confuse cleavage with crystal shape. When a mineral exhibits cleavage, it will break into pieces that all have the same geometry. By contrast, the smooth-sided quartz crystals shown in Figure 2.1 (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.

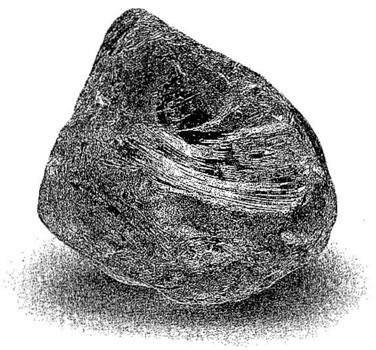


FIGURE 2.16 Conchoidal fracture. The smooth, curved surfaces result when minerals break in a glasslike manner. (Photo by E. J. Tarbuck)

BOX 2.1 ▶ PEOPLE AND THE ENVIRONMENT

Making Glass from Minerals

Many everyday objects are made of glass, including windowpanes, jars and bottles, and the lenses of some eyeglasses. People have been making glass for at least 2,000 years. Glass is manufactured by melting naturally occurring materials and cooling the liquid quickly before the atoms have time to arrange themselves into an orderly crystalline form. (This is the same way that natural glass, called *obsidian*, is generated from lava.)

It is possible to produce glass from a variety of materials, but the primary ingredient (75 percent) of most commercially produced glass is the mineral quartz (SiO_2). Lesser amounts of the minerals calcite (calcium carbonate) and trona (sodium carbonate) are added to the mix. These materials lower the melting temperature and improve the workability of the molten glass.

In the United States, high-quality quartz (usually quartz sandstone) and calcite (limestone) are readily available in many areas. Trona, on the other hand, is mined almost exclusively in the Green River area of southwestern Wyoming. In addition to its use in making glass, trona is used in making detergents, paper, and even baking soda.

Manufacturers can change the properties of glass by adding minor amounts of several other ingredients (Figure 2.A). Coloring agents include iron sulfide (amber), selenium (pink), cobalt oxide (blue), and iron oxides (green, yellow, brown). The addition of lead imparts clarity and brilliance to glass and is therefore used in the manufacture of fine crystal tableware. Ovenware, such as Pyrex®, owes its heat resistance to boron, whereas aluminum makes glass resistant to weathering.

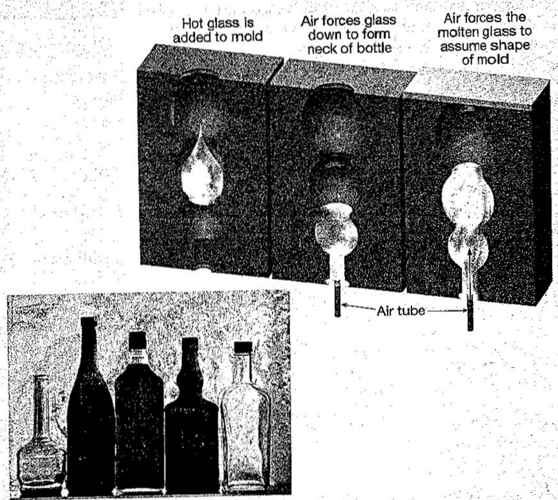


FIGURE 2.A Glass bottles are made by adding molten glass to a mold and using air to shape the glass. Metallic compounds are mixed with the raw ingredients to color the glass. (Photo by Poligons Photo Index Alamy)

residual clay minerals. However, even the highly insoluble clay minerals are very slowly removed by subsurface water.

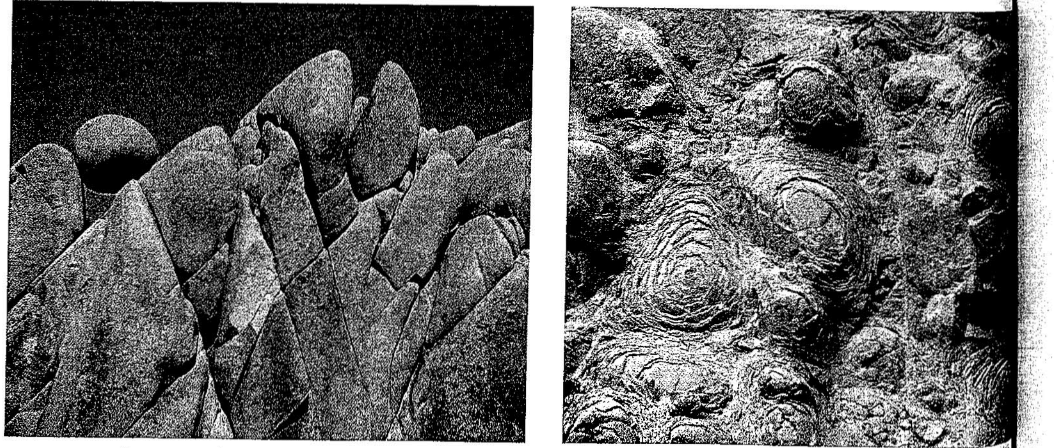
Spheroidal Weathering

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 discussed earlier. In sheeting, the fracturing occurs as a result of unloading, and the rock layers that separate from the main body are largely unaltered at the time of separation.

FIGURE 4.8 A. Spheroidal weathering is evident in this exposure of granite in California's Joshua Tree National Park. Because the rocks are attacked more vigorously on the corners and edges, they take on a spherical shape. The lines visible in the rock are called *joints*. Joints are important rock structures that allow water to penetrate and start the weathering process long before the rock is exposed. (Photo by E. J. Tarbuck) B. Sometimes successive shells are loosened as the weathering process continues to penetrate ever deeper into the rock. (Photo by Martin Schmidt, Jr.)



A.

B.

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 old headstones 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 acidic 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. 61), you can see that olivine crystallizes first and is therefore the least resistant to chemical weathering, whereas quartz, which crystallizes last, is the most resistant.

FIGURE 4.9 An examination of two headstones (in the same cemetary) reveals the rate of chemical weathering on diverse rock types. The granite headstone (left) was erected four years before the marble headstone (right). The inscription date of 1872 on the marble monument is nearly illegible. (Photos by E. J. Tarbuck)

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).

Differential Weathering

Masses of rock do not weather uniformly. Take a moment to look at the photo of Shiprock, New Mexico, in Figure 9.24 (p. 266). The durable volcanic neck protrudes high above the surrounding terrain. A glance at the chapter-opening photo shows an additional example of this phenomenon, called **differential weathering**. The results vary in scale from the rough, uneven surface of the marble headstone in Figure 4.9 to the boldly sculpted exposures in Arizona's Monument Valley (Figure 4.11).

Many factors influence the rate of rock weathering. Among the most important are variations in the composition of the rock. More resistant rock protrudes as ridges or pinnacles, or as steeper cliffs on a canyon wall (see Figure 11.3, p. 313). The number and spacing of joints can also be a significant factor (see Figure 4.8A and Figure 10.12, p. 294). Differential weathering and subsequent erosion are responsible for creating many unusual and sometimes spectacular rock formations and landforms.

FIGURE 4.10 As a consequence of burning large quantities of coal and petroleum, more than 40 million tons of sulfur and nitrogen oxides are released into the atmosphere each year in the United States. Through a series of complex chemical reactions, some of these pollutants are converted into acids that then fall to Earth's surface as rain or snow. Among its many environmental effects, acid rain accelerates the chemical weathering of stone monuments and structures, including this building facade in Leipzig, Germany. (Photo by Doug Plummer/Photo Researchers, Inc.)

TABLE 4.2 World Soil Orders

Alfisols	Moderately weathered soils that form under boreal forests or 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.
Andisols	Young soils in which the parent material is volcanic ash and cinders, deposited by recent volcanic activity.
Aridosols	Soils that develop in dry places; insufficient water to remove soluble minerals, may have an accumulation of calcium carbonate, gypsum, or salt in subsoil; low organic content.
Entisols	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 forming on shifting sand or rocky slopes.
Gelisols	Young soils with little profile development that occur in regions with permafrost. Low temperatures and frozen conditions for much of the year slow soil-forming processes.
Histosols	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*.
Inceptisols	Weakly developed young soils in which the beginning (inception) of profile development is evident. Most common in humid climates, they exist from the Arctic to the tropics. Native vegetation is most often forest.
Mollisols	Dark, soft soils that have developed under grass vegetation, generally found in prairie areas. Humus-rich surface horizon that is rich in calcium and magnesium. Soil fertility is excellent. Also found in hardwood forests with significant earthworm activity. Climatic range is boreal or alpine to tropical. Dry seasons are normal (see Figure 4.16A).
Oxisols	Soils that occur on old 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, oxisols are heavily leached, hence are poor soils for agricultural activity (see Figure 4.16B).
Spodosols	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 weathered organic material lies a light-colored horizon of leached material, the distinctive property of this soil.
Ultisols	Soils that represent the products of long periods of weathering. Water percolating through the soil concentrates clay particles in the lower horizons (argillic horizons). Restricted to humid climates in the temperate regions and the tropics, where the growing season is long. Abundant water and a long frost-free period contribute to extensive leaching, hence poorer soil quality.
Vertisols	Soils containing large amounts of clay, which shrink upon drying and swell with the addition of water. Found in subhumid to arid 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.

Brief descriptions of the 12 basic soil orders are provided in Table 4.2. Figure 4.18 shows the complex worldwide distribution pattern 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

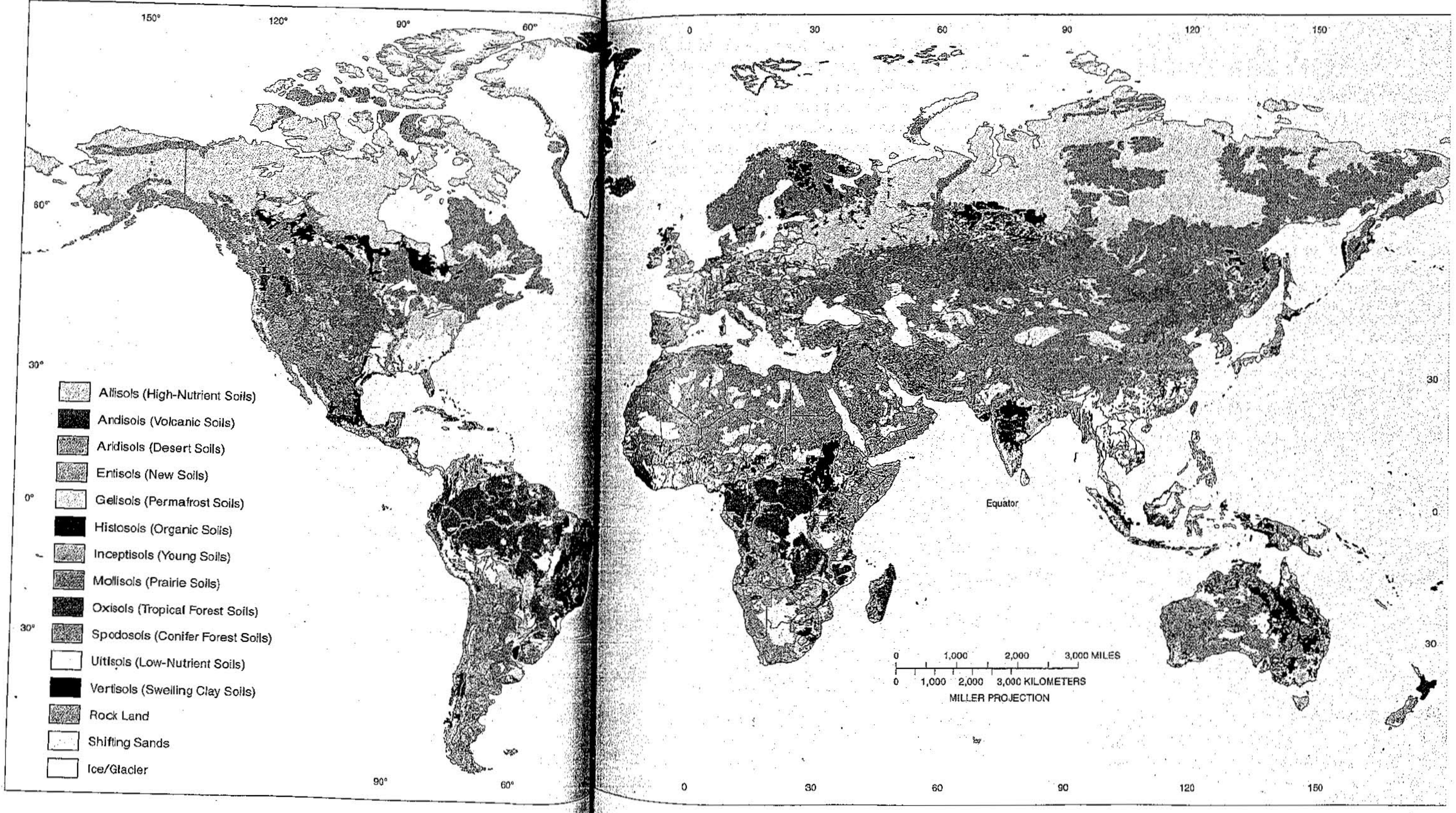
Soils are just a tiny fraction of all Earth materials, yet they are a vital resource. Because soils are necessary for the growth of rooted plants, they are the very foundation of the human life-support system. Just as human ingenuity can increase the agricultural productivity of soils through fertilization 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

FIGURE 4.18 Global soil regions. Worldwide distribution of the Soil Taxonomy's 12 soil orders. (After U.S. Department of Agriculture, Natural Resources Conservation Service, World Soil Resources Staff)



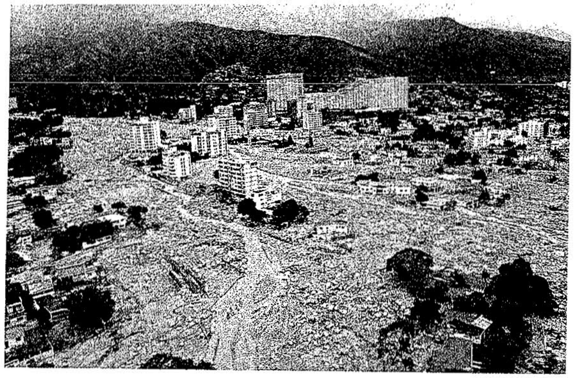


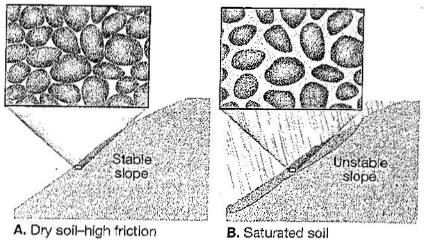
FIGURE 4.24 Aerial view of a large debris flow at Caraballeda, Venezuela, in December 1999. Heavy rains triggered thousands of debris flows and other types of mass wasting in the adjacent mountains. Once created, these moving masses of mud and rock coalesced to form giant debris flows that moved rapidly through steep, narrow canyons and engulfed the city. The result was severe property damage and the tragic loss of an estimated 19,000 lives. (Kimberly White/REUTERS/CORBIS/Bettmann)

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 (Figure 4.24). A case study of another rain-triggered mass-wasting event that occurred at La Conchita, California, in January 2005, is found in Box 4.2.

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.

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

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** (*reposen* = 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.

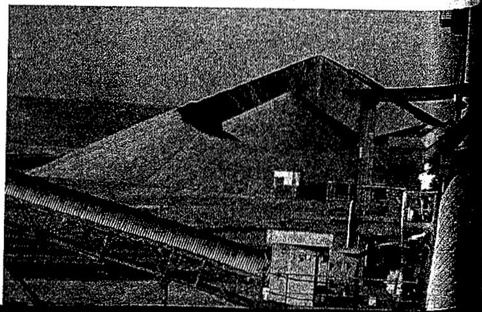
Oversteepening is important not only because it triggers movements of unconsolidated granular materials, but it also produces unstable slopes and mass movements in cohesive soils, regolith, and bedrock. The response will not be immediate, as with loose, granular material, but sooner or later one or more 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 together. Where plants are lacking, mass wasting is enhanced, especially if slopes are steep and water is plentiful. When anchoring vegetation is removed by forest fires 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

FIGURE 4.26 The angle of repose for this granular material is about 30°. (Photo by G. Leavens/Photo Researchers, Inc.)



BOX 4.2 ▶ PEOPLE AND THE ENVIRONMENT

Landslide Hazards at La Conchita, California*

Southern California lies astride a major plate boundary defined by the San Andreas Fault and numerous other related faults that are spread across the region. It is a 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.

The town is situated on a narrow coastal strip about 250 meters (800 feet) wide between the shoreline and a steep 180-meter (600-foot) bluff (Figure 4.B). The bluff consists of poorly sorted marine sediments and weakly cemented layers of shale, siltstone, and sandstone.

The deadly 2005 debris flow involved little or no newly failed material, 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 rain. 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.C 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.

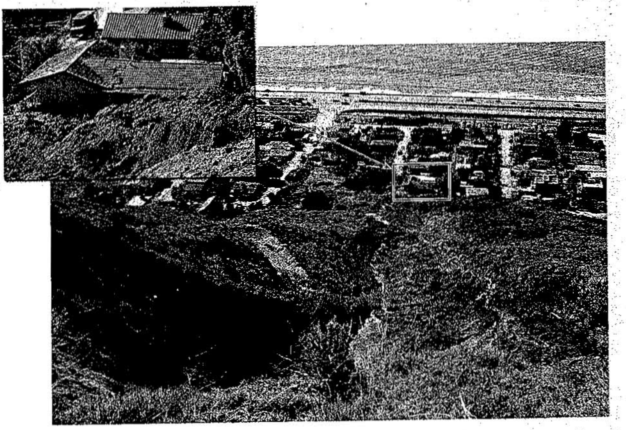


FIGURE 4.B The larger image is a view down the length of the 2005 La Conchita debris flow. It also depicts the setting of the small town between the ocean and a steep cliff. The arrow on the larger photo is pointing to the house shown on the inset. The flow was quite viscous and moved houses in its path 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)

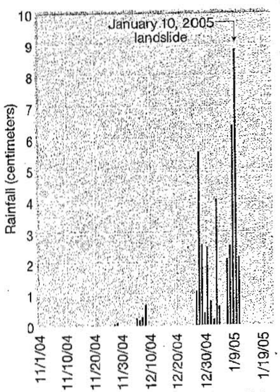


FIGURE 4.C Daily rainfall at the nearby town of Ventura during the weeks leading up to the January 2005 La Conchita event. Each line on the bar graph shows rain for a particular day. The 2005 debris flow occurred at the culmination of the heaviest rainfall of the season. About 80 percent of the season's exceptional total fell in this short span. (After National Weather Service)

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

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 is made unstable and reacts to the pull of gravity. A common example is a valley wall that becomes oversteepened by a meandering river. Another is a coastal area that has been undercut by wave activity at its base.

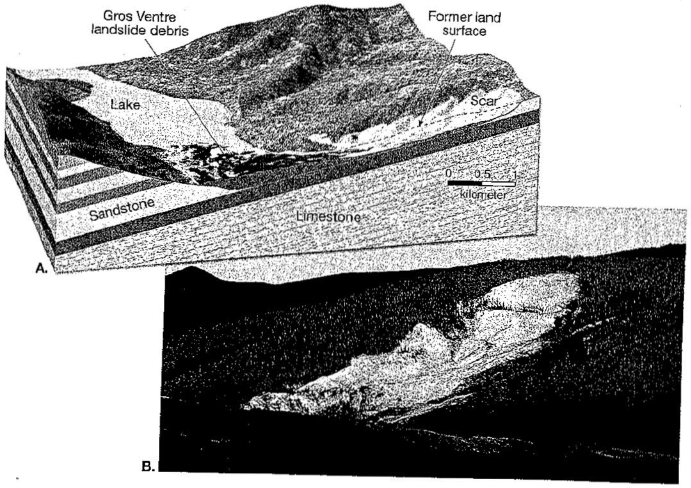
Rockslide

Sculpturing Earth's Surface
▸ Mass Wasting: The Work of Gravity

Rockslides frequently occur in high mountain areas such as the Andes, Alps, and Canadian Rockies. They are sudden and rapid movements that happen when detached segments of bedrock break loose and slide downslope (Figure 4.28B). As the moving mass thunders along the surface, it breaks into many smaller pieces. Such events are among the fastest and most destructive mass movements.

Rockslides usually take place where there is an inclined surface of weakness. Such surfaces tend to form where strata are tilted or where joints and fractures exist parallel to the slope. When rock in such a setting 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 rockslide 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. Later, the lake created by the debris dam overflowed, resulting in a devastating flood downstream. A. Cross-sectional view. The slide occurred when the tilted and undercut sandstone bed could no longer maintain its position atop the saturated bed of clay. B. Even though the Gros Ventre rockslide occurred in 1925, the scar left on the side of Sheep Mountain is still a prominent feature. (Part A after W. C. Alden, "Landslide and Flood at Gros Ventre, Wyoming," *Transactions* (AIME) 76 (1928); 348. Part B photo by Stephen Trimble)



Students Sometimes Ask...

I noticed that none of the mass-wasting processes described in this chapter are actually called "landslides." Why?

That's very observant! Although many people, including geologists, frequently use the word *landslide*, the term has no specific definition in geology. Rather, it should be considered as a popular nontechnical term to describe all relatively rapid forms of mass wasting, including those in which sliding does not occur.

Debris Flow

Sculpturing Earth's Surface
▸ Mass Wasting: The Work of Gravity

Debris flow is a relatively rapid type of mass wasting that involves a flow of soil and regolith containing a large amount of water (Figure 4.28C). Debris flows, which are also called *mudflows*, are most characteristic of semiarid mountainous regions and are also common on the slopes of some volcanoes. Because of their fluid properties, debris flows follow canyons and stream channels. As Figure 4.24 (p. 104) and Box 4.2 illustrate, debris flows in populated areas can pose a significant hazard to life and property.

Debris Flows in Semiarid Regions

When a cloudburst 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 have 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 volcano hazards. They can occur either during an eruption or 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 rainfalls often trigger 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-molten 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.

Earthflow

Sculpturing Earth's Surface
▸ Mass Wasting: The Work of Gravity

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 4.28D). When water saturates the soil and regolith on a hillside, the material may break away, leaving a scar on the slope and forming a tongue- or teardrop-shaped mass that flows downslope (Figure 4.32). The materials most commonly involved are rich in clay and silt and contain only small proportions of sand and coarser particles. Earthflows range in size from bodies a few meters

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

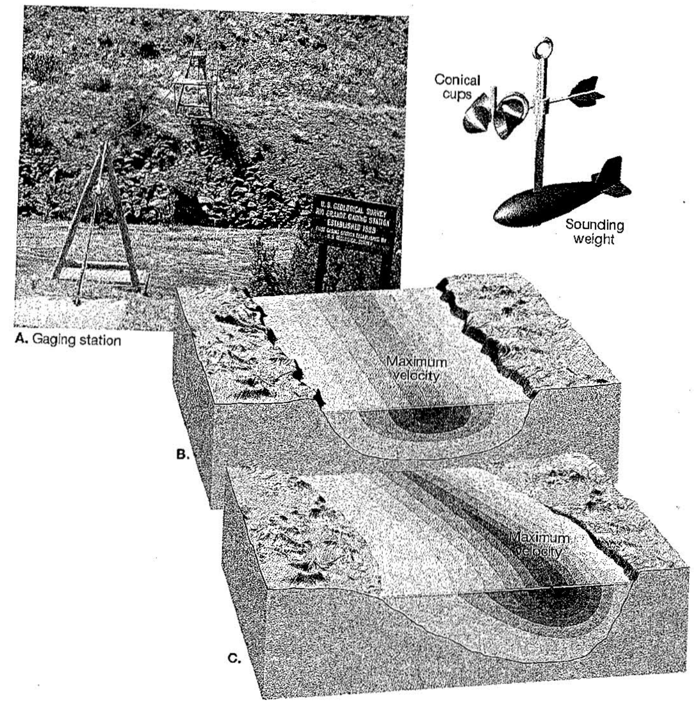


FIGURE 5.5 **A.** Continuous records of stage and discharge are collected by the U.S. Geological Survey at more than 7,000 gauging stations in the United States. Average velocities are determined by using measurements from several spots across the stream. This station is on the Rio Grande south of Taos, New Mexico. (Photo by E. J. Tarbuck) **B.** Along straight stretches, stream velocity is highest at the center of the channel. **C.** When a stream curves, its zone of maximum speed shifts toward the outer bank.

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 its 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 decrease in elevation at a rate of more than 40 meters per kilometer, or a gradient 400 times steeper than the lower Mississippi (Figure 5.6). Gradient varies not only among different streams but also over 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 the water 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 water flowing past 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.

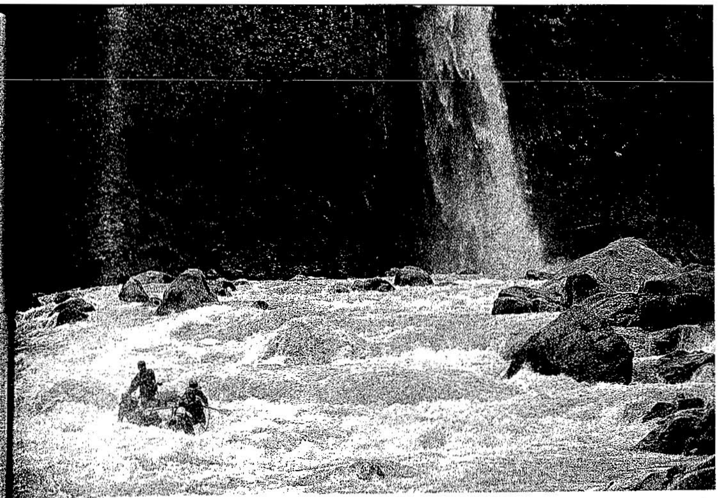


FIGURE 5.6 Rapids are common in mountain streams where the gradient is steep and the channel is rough and irregular. Although most streamflow is turbulent, it is usually not as rough as that experienced by these river runners at Lost Yak Rapids on Chile's Rio Bio Bio. (Photo by Carr Clifton)

The discharges of most rivers are far from constant. This is true because of such variables as rainfall and snowmelt. In areas with seasonal variations in precipitation, streamflow will tend to be highest during the wet season, or during spring snowmelt, and lowest during the dry season or during periods when high temperature increases the water losses through evapotranspiration. However, not all channels maintain a continuous flow of water. Streams that exhibit flow only during "wet" periods are referred to as *intermittent streams*. In arid climates many streams carry water only occasionally after a heavy rainstorm and are called *ephemeral streams*.

Changes from Upstream to Downstream

One useful way of studying a stream is to examine its *profile*. A profile is simply a cross-sectional view of a stream from its source area (called the *head* or *headwaters*) to its *mouth*, the point downstream where the river empties into another water body. By examining Figure 5.7, you can see that the most obvious feature of a typical profile is a constantly decreasing gradient from the head to the mouth. Although many local irregularities may exist, the overall profile is a smooth, concave, upward curve.

The profile shows that the gradient decreases downstream. To see how other factors change in a downstream direction, observations and measurements must be made. When data are collected from several gaging stations along a river, they show that in a humid region discharge increases from the head toward the mouth. This should come as no surprise because, as we move downstream, more and more tributaries contribute water to the main channel (Figure 5.6). Furthermore, in most humid regions, additional water is added from the groundwater supply. Thus, as you move downstream, the stream's width, depth, and velocity change in response to the increased volume of water carried by the stream.

Streams that begin in mountainous areas where precipitation is abundant and then flow through arid regions may experience the opposite situation. Here discharge may actually decrease downstream because of water loss due to evaporation, infiltration into the streambed, and removal by irrigation. The Colorado River in the southwestern United States is such an example.

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

TABLE 5.1 World's Largest Rivers Ranked by Discharge

			Drainage Area		Average Discharge	
Rank	River	Country	Square kilometers	Square miles	Cubic meters per second	Cubic feet per second
1	Amazon	Brazil	5,778,000	2,231,000	212,400	7,500,000
2	Congo	Zaire	4,014,500	1,550,000	39,650	1,400,000
3	Yangtze	China	1,942,500	750,000	21,800	770,000
4	Brahmaputra	Bangladesh	935,000	361,000	19,800	700,000
5	Ganges	India	1,059,300	409,000	18,700	660,000
6	Yenisei	Russia	2,590,000	1,000,000	17,400	614,000
7	Mississippi	United States	3,222,000	1,244,000	17,300	611,000
8	Orinoco	Venezuela	880,600	340,000	17,000	600,000
9	Lena	Russia	2,424,000	936,000	15,500	547,000
10	Parana	Argentina	2,305,000	890,000	14,900	526,000

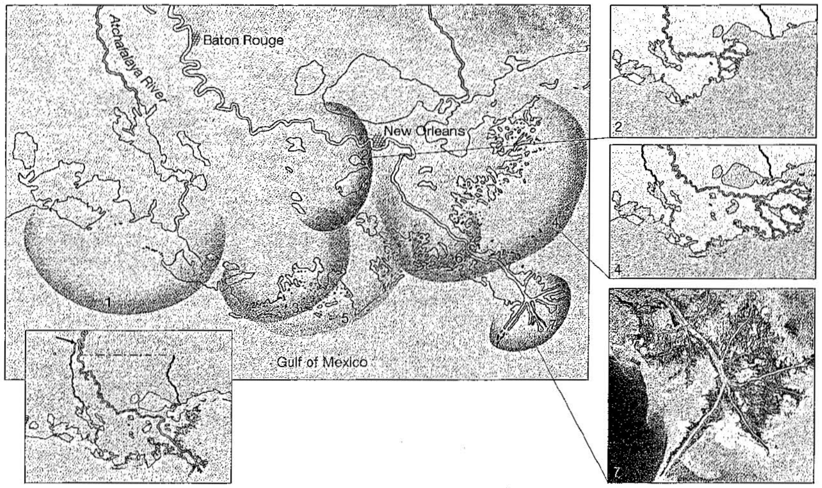
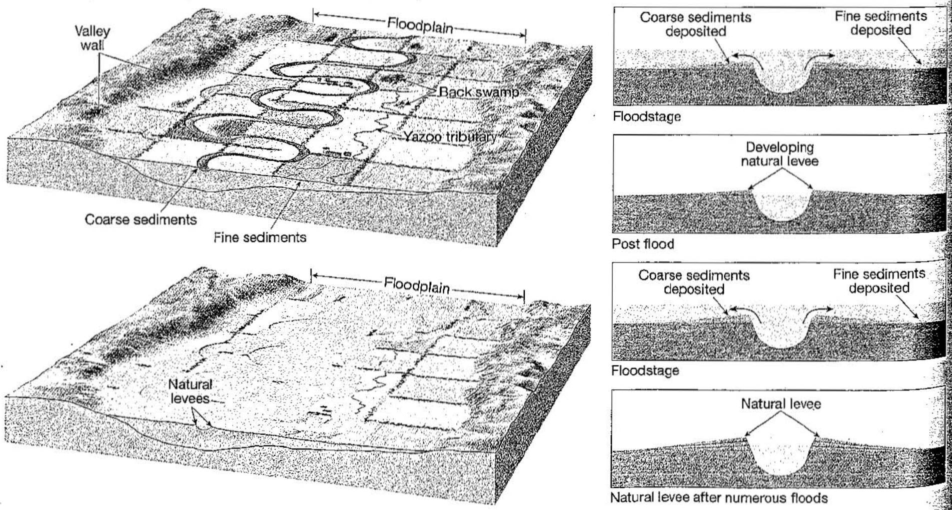


FIGURE 5.20 During the past 5,000 to 6,000 years, the Mississippi River has built a series of seven coalescing subdeltas. The numbers indicate the order in which the subdeltas were deposited. The present birdfoot delta (number 7) represents the activity of the past 500 years. (Image courtesy of JPL/Cal Tech/NASA) Without ongoing human efforts, the present course will shift and follow the path of the Atchafalaya River. The inset on the left shows the point where the Mississippi may someday break through (arrow) and the shorter path it would take to the Gulf of Mexico. (After C. R. Kolb and J. R. Van Lopik)

FIGURE 5.21 Natural levees are gently sloping deposits that are created by repeated floods. The diagrams on the right show the sequence of development. Because the ground next to the stream channel is higher than the adjacent floodplain, back swamps and yazoo tributaries may develop.



BOX 5.1 ▶ PEOPLE AND THE ENVIRONMENT

Coastal Wetlands Are Vanishing on the Mississippi Delta

Coastal wetlands form in sheltered environments that include swamps, tidal flats, coastal marshes, and bayous. They are rich in wildlife and provide nesting grounds and important stopovers for waterfowl and migratory birds, as well as spawning areas and valuable habitats for fish.

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 low-lying 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 (1,900 square miles) of coastal land between 1932 and 2000. The state continues to lose between 65 and 91 square kilometers (25 to 35 square miles) each year. At this rate another 1,800 to 4,500 square kilometers (700 to 1,750 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?

FIGURE 5.A This group of dead cypress trees, known as a ghost forest, was killed by encroaching salt water in Terrebonne Parish, Louisiana. (Photo by Robert Caputo/Aurora Photos)

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 50 percent over the past 100 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 laced with 13,000 kilometers (8,000 miles) of navigation channels and canals. These artificial openings to the sea allow salty Gulf waters to flow far inland. The invasion of saltwater and tidal action causes massive "brownouts" or marsh die-offs (Figure 5.A).

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 coasts 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.

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[*] See "Louisiana's Vanishing Wetlands: Going, Going . . ." in *Science*, Vol. 289, 15 September 2000, pp. 1860–63. Also see Elizabeth Kolbert, "Watermark—Can Southern Louisiana, be Saved?" *The New Yorker*, February 27, 2006, pp. 46–57.

[**] "For more on this possibility, see "Some Possible Consequences of Global Warming" in Chapter 20.

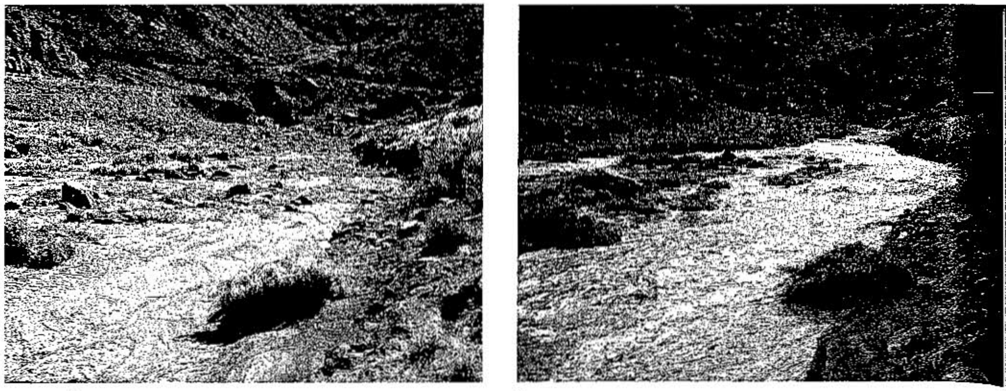

FIGURE 6.28 A. Most of the time, desert stream channels are dry. B. An ephemeral stream shortly after a heavy shower. Although such floods are short-lived, large amounts of erosion occur. (Photos by E. J. Tarbuck)

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 largely unhindered and consequently rapid, often creating flash floods along valley floors (Figure 6.28B). Such floods, however, are quite unlike floods in humid regions. A flood on a river such as the Mississippi may take many days to reach its crest and then subside. But desert floods arrive suddenly and subside quickly. Because much of the surface material is not anchored by vegetation, the amount of erosional work that occurs during a single short-lived rain event is impressive.

In the dry western United States a number of different names are used for ephemeral streams. Two of the most common are *wash* and *arroyo*. In other parts of the world, a dry desert stream may be called a *wadi* (Arabia and North Africa), a *donga* (South America), or a *nullah* (India).

Humid regions are notable for their integrated drainage systems. But in arid regions streams usually lack an extensive system of tributaries. In fact, a basic characteristic of desert streams is that they are small and die out before reaching the sea. Because the water table is usually far below the surface, few desert streams can draw upon it as streams do in humid regions. Without a steady supply of water, the combination of evaporation and infiltration soon depletes the stream.

The few permanent streams that do cross arid regions, such as the Colorado and Nile rivers, originate *outside* the desert, often in well-watered mountains. Here the water supply must be great to compensate for the losses occurring as the stream crosses the desert (Box 6.2). For example, after the Nile leaves the lakes and mountains of central Africa that are its source, it traverses almost 3,000 kilometers (nearly 1,900 miles) of the Sahara *without a single tributary*. By contrast, in humid regions the discharge of a river usually increases in the downstream direction because tributaries and groundwater contribute additional water along the way.

It should be emphasized that *running water, although infrequent, nevertheless does most of the erosional 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 nevertheless 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

Sculpturing Earth's Surface
▸ Deserts and Winds

Because arid regions typically lack permanent streams, they are characterized as having **interior 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

BOX 6.2 A PEOPLE AND THE ENVIRONMENT

The Disappearing Aral Sea

The Aral Sea lies on the border between Uzbekistan and Kazakhstan in central Asia (Figure 6.C). The setting is the Turkestan desert, a middle-latitude desert in the rainshadow of Afghanistan's high mountains. In this region of interior drainage, two large rivers, the Amu 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, Lake Superior, and Lake Victoria were larger. By the year 2000 the area of the Aral Sea was less than 50 percent of its 1960 size, and its volume was reduced by 80 percent. The shrinking of this water body is depicted in Figure 6.D. By about 2010 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 then all but eliminated. As recently as 1965, 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 reason was that the waters of the Amu Darya and Syr Darya were diverted to supply a major expansion of irrigated agriculture in this dry realm.

FIGURE 6.C The Aral Sea lies east of the Caspian Sea in the Turkestan Desert. Two rivers, the Amu Darya and Syr Darya, bring water from the mountains to the sea.

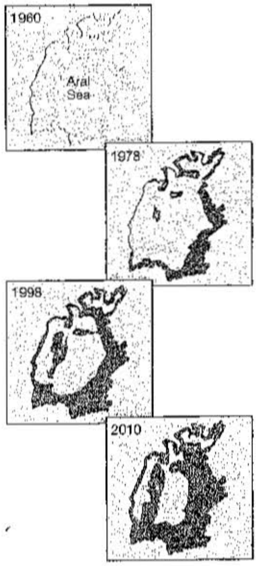

FIGURE 6.D The shrinking Aral Sea. By the year 2010 all that will remain are three small remnants.

The intensive irrigation greatly increased agricultural productivity, but not 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 24 species of fish that once lived in the Aral Sea are no longer there. The shoreline is now tens of kilometers from the towns that were once fishing centers (Figure 6.E).

The shrinking sea has exposed millions of acres of former seabed to sun and wind. The surface is encrusted with salt and with agrochemicals brought by the rivers. 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-rich sediments on arable land.

The shrinking Aral Sea has had a 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 farms 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 ruining 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.

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*For more on this, see "Coming to Grips with the Aral Sea's Grim Legacy," in *Science*, vol. 284, April 2, 1999, pp. 30–31 and "To Save a Vanishing Sea," in *Science*, vol. 307, February 18, 2005, pp. 1032–33.

FIGURE 6.E In the town of Jamboul, Kazakhstan, boats now lie in the sand because the Aral Sea has dried up. (Photo by Ergun Cagatay/Liaison Agency, Inc.)

BOX 8.1 ▸ PEOPLE AND THE ENVIRONMENT

Damaging Earthquakes East of the Rockies

When you think earthquake, 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 had estimated Richter magnitudes of 7.5, 7.3, and 7.8, and they were centered near the Mississippi River Valley in southeastern Missouri. Occurring on December 16, 1811, January 23, 1812, and February 7, 1812, these earthquakes, plus numerous smaller tremors, destroyed the town of New Madrid, Missouri, triggered massive landslides, and caused damage over a six-state area. The course of the Mississippi River was altered, and Tennessee's Reelfoot Lake was enlarged. The distances over which these earthquakes were felt are truly remarkable. Chimneys were reported downed in Cincinnati, Ohio, and Richmond, Virginia, while Boston residents, located 1,770 kilometers (1,100 miles) to the northeast, felt the tremor.

Despite the history of the New Madrid earthquake, Memphis, Tennessee, the largest population center in the area today, does not have adequate earthquake provisions in its building code. Furthermore, because Memphis is located on unconsolidated floodplain deposits, buildings are more susceptible to damage than similar structures built on bedrock. It has been estimated that if an earthquake the size of the 1811–1812 New Madrid 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 Aurora, Illinois (1909), and Valentine, Texas (1931), remind us that other areas in the central United States are vulnerable.

The greatest historical earthquake in the eastern states occurred August 31, 1886, in Charleston, South Carolina. The event, which spanned 1 minute, caused 60 deaths, numerous injuries, and great economic loss within a radius of 200 kilometers (120 miles) of Charleston. Within 8 minutes, effects were felt as far away as Chicago and St. Louis, where strong vibrations shook the upper floors of buildings, causing people to rush outdoors. In Charleston alone, over 100 buildings were destroyed, and 90 percent of the remaining structures were damaged (Figure 8.A).

FIGURE 8.A Damage to Charleston, South Carolina, caused by the August 31, 1886, earthquake. Damage ranged from toppled chimneys and broken plaster to total collapse. (Photo courtesy of U.S. Geological Survey)

Numerous other strong earthquakes have been recorded in the eastern United States. New England and adjacent areas have experienced sizable shocks since colonial times. The first reported earthquake in the Northeast took place in Plymouth, Massachusetts, in 1683, and was followed in 1755 by the destructive Cambridge, Massachusetts, earthquake. Moreover, ever since records have been kept, New York State alone has experienced over 300 earthquakes large enough to be felt.

Earthquakes in the central and eastern United States occur far less frequently than in California. Yet history indicates that the East is vulnerable. Furthermore, these shocks east of the Rockies have generally produced structural damage over a larger area than counterparts of similar magnitude in California. The reason is that the underlying bedrock in the central and eastern United States is older and more rigid. As a result, seismic waves are able to travel greater distances with less 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 rate of earthquake occurrence in the western United States is balanced somewhat by the fact that central and eastern U.S. quakes can damage larger areas.

San Andreas Fault: An Active Earthquake Zone

The San Andreas 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 behaves somewhat differently from the others. Some portions of the San Andreas exhibit a slow, gradual displacement known as **fault creep**, which occurs relatively smoothly and therefore with little noticeable seismic activity. Other segments regularly slip, producing small earthquakes.

FIGURE 8.6 Trace of the San Andreas Fault, north of Landers California. (Photo by Roger Ressmeyer/CORBIS)

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 sudden slippage. It is estimated that great earthquakes should occur about every 50 to 200 years along those sections of the San Andreas Fault that exhibit stick-slip motion. This knowledge is useful when assigning a potential earthquake risk to a given segment of the fault zone.

The tectonic forces along the San Andreas Fault zone 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 2–5 centimeters (1–2 inches) 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 each year produces 2 meters of offset every 100 years. Consequently, the 4 meters of displacement produced during the 1906 San Francisco earthquake should occur at least every 200 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."

Students Sometimes Ask . . .

Do moderate earthquakes decrease the chances of a major quake in the same region?

No. This is due to the vast increase in release of energy associated with higher-magnitude earthquakes. For instance, an earthquake with a magnitude of 8.5 releases millions of times more energy than the smallest earthquakes felt by humans. Similarly, thousands of moderate tremors would be needed to release the huge amount of energy equal to one "great" earthquake.

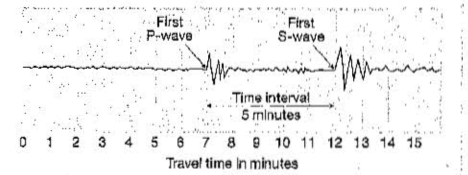
Seismology: The Study of Earthquake Waves

Forces Within
▸ Earthquakes

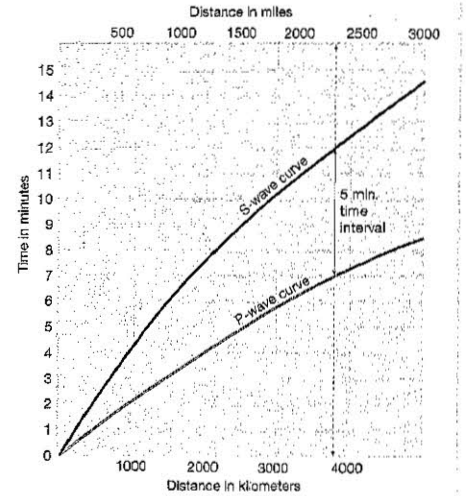
The study of earthquake waves, **seismology** (*seismos* = shake, *ology* = the study of), dates back to attempts by the Chinese almost 2,000 years ago to determine the direction of the source of each earthquake. Modern **seismographs** (*seismos* = shake, *graph* = write) are instruments that record earthquake waves. Their principle is simple: A weight is freely suspended from a support that is attached to bedrock (Figure 8.7). When waves from an earthquake reach 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 weight is recorded on a rotating drum. (*Inertia* is the tendency of a stationary object to remain still, or a moving object to stay in motion.)

Modern seismographs amplify and record ground motion, producing a trace as shown in Figure 8.8. These records, called **seismograms** (*seismos* = shake, *gramma* = what is written), reveal that seismic waves are elastic energy. This energy radiates outward in all directions from the focus, as you saw in Figure 8.2. The transmission of this energy can be compared to the shaking of gelatin in a bowl 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 through Earth's interior and are called **body waves**. Body waves are further divided into **primary waves (P waves)** and **secondary waves (S waves)**.

Body waves are divided into P and S waves by their mode of travel through intervening materials. 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 the Earth. This wave motion is analogous to that generated by human vocal cords as they move air to create



A. Seismogram



B. Travel-time graph

FIGURE 8.10 Using a seismogram and a travel-time graph to determine the distance to an earthquake's epicenter. **A.** The time delay between the arrival of the first P- and S-waves on this seismogram is 5 minutes. **B.** Using the travel-time graph, it is determined that the epicenter is roughly 3,800 kilometers (2,350 miles) from the seismic station.

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**—a 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 an earthquake based on seismic records rather than uncertain personal estimates of damage was desirable. The measurement that was developed, called **magnitude**, relies on calculations that use data provided by seismic records (and other techniques) to estimate the amount of energy released at the source of the earthquake.

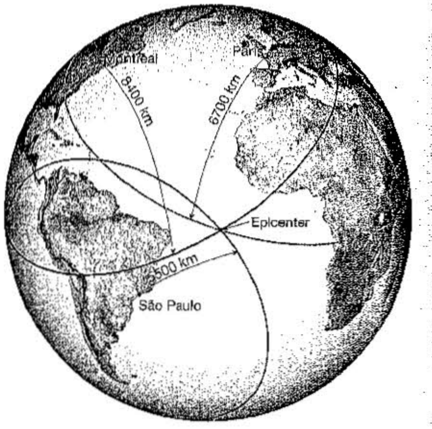


FIGURE 8.11 An earthquake epicenter is located using the distances obtained from three seismic stations. On a globe, a circle is drawn around each station, with each circle's radius equal to the station's distance from the earthquake's epicenter. Today, computers using data from numerous seismic stations can rapidly pinpoint large earthquakes.

Intensity Scales

Until a little more than a century ago, historical records provided the only accounts of the severity of earthquake shaking and destruction. Using these descriptions—which were compiled without any established standards for reporting—made accurate comparisons of earthquake sizes difficult, at best.

In order to standardize the study of earthquake severity, scientists developed various intensity scales that considered damage done to buildings, as well as individual descriptions of the event, and secondary effects such as landslides and the extent of ground rupture. By 1902, Guiseppe Mercalli had developed a relatively reliable intensity scale, which in a modified form is still used today. The **Modified Mercalli Intensity Scale** shown in Table 8.1 was developed using California buildings as its standard, but it is appropriate for use throughout most of the world to estimate the strength of an earthquake (Figure 8.13). For example, if some well-built wood structures and most masonry buildings are destroyed by an earthquake, a region would be assigned an intensity of X on the Mercalli scale (Table 8.1).

Despite their usefulness in providing seismologists with a tool to compare earthquake severity, particularly in regions where there are no seismographs, intensity scales have severe drawbacks. In particular, intensity scales are based on effects (largely destruction) of earthquakes that depend not only on the severity of ground shaking but also on factors such as population density, building design, and the nature of surface materials.

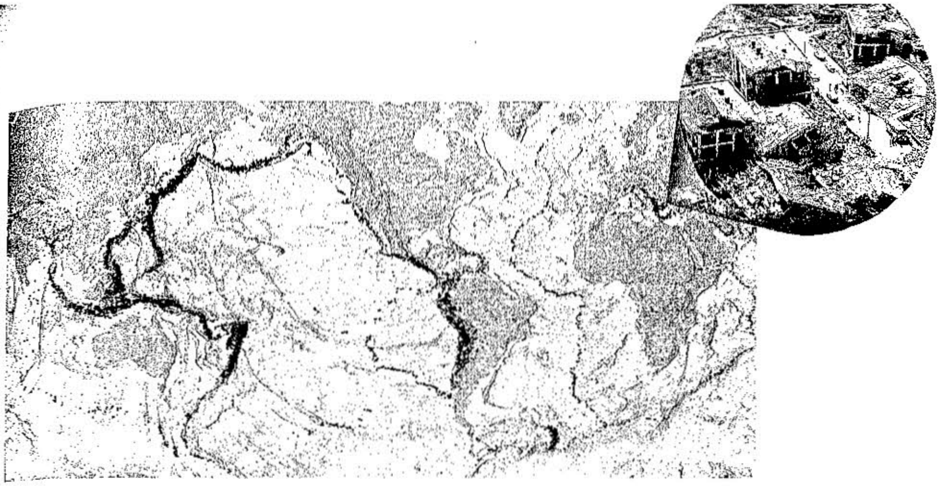


FIGURE 8.12 Distribution of the 14,229 earthquakes with magnitudes equal to or greater than 5 for a 10-year period. Inset photo shows earthquake damage near Ismit, Turkey, in 1999. (Photo courtesy of CORBIS/SYGMA)

Magnitude Scales

In order to compare earthquakes across the globe, a measure was needed that did not rely on parameters that vary considerably from one part of the world to another, such as construction practices. As a consequence, a number of magnitude scales were developed.

Richter Magnitude In 1935, Charles Richter of the California Institute of Technology developed the first magnitude scale using seismic records to estimate the relative sizes of earthquakes. As shown in Figure 8.14 (top), the **Richter scale** is based on the amplitude of the largest seismic wave (P, S, or surface wave) recorded on a seismogram. 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^{26} ergs of energy—roughly equivalent to the detonation of 1 billion 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.

TABLE 8.1 Modified Mercalli Intensity Scale

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake.
IV	During the day felt indoors by many, outdoors by few. Sensation like heavy truck striking building.
V	Felt by nearly everyone, many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight-to-moderate in well-built ordinary structures; considerable in poorly built or badly designed structures.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. (Fall of chimneys, factory stacks, columns, monuments, walls.)
IX	Damage considerable in specially designed structures. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed. Most masonry and frame structures destroyed. Ground badly cracked.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces. Objects thrown upward into air.

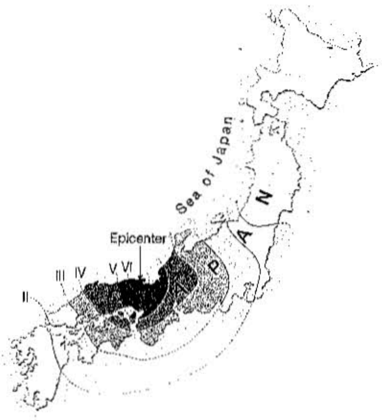
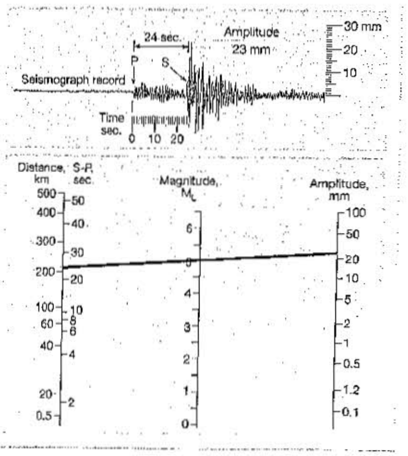


FIGURE 8.13 Zones of destruction associated with an earthquake that struck Japan in 1925. Intensity levels based on the Modified Mercalli Intensity Scale.

FIGURE 8.14 Illustration showing how the Richter magnitude of an earthquake can be determined graphically using a seismograph record from a Wood-Anderson instrument. First, measure the height (amplitude) of the largest wave on the seismogram (23 mm) and then the distance to the focus using the time interval between S and P waves (24 seconds). Next, draw a line between the distance scale (left) and the wave amplitude scale (right). By doing this, you should obtain the Richter magnitude (M_L) of 5. (Data from California Institute of Technology)



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-magnitude earthquake is 10 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 *32-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 (M_L) where M is for *magnitude* and L is 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 assigned to earthquakes in 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.

Moment Magnitude Seismologists have recently been employing a more precise measure called **moment magnitude** (M_W), 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 the rupture surface, and the shear strength of the faulted 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 small- and moderate-sized earthquakes have moment magnitudes that 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 demoted to 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 on record is the 1960 Chilean earthquake with a moment magnitude of 9.5.

TABLE 8.2 Earthquake Magnitudes and Expected World Incidence

Richter Magnitudes	Effects Near Epicenter	Estimated Number per Year
<2.0	Generally not felt, but recorded	600,000
2.0–2.9	Potentially perceptible	300,000
3.0–3.9	Felt by some	49,000
4.0–4.9	Felt by most	6,200
5.0–5.9	Damaging shocks	800
6.0–6.9	Destructive in populous regions	266
7.0–7.9	Major earthquakes; inflict serious damage	18
8.0 and above	Great earthquakes; destroy communities near epicenter	1.4

Source: *Earthquake Information Bulletin* and others.

Moment magnitude has gained wide 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 this century—the Good Friday Alaskan Earthquake—occurred in 1964. Felt throughout the state, the earthquake had a moment magnitude of 9.2 and reportedly lasted 3–4 minutes. This event left 131 people dead, thousands homeless, and the economy of the state badly disrupted because it occurred near major towns and seaports (Figure 8.15). Had the schools and business districts been open on this holiday, the toll surely would have been higher. Within 24 hours of the initial shock, 28 aftershocks were recorded, 10 of which exceeded a Richter magnitude of 6.

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

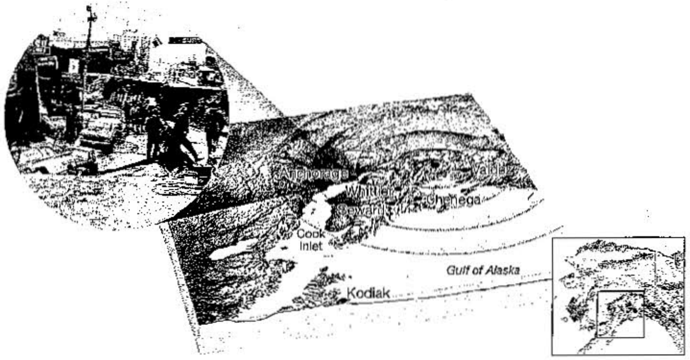
Students Sometimes Ask . . .

I've heard that the safest place to be in a house during an earthquake is in a doorframe. Is that really the best place?

No! An enduring earthquake image of California is a collapsed adobe home with the door frame as the only standing part. From this came the belief that a doorway is the safest place to be during an earthquake. In modern homes, doorways are no stronger than any other part of the house and usually have doors that will swing and can injure you.

If you're inside, the best advice is to *duck, cover,* and *hold*. When you feel an earthquake, *duck* under a desk or sturdy table. Stay away from windows, bookcases, file cabinets, heavy mirrors, hanging plants, and other heavy objects that could fall. Stay under *cover* until the shaking stops. And, *hold* on to the desk or table: If it moves, move with it.

FIGURE 8.15 Region most affected by the Good Friday earthquake of 1964. Note the location of the epicenter (red dot). Inset photo shows the collapse of a street in Anchorage, Alaska, caused by this earthquake. (Photo courtesy of U.S. Geological Survey)



Fire

The 1906 San Francisco earthquake reminds us of the formidable threat 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 uncontrolled 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 250 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 57 deaths and about $40 billion in damage (Figure 8.23). This was from a brief earthquake (about 40 seconds) of moderate rating (M_W 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 monitoring possible *precursors*—phenomena that precede and thus provide a warning of a forthcoming earthquake. In California, for example, some seismologists are measuring uplift, subsidence, and strain in the rocks near active faults. Some Japanese scientists are studying peculiar anomalous 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 16,980 injuries resulted from this earthquake.

FIGURE 8.23 Damage to Interstate 5 caused by the January 17, 1994, Northridge earthquake. (Photo by Tom McHugh/Photo Researchers, Inc.)

TABLE 8.3 Some Notable Earthquakes

Year	Location	Deaths(est.)	Magnitude	Comments
1556	Shensi, China	830,000	Unknown	Possibly the greatest natural disaster.
1755	Lisbon, Portugal	70,000	Unknown	Tsunami damage extensive.
*1811–1812	New Madrid, Missouri	Few	Unknown	Three major earthquakes.
*1886	Charleston, South Carolina	60	Unknown	Greatest historical earthquake in the eastern United States.
*1906	San Francisco, California	1,500	8.3	Fires caused extensive damage.
1908	Messina, Italy	120,000	Unknown	
1923	Tokyo, Japan	143,000	7.9	Fire caused extensive destruction.
1960	Southern Chile	5,700	9.5	The largest-magnitude earthquake ever recorded.
*1964	Alaska	131	9.2	Greatest North American earthquake.
1970	Peru	66,000	7.8	Great rockslide.
*1971	San Fernando, California	65	6.5	Damage exceeded $1 billion.
1975	Liaoning Province, China	1,328	7.5	First major earthquake to be predicted.
1976	Tangshan, China	240,000	7.6	Not predicted.
1985	Mexico City	9,500	8.1	Major damage occurred 400 km from epicenter.
1988	Armenia	25,000	6.9	Poor construction practices.
*1989	San Francisco Bay area	62	7.1	Damages exceeded $6 billion.
1990	Iran	50,000	7.3	Landslides and poor construction practices caused great damage.
1993	Latur, India	10,000	6.4	Located in stable continental interior.
*1994	Northridge, California	51	6.7	Damages in excess of $15 billion.
1995	Kobe, Japan	5,472	6.9	Damages estimated to exceed $100 billion.
1999	Izmit, Turkey	17,127	7.4	Nearly 44,000 injured and more than 250,000 displaced.
1999	Chi-Chi, Taiwan	2,300	7.6	Severe destruction; 8,700 injuries.
2001	Bhuj, India	25,000+	7.9	Millions homeless.
2003	Bam, Iran	41,000+	6.6	Ancient city with poor construction.
2004	Indian Ocean	230,000	9.0	Devastating tsunami damage.
2005	Pakistan/Kashmir	83,000	7.6	Many landslides; 4 million homeless.

*U.S. earthquakes.

Source: U.S. National Oceanic and Atmospheric Administration

One year after the Liaoning earthquake at least 240,000 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 few failures, or false alarms.* Can you imagine the 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 living accommodations, and providing for their lost 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 like, 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 is over, 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 30 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 (90 percent) of generating a quake is the Parkfield section. This area has been called the "Old Faithful" of

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 24 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.A).

By reconciling historical records with detailed scientific studies of the region, volcanologists have pieced together the chronology of the destruction of Pompeii. The eruption most likely began as steam discharges on the morning of August 24. By early afternoon fine ash and pumice fragments formed a tall eruptive cloud emanating from Vesuvius. Shortly thereafter, debris from this cloud began to shower Pompeii, located 9 kilometers (6 miles) downwind of the volcano. Undoubtedly, many people fled during this early phase of the eruption. For the next several hours pumice fragments as large as 5 centimeters (2 inches) fell on Pompeii. One historical record of this eruption states that people located more distant than Pompeii tied pillows to 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 surge of searing hot dust and gas 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 cemented into a hard mass before their bodies had time to decay. The subsequent decomposition of the bodies produced cavities in the hardened ash that replicated the form of the entombed bodies, preserving in some cases even facial expressions. Nineteenth-century excavators found these cavities and created casts of the corpses by pouring plaster of Paris into the voids (Figure 9.A). Some of the plaster casts show victims covering their mouths

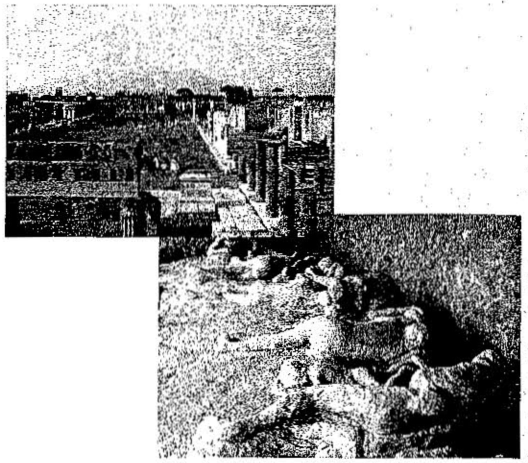


FIGURE 9.A The Roman city of Pompeii was destroyed in A.D. 79 during an eruption of Mount Vesuvius. **Upper.** Ruins of Pompeii. (Photo by Roger Ressmeyers/CORBIS) **Lower.** Plaster casts of several victims of that eruption. (Photo by Leonard'von Matt/Photo Researchers, Inc.)

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thus, another caldera-forming eruption is likely, but not imminent.

Calderas produced by Yellowstone-type eruptions are the largest volcanic structures on Earth. Volcanologists have compared their destructive force with that of the impact of a small asteroid. Fortunately, no eruption of that type has occurred in historic times.

Unlike calderas associated with shield volcanoes or composite cones, these depressions are so large and poorly defined that many remained undetected until high-quality aerial or satellite images became available. Other examples of large calderas located in the United States are California's Lone Valley Caldera; LaGarita Caldera, located in the San Juan Mountains of southern Colorado; and the Valles Caldera, located west of Los Alamos, New Mexico.

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 fractures in the crust called fissures (*fissura* = to split). Rather than building a cone, these long narrow 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 (Figure 9.23). Successive flows, some 50 meters (160 feet) thick, buried the existing landscape as they built a lava 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 basalts** 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 flat-lying basalt 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 basalts, called the Ontong Java Plateau, is found on the floor of the Pacific Ocean.

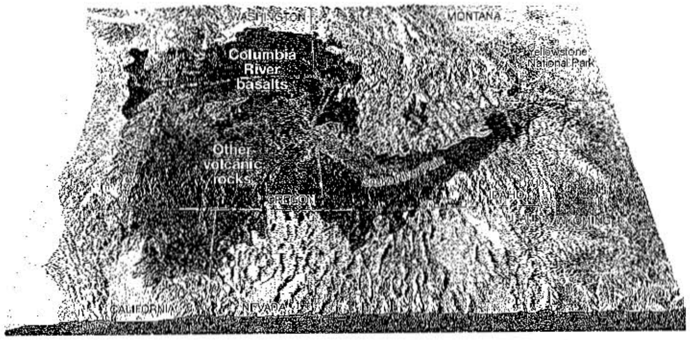


FIGURE 9.22 Volcanic areas in the northwestern United States. The Columbia River basalts cover an area of nearly 200,000 square kilometers (80,000 square miles). Activity here began about 17 million years ago as lava poured out of large fissures, eventually producing a basalt plateau with an average thickness of more than 1 kilometer. (After U.S. Geological Survey)

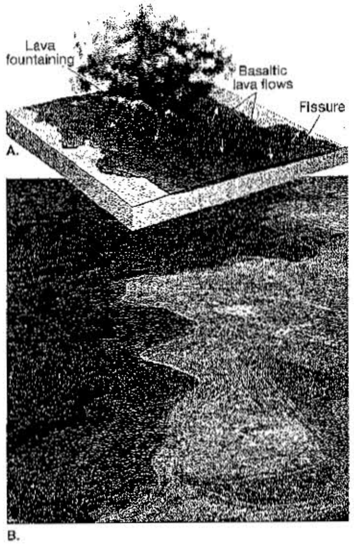
Volcanic Pipes and Necks

Most 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 200 kilometers (125 miles). When this occurs, the ultramafic magmas that migrate up these structures produce 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 rock 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 150 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 standing above the surrounding terrain long after most of the cone has vanished. Ship Rock, New Mexico, is such a feature and is called a **volcanic neck** (Figure 9.24). This structure, higher than many skyscrapers, is but one of many such landforms that protrude conspicuously from the red desert landscapes of the American Southwest.

FIGURE 9.23 Basaltic fissure eruption. **A.** Lava fountaining from a fissure forming fluid lava flows called flood basalts. **B.** Photo of basalt flows (dark) near Idaho Falls. (Photo by John S. Shelton)



BOX 9.2 ▸ EARTH AS A SYSTEM

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 climatic variability. Explosive eruptions emit huge 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.B).

The Basic Premise

The basic premise is that this suspended volcanic material will filter out a portion of the incoming solar radiation, which in turn will drop temperatures in the lowest layer 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 of modern times. During April 7–12, 1815, this nearly 4,000-meter-high (13,000-foot) 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 the Northern Hemisphere. From May through September 1816 an unprecedented series of cold spells affected the northeastern United States and adjacent portions of Canada. There was heavy snow in June and frost in July and August. Abnormal cold was also experienced in much of western Europe. Similar, although apparently less dramatic, effects were associated with other great explosive volcanoes, including Indonesia's Krakatau in 1883.

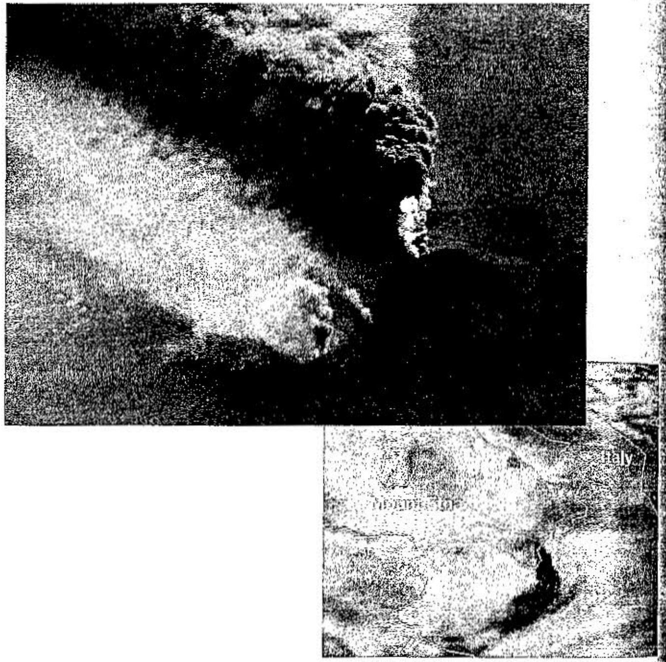


FIGURE 9.B Mount Etna, a volcano on the island of Sicily, erupting in late October 2002. Mount Etna is Europe's largest and most active volcano. **Upper.** This photo of Mount Etna looking southeast was taken by a crew member aboard the International Space Station. It shows a plume of volcanic ash streaming southeastward from the volcano. **Lower.** This image from the Atmospheric Infrared Sounder on NASA's *Aqua* satellite shows the sulfur dioxide (SO_2) plume in shades of purple and black. (Images courtesy of NASA)

Three Modern Examples

Three major volcanic events have provided considerable data and insight regarding the impact of volcanoes on global temperatures. The eruptions of Washington State's Mount St. Helens in 1980, the Mexican volcano El Chichón in 1982, and the Philippines' Mount Pinatubo in 1991 have given scientists an opportunity to study the atmospheric effects of volcanic eruptions with the aid of more sophisticated technology than had been available in the past. Satellite images and remote-sensing instruments allowed scientists to monitor closely the effects of the clouds of gases and ash that these volcanoes emitted.

Mount St. Helens

When Mount St. Helens erupted, there was immediate speculation about the possible effects on our climate. Could such an eruption cause our climate to change? There is no doubt that the large quantity of volcanic ash emitted by the explosive eruption had significant local and regional effects for a short period. Still, studies indicated that any longer-term lowering of hemispheric temperatures was negligible. The cooling was so slight, probably less than 0.1°C (0.2°F), that it could not be distinguished from other natural temperature fluctuations.

El Chichón

Two years of monitoring and studies following the 1982 El Chichón eruption indicated that its cooling effect on global mean temperature was greater than that of Mount St. Helens, on the order of 0.3–0.5°C (0.5–0.9°F). The eruption of El Chichón was *less explosive* than the Mount St. Helens blast, so why did it have a greater impact on global temperatures? The reason is that the material emitted by Mount St. Helens was largely fine ash that settled out in a relatively short time. El Chichón, on the other hand, emitted far greater quantities of sulfur dioxide gas (an estimated 40 times more) than Mount St. Helens. This gas combines with water vapor high in the atmosphere to produce a dense cloud of tiny sulfuric-acid particles. The particles, called *aerosols*, take several years to settle out completely. They lower the atmosphere's mean temperature because they reflect solar radiation back to space.

We now understand that volcanic clouds that remain in the stratosphere for a year or more are composed largely of sulfuric-acid droplets and not of dust, as was once thought. Thus, the volume of fine debris emitted during an explosive event is not an accurate criterion for predicting the global atmosphere effects of an eruption.

Mount Pinatubo

The Philippines volcano Mount Pinatubo erupted explosively in June 1991, injecting 25–30 million tons of sulfur dioxide high into the atmosphere. The event provided scientists with an opportunity to study the climatic impact of a major explosive volcanic eruption using NASA's spaceborne Earth Radiation Budget Experiment. During the next year the haze of tiny aerosols increased the percentage of light reflected by the atmosphere and thus lowered global temperatures by 0.5° C (0.9°F).

It may be true that the impact on global temperature of eruptions like El Chichón and Mount Pinatubo is relatively minor, but many scientists agree that the cooling produced could alter the general pattern of atmospheric circulation for a limited period. Such a change, in turn, could influence the weather in some regions. Predicting or even identifying specific regional effects still presents a considerable challenge to atmospheric scientists.

The preceding examples illustrate that the impact on climate of a single volcanic eruption, no matter how great, is relatively small and short-lived. Therefore, if volcanism is to have a pronounced impact over an extended period, many great eruptions, closely spaced in time, need to occur. If this happens, the atmosphere could become loaded with enough sulfur dioxide and volcanic dust to seriously diminish the amount of solar radiation reaching the surface.

Although no such period of explosive volcanism is known to have occurred in historic times, such events may have altered climates in the geologic past. For example, massive eruptions of basaltic lava that began about 250 million years ago and lasted for a million years or more may have contributed to one of Earth's most profound mass extinctions. A discussion of a possible link between volcanic activity and the *Great Permian Extinction* is found in Chapter 12.

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move away from each other and new seafloor 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 (mostly H_2O) from the oceanic crust. These mobile fluids migrate upward into the wedge-shaped piece of mantle located between the subducting slab and overriding plate (see Figure 9.32). Once the sinking slab reaches a depth of about 100 to 150 kilometers, these water-rich fluids reduce the melting point of hot 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—at distances of 200–300 kilometers (100–200 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 *island archipelagos* in most atlases. Geologists prefer the more descriptive term **volcanic island arcs**, or simply **island arcs** (Figure 9.34, upper left). Several young volcanic island arcs of this type border the western Pacific basin, including the Aleutians, the Tongas, and the Marianas.

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). The mechanisms that generate these magmas are essentially the same as those operating at island arcs. The major difference is that continental crust is much thicker and is composed of rocks having a higher silica content than oceanic crust. Hence through the assimilation of silica-rich crustal rocks a magma body may change composition as it rises through continental crust. Stated another way, magmas generated in the mantle may change from a comparatively dry, fluid basaltic magma to a viscous andesitic or rhyolitic magma having a high concentration of volatiles as it moves up through the continental crust. The volcanic chain of the Andes Mountains along the western edge of South America 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 explosive volcanoes we call the Ring of Fire formed in this region. The volcanoes of the Cascade Range in the northwestern United States, including Mount Hood, Mount Rainier, and Mount Shasta, are included in this group (Figure 9.35).

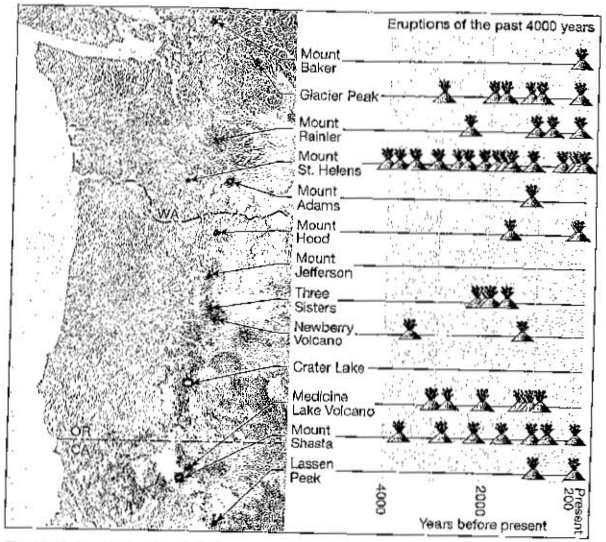


FIGURE 9.35 Of the 13 potentially active volcanoes in the Cascade Range, 11 have erupted in the past 4,000 years and 7 in just the past 200 years. More than 100 eruptions, most of which were explosive, have occurred in the past 4,000 years. Mount St. Helens is the most active volcano in the Cascades. Its eruptions have ranged from relatively quiet outflows of lava to explosive events much larger than that of May 18, 1980. Each eruption symbol in the diagram represents from one to several dozen eruptions closely spaced in time. (After U.S. Geological Survey)

Igneous Activity at Divergent Plate Boundaries

The greatest volume of magma (perhaps 60 percent of Earth's total yearly output) is produced along the oceanic ridge system in association with seafloor spreading (Figure 9.34, upper right). Here, below the ridge axis where the lithospheric plates are being continually pulled apart, the solid yet mobile mantle responds to the decrease in overburden and rises upward to fill in the rift. Recall that as rock rises, it experiences a decrease in confining pressure and undergoes melting without the addition of heat. This process, called *decompression melting*, generates large quantities of magma.

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 buoyantly rises. Collecting in reservoirs located just beneath the ridge crest, about 10 percent of this molten material eventually migrates upward along fissures to erupt as flows on the ocean This activity continuously adds new bas rock to the plate margins, temporarily we ing them together, only to break again spreading continues. Along some rid outpouring of bulbous pillow lavas be numerous small seamounts. At other tions erupted lavas produce fluid flows create more subdued topography.

Although most spreading centers are cated along the axis of an oceanic some are not. In particular, the East Af Rift is a site where continental crust is ripped apart (Figure 9.34, lower right). outpourings of fluid basaltic lavas are mon in this region. The East African zone also contains numerous small vol noes and even a few large composite co as exemplified by Mount Kilimanjaro.

Intraplate Igneous Activity

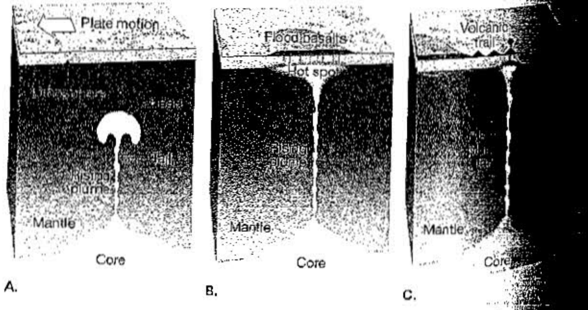
We know why igneous activity is initia along plate boundaries, but why do tions occur in the interiors of pla Hawaii's Kilauea is considered the world most active volcano, yet it is situated sands of kilometers from the nearest boundary in the middle of the vast plate. Other sites of **intraplate volcani** (meaning "within the plate") include the nary Islands, Yellowstone, and several canic centers that you may be surprised learn are located in the Sahara Desert northern Africa.

We now recognize that most intraplate volcanism where a mass of hotter than normal mantle material called **mantle plume** ascends toward the surface (Figure 9.36). though the depth at which (at least some) mantle plumes originate is still hotly debated, many appear to form deep within Earth at the core–mantle boundary. These plumes of solid yet mobile mantle rock rise toward the surface in a manner similar to the blobs that form within a lava lamp. (These are the gaudy lamps that contain two immiscible liquids in a glass container. As the base of the lamp is heated, the denser liquid at the bottom becomes buoyant and forms blobs that rise to the top.) Like the blobs in a lava lamp, a mantle plume has a bulbous head that draws out a narrow stalk beneath it as it rises. Once the plume head nears the top of the mantle, decompression melting generates basaltic magma that may eventually trigger volcanism at the surface. The result is a localized volcanic region a few hundred kilometers across called a **hot spot** (Figure 9.34, right). More than 100 hot spots have been identified, and most have persisted for millions of years. The land surface around hot spots is often elevated, showing that it is buoyed up by a plume of warm low-density material. Furthermore, by measuring the heat flow in these regions, geologists have determined that the mantle beneath hot spots must be 100–150°C hotter than normal.

The volcanic activity on the island of Hawaii, with its outpourings of basaltic lava, is certainly the result of hot-spot volcanism (Figure 9.34, left). Where a mantle plume has persisted for long periods of time, a chain of volcanic structures may form as the overlying plate moves over it. In the Hawaiian Islands, hot-spot activity is currently centered on Kilauea. However, over the past 80 million years the same mantle plume generated a chain of volcanic islands (and seamounts) that extend thousands of kilometers from the Big Island in a northwestward direction across the Pacific.

Mantle plumes are also thought to be responsible for the vast outpourings of basaltic lava that create large basalt plateaus such as the Columbia Plateau in the northwestern United States, India's Deccan Plateau, and the Ontong Java Plateau in the western Pacific (Figure 9.34, right).

FIGURE 9.36 Model of a mantle plume and associated hot-spot volcanism. **A.** A rising mantle plume with large bulbous head and narrow tail. **B.** Rapid decompression melting of the head of a mantle plume produces vast outpourings of basalt. **C.** Less voluminous activ caused by the plume tail produces a linear volcanic chain on the seafloor.



Students Sometimes Ask . . .

Some of the larger volcanic eruptions, like the eruption of Krakatau, must have been impressive. What was it like?

On August 27, 1883, in what is now Indonesia, the volcanic island of Krakatau exploded and was nearly obliterated. The sound of the explosion was heard an incredible 4,800 kilometers (3,000 miles) away at Rodriguez Island in the western Indian Ocean. Dust from the explosion was propelled into the atmosphere and circled Earth on high-altitude winds. This dust produced unusual and beautiful sunsets for nearly a year.

Not many were killed directly by the explosion, because the island was uninhabited. However, the displacement of water from the energy released during the explosion was enormous. The resulting *seismic sea wave* or *tsunami* exceeded 35 meters (116 feet) in height. It devastated the coastal region of the Sunda Strait between the nearby islands of Sumatra and Java, drowning over 1,000 villages and taking more than 36,000 lives. The energy carried by this wave reached every ocean basin and was detected by tide-recording stations as far away as London and San Francisco.

Although the plate tectonics theory has answered many questions regarding the distribution of igneous activity, many new questions have arisen: Why does seafloor spreading occur in some areas but not others? How do mantle plumes and associated hot spots originate? These and other questions are the subject of continuing geologic research.

Living with Volcanoes

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, Mexico; Tokyo, Japan; Naples, Italy; and Quito, Ecuador, are located on or near a volcano.

Until recently, the dominant view of Western societies 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. With this awareness, the new focus is on how to live with volcanoes.

Volcanic Hazards

As shown in Figure 9.37, volcanoes produce a wide variety of potential hazards that can kill people and wildlife and destroy property. Perhaps the greatest threats to life are pyroclastic flows. These hot mixtures of gas, ash, and pumice that sometimes exceed 800°C (1500°F) speed down the flanks of volcanoes, giving people little chance of surviving.

Lahars, which can occur even when a volcano is not erupting, are perhaps the next most dangerous volcanic phenomenon. These mixtures of volcanic debris and water can flow for tens of kilometers down a valley at speeds that may exceed 100 kilometers (62 miles) per hour. Lahars pose a potential hazard to many communities downstream from glacier-clad volcanoes such as Mount Rainier. Other potentially destructive mass-wasting events include the rapid collapse of the volcano's summit or flank.

Other obvious hazards include explosive eruptions that can endanger people and property at great distances from a volcano. During the past 15 years, at least 80 commercial jets have been damaged by inadvertently flying into clouds of volcanic ash. One of these was a near crash that occurred in 1989 when a Boeing 747, with more than 300 passengers aboard, encountered an ash cloud from Alaska's Redoubt volcano. All four engines stalled after they became clogged with ash. Fortunately, the engines were restarted at the last minute and the aircraft managed to land safely in Anchorage.

Monitoring Volcanic Activity

A number of volcano monitoring techniques are now employed; most of them aimed at detecting the movement of magma from a subterranean reservoir (typically several kilometers deep) toward the surface. The four most noticeable changes in a volcanic landscape caused by the migration of

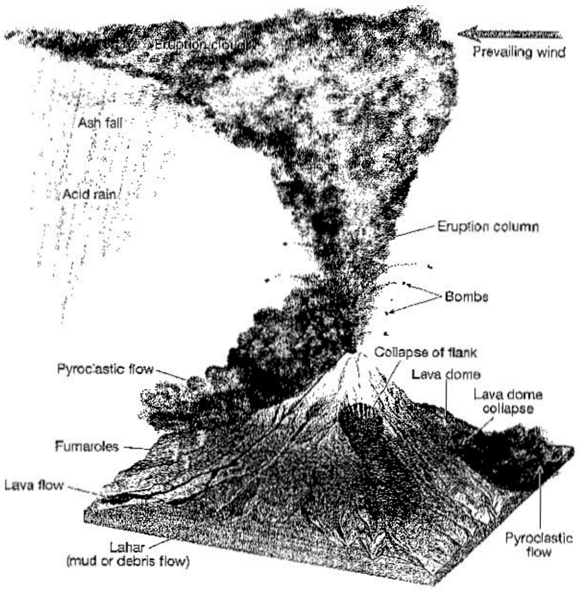


FIGURE 9.37 Simplified drawing showing a wide variety of natural hazards associated with volcanoes. (After U.S. Geological Survey)

magma are (1) changes in the pattern of volcanic earthquakes; (2) expansion of a near-surface magma chamber, which leads to inflation of the volcano; (3) changes in the amount and/or composition of the gases that are released from a volcano; and (4) an increase in ground temperature caused by the emplacement of new magma.

Almost a third of all volcanoes that have erupted in historic times are now monitored seismically (through the use of instruments that detect earthquake tremors). In general, a sharp increase in seismic unrest followed by a period of relative quiet has been shown to be a precursor for many volcanic eruptions. However, some large volcanic structures have exhibited lengthy periods of seismic unrest. For example, Rabaul Caldera in New Guinea recorded a strong increase in seismicity in 1981. This activity lasted 13 years and finally culminated with an eruption in 1994. Occasionally, a large earthquake has triggered a volcanic eruption, or at least disturbed the volcano's plumbing. Kilauea, for example, began to erupt after the Kalapana earthquake of 1975.

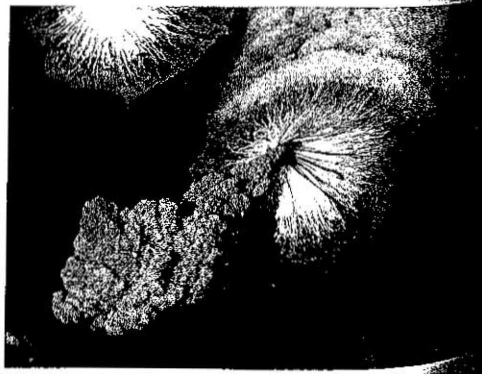
The roof of a volcano may rise as new magma accumulates in its interior—a phenomena that precedes many volcanic eruptions. Because the accessibility of many volcanoes is limited, remote sensing devices, including lasers, Doppler radar, and Earth-orbiting satellites, are often used to determine whether or not a volcano is swelling. The recent discovery of ground doming at Three Sisters volcanoes in Oregon was first detected using radar images obtained from satellites.

Volcanologists also frequently monitor the gases that are released from volcanoes in an effort to detect even minor changes in their amount and/or composition. Some volcanoes show an increase in sulfur dioxide (SO_2) emissions months or years prior to an eruption. On the other hand, a few days prior to the 1991 eruption of Mount Pinatubo, emission of carbon dioxide (CO_2) dropped dramatically.

The development of remote sensing devices has greatly increased our ability to monitor volcanoes. These instruments and techniques are particularly useful for monitoring eruptions in progress. Photographic images and infrared (heat) sensors can detect lava flows and volcanic columns rising from a volcano (Figure 9.38). Furthermore, satellites can detect ground deformation as well as monitor SO_2 emissions.

The overriding goal of all monitoring techniques is to discover precursors that may warn of an imminent eruption. This is accomplished by first diagnosing the current condition of a volcano and then using this baseline data to predict its future behavior. Stated another way, a volcano must be observed over an extended period to recognize significant changes from its "resting state."

FIGURE 9.38 Photo taken by Jeff Williams from the International Space Station of a steam-and-ash eruption emitted from Cleveland Volcano in the Aleutian Islands. This event was reported to the Alaska Volcano Observatory, which issued a warning to air traffic control. (Photo courtesy of NASA)



Chapter Summary

- The primary factors that determine the nature of volcanic eruptions include the magma's *temperature*, its *composition*, and the *amount of dissolved gases* it contains. As lava cools, it begins to congeal, and as *viscosity* increases, its mobility decreases. *The viscosity of magma is directly related to its silica content. Rhyolitic* lava, with its high silica content, is very viscous and forms short, thick flows. *Basaltic* lava, with a lower silica content, is more fluid and may travel a long distance before congealing. Dissolved gases provide the force that propels molten rock from the vent of a volcano.
- The materials associated with a volcanic eruption include *lava flows* (*pahoehoe* and *aa* flows for basaltic lavas), *gases* (primarily in the form of *water vapor*), and *pyroclastic material* (pulverized rock and lava fragments blown from the volcano's vent, which include *ash, pumice, lapilli, cinders, blocks*, and *bombs*).
- Successive eruptions of lava from a central vent result in a mountainous accumulation of material known as a *volcano*. Located at the summit of many volcanoes is a steep-walled depression called a *crater*. *Shield cones* are broad, slightly domed volcanoes built primarily of fluid, basaltic lava. *Cinder cones* have steep slopes composed of pyroclastic material. *Composite cones*, or *stratovolcanoes*, are large, nearly symmetrical structures built of interbedded lavas and pyroclastic deposits. Composite cones produce some of the most violent volcanic activity. Often associated with a violent eruption is a *nuée ardente*, a fiery cloud of hot gases infused with incandescent ash that races down steep volcanic slopes. Large composite cones may also generate a type of mudflow known as a *lahar*.
- Most volcanoes are fed by *conduits* or *pipes*. As erosion progresses, the rock occupying the pipe is often more resistant and may remain standing above the surrounding terrain as a *volcanic neck*. The summits of some volcanoes have large, nearly circular depressions called *calderas* that result from collapse. Calderas also form on shield volcanos by subterranean drainage from a central magma chamber, and the largest calderas form by the discharge of colossal volumes of silica-rich pumice along ring fractures. Although volcanic eruptions from a central vent are the most familiar, by far the largest amounts of volcanic material are extruded from cracks in the crust called *fissures*. The term *flood basalts* describes the fluid, waterlike, basaltic lava flows that cover an extensive region in the northwestern United States known as the Columbia Plateau. When silica-rich magma is extruded, *pyroclastic flows* consisting largely of ash and pumice fragments usually result.
- Igneous intrusive bodies are classified according to their *shape* and by their *orientation with respect to the host rock*, generally sedimentary rock. The two general shapes are *tabular* (tablelike) and *massive*. Intrusive igneous bodies that cut across existing sedimentary beds are said to be *discordant*, whereas those that form parallel to existing sedimentary beds are *concordant*.
- *Dikes* are tabular, discordant igneous bodies produced when magma is injected into fractures that cut across rock layers. Tabular, concordant bodies called *sills* form when magma is injected along the bedding surfaces of sedimentary rocks. *Laccoliths* are similar to sills but form from less-fluid magma that collects as a lens-shaped mass that arches the overlying strata upward. *Batholiths*, the largest intrusive igneous bodies with surface exposures of more than 100 square kilometers (40 square miles), frequently make up the cores of mountains.
- Magma originates from essentially solid rock of the crust and mantle. In addition to a rock's composition, its temperature, depth (confining pressure), and water content determine whether it exists as a solid or liquid. Thus, magma can be generated by *raising a rock's temperature*, as occurs when a hot mantle plume "ponds" beneath crustal rocks. A *decrease in pressure* can cause *decompression melting*. Furthermore, the *introduction of volatiles* (water) can lower a rock's melting point sufficiently to generate magma. Because melting is generally not complete, a process called *partial melting* produces a melt made of the lowest-melting-temperature minerals, which are higher in silica than the original rock. Thus, magmas generated by partial melting are nearer to the granitic (felsic) end of the compositional spectrum than are the rocks from which they formed.
- *Most active volcanoes are associated with plate boundaries.* Active areas of volcanism are found along oceanic ridges where seafloor spreading is occurring (*divergent plate boundaries*), in the vicinity of ocean trenches where one plate is being subducted beneath another (*convergent plate boundaries*), and in the interiors of plates themselves (*intraplate volcanism*). Rising plumes of hot mantle rock are the source of most intraplate volcanism.

Key Terms

aa flow (p. 253)
batholith (p. 268)
caldera (p. 262)
cinder cone (p. 257)
columnar joint (p. 268)
composite cone (p. 258)
conduit (p. 254)
continental volcanic arc (p. 273)
crater (p. 254)
decompression melting (p. 270)
dike (p. 266)
eruption column (p. 251)
fissure (p. 254, 264)
fissure eruption (p. 264)
flood basalt (p. 265)
furmarole (p. 256)
geothermal gradient (p. 269)
hot spot (p. 277)
intraplate volcanism (p. 276)
island arc (p. 273)
laccolith (p. 268)
lahar (p. 262)

BOX 10.1 ▸ PEOPLE AND THE ENVIRONMENT

The San Andreas Fault System

The San Andreas, the best-known and largest fault system in North America, first attracted wide attention after the great 1906 San Francisco earthquake and fire. Following this devastating event, geologic studies demonstrated that a displacement of as much as 5 meters (3 feet) along the fault had been responsible for the earthquake. It is now known that this dramatic event is just one of many thousands of earthquakes that have resulted from repeated movements along the San Andreas throughout its 29-million-year history.

Where is the San Andreas fault system located? As shown in Figure 10.A, it trends in a northwesterly direction for nearly 1,300 kilometers (780 miles) through much of western California. At its southern end, the San Andreas connects with a spreading center located in the Gulf of California. In the north, the fault enters the Pacific Ocean at Point Arena, where it is thought to continue its northwesterly trend, eventually joining the Mendocino fracture zone. In the central section, the San Andreas is relatively simple and straight. However, at its two extremities, several branches spread from the main trace, so that in some areas the fault zone exceeds 100 kilometers (60 miles) in width.

Over much of its extent, a linear trough reveals the presence of the San Andreas Fault. When the system is viewed from the air, linear scars, offset stream channels, and elongated ponds mark the trace in a striking manner. On the ground, however, surface expressions of the faults are much more difficult to detect. Some of the most distinctive landforms include long, straight escarpments, narrow ridges, and sag ponds formed by settling of blocks within the fault zone. Furthermore, many stream channels characteristically bend sharply to the right where they cross the fault (Figure 10.B).

With the development of the theory of plate tectonics, geologists began to realize the significance of this great fault system. The San Andreas Fault is a transform boundary separating two crustal plates that move very slowly. The Pacific plate, located to the west, moves northwestward relative to the North American plate, causing earthquakes along the fault (Table 10.A).

The San Andreas is undoubtedly the most studied of any fault system in the world. Although many questions remain unanswered, geologists have learned that each fault segment exhibits somewhat different behavior. Some portions of the San Andreas exhibit a slow creep with little noticeable seismic activity. Other segments regularly slip, producing small earthquakes, whereas still other segments seem to store elastic energy for hundreds of years and rupture in great earthquakes. This knowledge is useful when assigning earthquake-hazard potential to a given segment of the fault zone.

Because of the great length and complexity of the San Andreas Fault, it is more appropriately referred to as a "fault system." This major fault system consists primarily of the San Andreas Fault and several major branches, including the Hayward and Calaveras faults of central California and the San Jacinto and Elsinore faults of southern California (Figure 10.A). These major segments, plus a vast number of smaller faults that include the Imperial Fault, San Fernando Fault, and the Santa Monica Fault, collectively accommodate the relative motion between the North American and Pacific plates.

Ever since the great San Francisco earthquake of 1906, when as much as 5 meters of displacement occurred, geologists have attempted to establish the cumulative displacement along this fault over its 29-million-year history. By matching rock units across the fault, geologists have determined that the total accumulated displacement from earthquakes and creep exceeds 560 kilometers (340 miles).

FIGURE 10.A Map showing the extent of the San Andreas Fault system. Inset is an aerial view of the San Andreas Fault. (Photo by D. Parker/Photo Researchers)

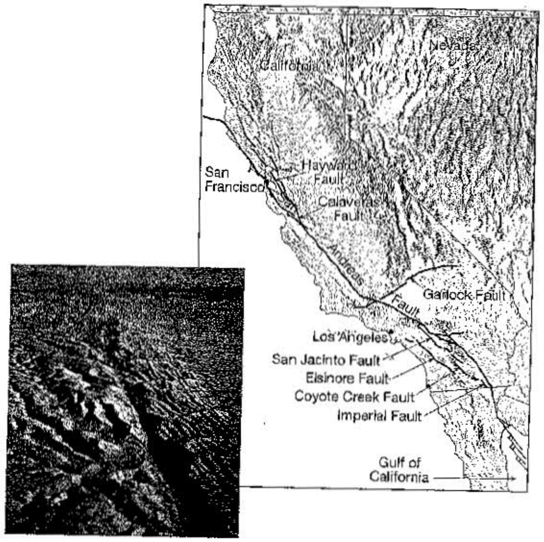


FIGURE 10.B Aerial view showing offset stream channel across the San Andreas Fault on the Carrizo Plain west of Taft, California. (Photo by Michael Collier)

TABLE 10.A Major Earthquakes on the San Andreas Fault System

Date	Location	Magnitude	Remarks
1812	Wrightwood, CA	7	Church at San Juan Capistrano collapsed, killing 40 worshippers.
1812	Santa Barbara channel	7	Churches and other buildings wrecked in and around Santa Barbara.
1838	San Francisco peninsula	7	At one time thought to have been comparable to the great earthquake of 1906.
1857	Fort Tejon, CA	8.25	One of the greatest U.S. earthquakes. Occurred near Los Angeles, then a city of 4,000.
1868	Hayward, CA	7	Rupture of the Hayward fault caused extensive damage in San Francisco Bay area.
1906	San Francisco, CA	8.25	The great San Francisco earthquake. As much as 80 percent of the damage caused by fire.
1940	Imperial Valley	7.1	Displacement on the newly discovered Imperial fault.
1952	Kern County	7.7	Rupture of the White Wolf fault. Largest earthquake in California since 1906. Sixty million dollars in damages and 12 people killed.
1971	San Fernando Valley	6.5	One-half billion dollars in damages and 58 lives claimed.
1989	Santa Cruz Mountains	7.1	Loma Prieta earthquake. Six billion dollars in damages, 62 lives lost, and 3,757 people injured.
1994	Northridge (Los Angeles area)	6.9	Over 15 billion dollars in damages, 51 lives lost, and over 5,000 injured.

Many rocks are broken by two or even 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 5 is such a case.

Mountain Building

GEODe Forces Within
▸ Mountain Building

Like other people, geologists have been inspired more by Earth's mountains than by any other landforms (Figure 10.13). Through extensive scientific exploration over the last 150 years much has been learned about the internal processes that generate these often spectacular terrains. The name for the processes that collectively produce a mountain belt is **orogenesis**, (*oros* = mountain, *genesis* = to come into being). The rocks comprising mountains provide striking visual evidence of the enormous compressional forces that have deformed large sections of Earth's crust and subsequently elevated them to their present positions. Although folding is often the most conspicuous sign of these forces, thrust faulting, metamorphism, and igneous activity are always present in varying degrees.

Mountain building has occurred during the recent geologic past in several locations around the world. These young mountainous belts include the American Cordillera, which runs along the western margin of the Americas from Cape Horn to Alaska and includes the Andes and Rocky mountains; the Alpine-Himalaya chain, which extends from the Mediterranean through Iran to northern India and into Indochina; and the mountainous terrains of the western Pacific, which include volcanic island arcs such as Japan, the Philippines, and Sumatra. Most of these young mountain belts have come into existence within the past 100 million years. Some, including the Himalayas, began their growth as recently as 45 million years ago.

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.A), with the majority located in arid 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 supply alternatives available in California (such as water transfers and groundwater pumping). 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. More than half of the world's desalination plants use *distillation* to purify water, while most of the remaining plants use *membrane processes*.

In distillation, saltwater is evaporated, and the resulting water vapor is collected and condensed 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 0.03‰, which is about 10 times fresher than bottled water.

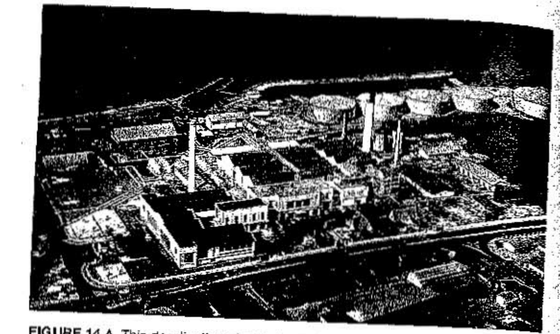


FIGURE 14.A This desalination plant is located on the island of Curacao, in the Netherlands Antilles off the northwest coast of Venezuela. (Photo by Peter Guttman/Corbis/Bettmann)

Membrane processes such as *electrolysis* or *reverse osmosis* use specialized semipermeable membranes to separate dissolved components from water molecules, thereby purifying water. Worldwide, at least 30 countries are operating reverse osmosis units. The world's largest plant, which is in Saudi Arabia, produces 485 million liters (128 million gallons) of desalted water daily. The largest plant in the United States is scheduled to open in 2008 in Florida's Tampa Bay area and will be capable of producing up to 95 million liters (25 million gallons) of fresh water per day. A new facility planned for Carlsbad, California, is designed to produce twice as much fresh water as the Tampa Bay plant. Reverse osmosis is also used in many household water purification units and aquariums.

Other methods of desalination include freeze separation, crystallization of dissolved components directly from seawater, solvent demineralization using chemical catalysts, and even making use of salt-eating bacteria!

Although fresh water produced by various desalination methods is becoming more important as a source of water for human and even industrial use, it is unlikely to be an important supply for agricultural purposes because of the enormous quantities of water necessary to support agriculture. Consequently, making the deserts "bloom" by irrigating them with fresh water produced by desalination is only a dream and, for economic reasons, is likely to remain so for the foreseeable future.

increase in temperature, on the other hand, causes thermal expansion and results in a decrease in seawater density. Such a relationship where one variable decreases as a result of another variable's increase is known as an *inverse relationship*, where one variable is *inversely proportional* with the other.

Temperature has the greatest influence on surface seawater density because variations in surface seawater temperature are greater than salinity variations. In fact, only in the extreme polar areas of the ocean, where temperatures are low and remain relatively constant, does salinity significantly affect density. Cold water that also has high salinity is some of the highest-density water in the world.

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 14.6 shows two graphs of density versus depth: one for high-latitude regions and one for low-latitude regions. Not surprisingly, the curves in Figure 14.6 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.

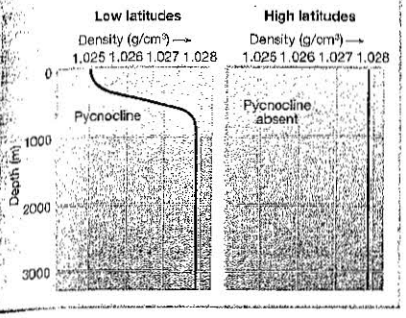


FIGURE 14.6 Variations in ocean water density with depth for low- and high-latitude regions. The layer of rapidly changing density, called the *pycnocline*, is present in the low latitudes but absent in the high latitudes.

The low-latitude curve in Figure 14.6 begins at the surface with low density (related to high surface water temperatures). However, density 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. From this depth to 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), where there is a rapid change of density with depth, is called the **pycnocline** (*pycno* = density, *cline* = slope). A pycnocline has a high gravitational stability and presents a significant barrier to mixing between low-density water above and high-density water below.

The high-latitude curve in Figure 14.6 is also related to the temperature curve for high latitudes shown in Figure 14.4. Figure 14.6 shows that in high latitudes, there is high-density (cold) water at the surface and high-density (cold) water below. Thus, the high-latitude density curve remains vertical, and there is no rapid change of density with depth. A pycnocline is not present in high latitudes; instead, the water column is *isopycnal* (*iso* = same, *pycno* = density).

Ocean Layering

The ocean, like Earth's interior, is layered according to density. Low-density water exists near the surface, and higher-density water occurs below. Except for some shallow inland seas with a high rate of evaporation, the highest-density water 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).

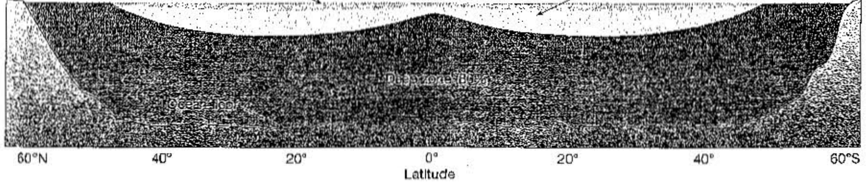
Because solar energy is received at the ocean surface, it is here that water temperatures are warmest. The mixing of these waters by waves as well as the turbulence from currents and tides creates a rapid vertical heat transfer. Hence, this *surface mixed zone* has nearly uniform temperatures. The thickness and temperature of this layer vary, depending on latitude and season. The zone usually extends to about 300 meters (980 feet) but may attain a thickness of 450 meters (1,500 feet). The surface mixed zone accounts for only about 2 percent of ocean water.

Below the sun-warmed zone of mixing, 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 zone of cold water below. The transition zone includes a prominent thermocline and associated pycnocline 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, water density remains constant 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 3,729 meters, or 12,234 feet).

In high latitudes, the three-layer structure of ocean layering does not exist because the water column is isothermal and isopycnal, which means that there is no rapid change in temperature or density 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 14.7 Oceanographers recognize three main layers in the ocean based on water density, which varies with temperature and salinity. The warm surface mixed layer accounts for only 2 percent of ocean water; the transition zone includes the thermocline and pycnocline and accounts for 18 percent of ocean water; the deep zone contains cold, high-density water that accounts for 80 percent of ocean water.



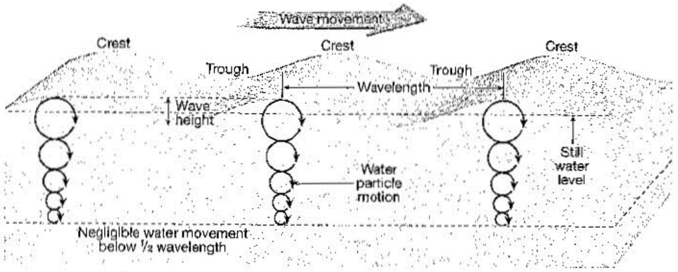
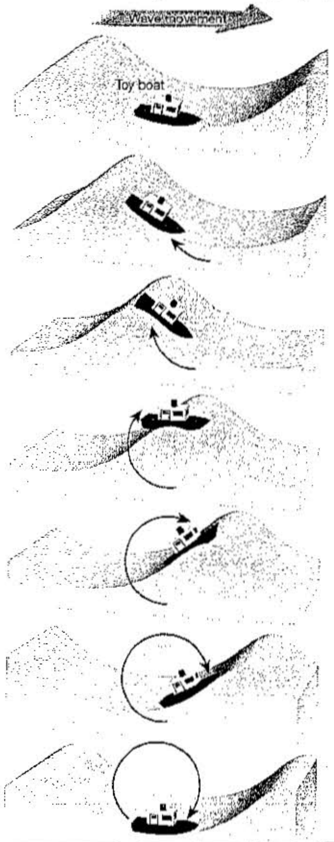


FIGURE 15.12 Diagrammatic view of an idealized non-breaking ocean wave showing the basic parts of a wave as well as the movement of water particles at depth. Negligible water movement occurs below a depth equal to one half the wavelength (*lower dashed line*).

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 no 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 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 *swells*, 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.

FIGURE 15.13 The movements of the toy boat show that the wave form advances, but the water does not advance appreciably from its original position. In this sequence, the wave moves from left to right as the boat (and the water in which it is floating) rotates in an imaginary circle.



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 wave form does. As the wave travels, the water passes the energy along by moving in a circle. This movement 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 backward as 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 that transmit the wave move around in a circle. Wind moving across a field of wheat causes a similar phenomenon: The wheat itself doesn't travel across the field, but the waves do.

BOX 15.2 ▶ PEOPLE AND THE ENVIRONMENT

Rogue Waves—Ships Beware!

Rogue waves are massive, solitary waves that can reach enormous height and often occur at times when normal ocean waves are not unusually large. In a sea of 2-meter (6.5-foot) waves, for example, a 20-meter (65-foot) rogue wave may suddenly appear. *Rogue* means "unusual" and, in this case, the waves are unusually large. Rogue waves—sometimes called *superwaves, monster waves, sleeper waves*, or *freak waves*—are defined as individual waves of exceptional height or abnormal shape that are more than twice the average of the highest one-third of all the wave heights in a given wave record. During 1966, for example, the luxury liner *Michelangelo*, 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 (Figure 15.B) and killed two passengers. Because of their size and destructive power, rogue waves have been popularized in literature and movies such as *The Perfect Storm* and the 2006 film *Poseidon*.

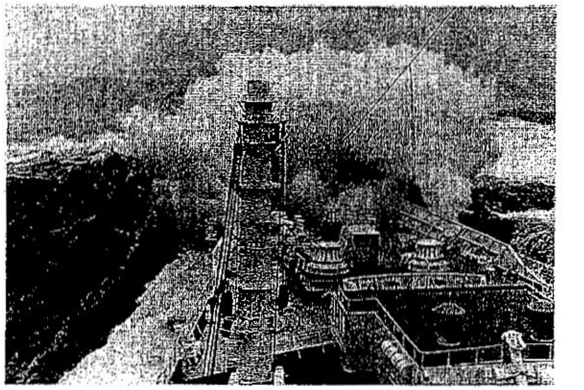


FIGURE 15.B When a rogue wave struck the luxury liner *Michelangelo* during a North Atlantic storm in 1966, it tore off part of the ship's superstructure and killed two passengers. (Photo by)

In the open ocean, one wave in 23 will be over twice the height of the wave average, one in 1,175 will be three times as high, and one in 300,000 will be four times as high. The chances of a truly monstrous wave, therefore, are only one in several billion. Nevertheless, rogue waves do occur, and satellite observations over a 3-week period in 2001 confirmed that rogue waves occur more frequently than was previously thought: The study documented more than 10 individual giant waves around the globe of over 25 meters (82 feet) in height. Even with monitoring of rogue waves by satellites, it remains difficult to forecast specifically when or where they will arise. For instance, the 17-meter (56-foot) NOAA research vessel R/V *Ballena* was flipped and sunk in 2000 by a 4.6-meter (15-foot) rogue wave off the California coast while conducting a survey in shallow, calm water. Fortunately, the three people on board survived the incident.

Worldwide each year, about 10 large ships such as supertankers or containerships are reported missing without a trace and the total number of vessels lost of all sizes may reach 1,000. Rogue waves are thought to be the cause for many of these disasters. Recent satellites designed to monitor the ocean have provided a wealth of data about ocean waves but, unfortunately, still do not allow the prediction of rogue waves.

The main cause of rogue waves is hypothesized to be an extraordinary case of constructive wave interference in which multiple waves overlap in phase to produce an extremely large wave. Rogue waves also tend to occur more frequently downwind from islands or shoals. In addition, rogue waves can occur when storm-driven waves move against strong ocean currents, which act like a lens, focusing wave energy and causing ordinary waves to shorten, steepen, and become larger such as along the "Wild Coast" off the southeast coast of Africa, where the Agulhas Current flows directly against large Antarctic storm waves.

The energy contributed by the wind to the water is transmitted not only along the surface of the sea but also downward. However, beneath the surface the circular motion rapidly diminishes until, at a depth equal to one half the wavelength measured from still water level, the movement of water particles becomes negligible. This depth is known as the *wave base*. The dramatic decrease of wave energy with depth is shown by the rapidly diminishing diameters of water-particle orbits in Figure 15.12.

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 farther out to sea catch up, decreasing the wavelength.

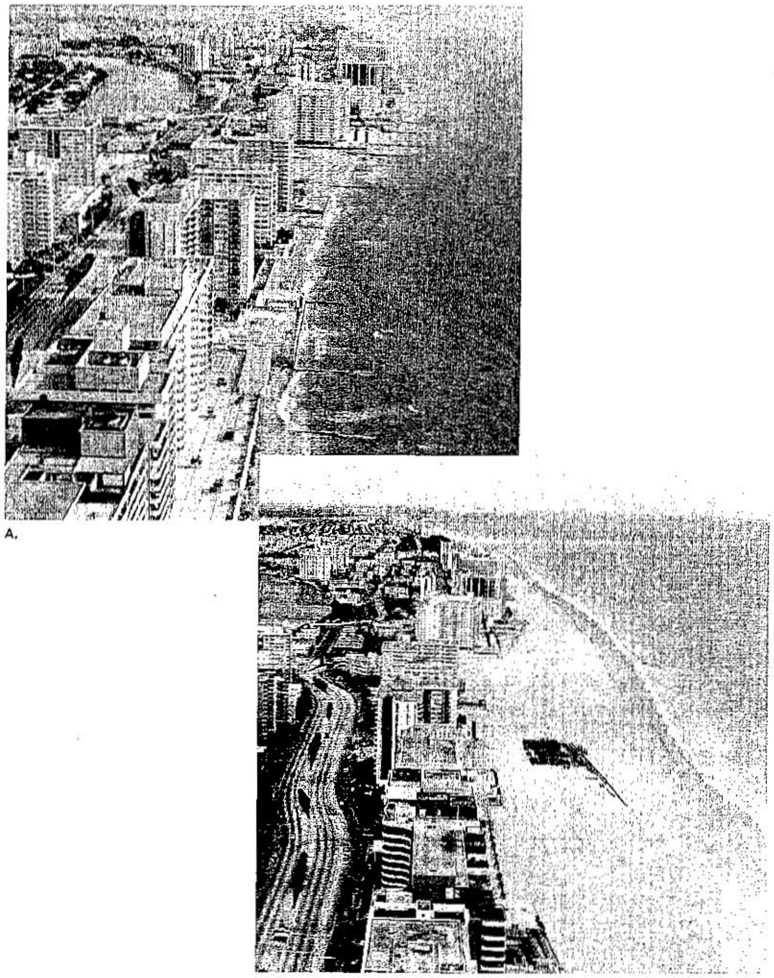


FIGURE 15.28 Miami Beach. A. Before beach nourishment and B. After beach nourishment. (Courtesy of the U.S. Army Corps of Engineers, Vicksburg District)

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 are abandoned and relocated on higher, safer ground.

Such proposals, of course, are controversial. People with significant shoreline investments shudder at the thought of not rebuilding and defending coastal developments from the erosional wrath of the sea. Others, however, argue that with sea level rising, the impact of coastal storms will only get worse in the decades to come. This group advocates that oft-damaged structures be relocated or abandoned to improve personal safety and to reduce costs. Such ideas will no doubt be the focus of much study and debate 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 strikingly 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 and continues to experience active uplift and deformation. By contrast, the East Coast is a tectonically quiet region that is far from any active plate margin. Because of this basic geological 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 lagoons. The broad expanses of sand and exposure to the ocean have made barrier islands exceedingly attractive sites for development. Unfortunately, development has taken place more 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, depositing sand onto the beach or carrying it out to sea; or they may carry sand from the beach and the dunes into the marshes 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.
>
> This 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 roadways. Moreover, since the dynamic nature of the barriers 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 their homes 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.*

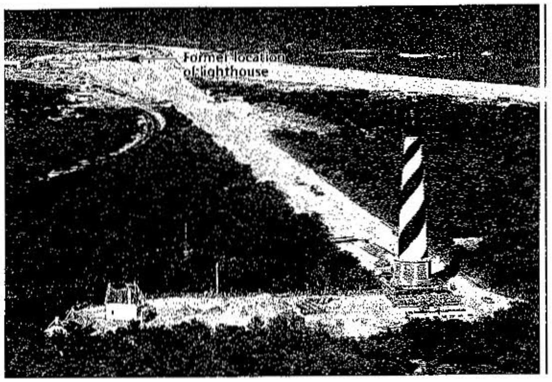


FIGURE 15.29 When the lighthouse at Cape Hatteras, North Carolina, was built in 1870, it was situated 457 meters (1,500 feet) from the shoreline. By 1970, waves began to lap just 37 meters (120 feet) from its base. In order to save the historic structure, it was moved 488 meters (1,600 feet) back from 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)

Pacific Coast

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 rise in sea level 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—is a 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.

Although the retreat of the cliffs provides material to replace some of the sand impounded behind dams, it also endangers homes and roads built on the bluffs. In addition, development atop the cliffs aggravates the problem. Urbanization increases runoff, which, if not carefully controlled, can result in serious bluff erosion. Watering lawns and gardens adds significant quantities of water to the slope. This water percolates downward toward the base of the cliff,

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*Frank Lowenstein, "Beaches or Bedrooms—The Choice as Sea Level Rises," *Oceanus* 28 (No. 3, Fall 1985): 22.

the character of an area, variations and extremes must also be included, as well as the probabilities that such departures will take place. For example, it is not only necessary for farmers to know the average rainfall during the growing season, but it is also important to know the frequency of extremely wet and extremely dry years. Thus, climate is the sum of all statistical weather information that helps describe a place or region.

Suppose you were planning a vacation trip to an unfamiliar place. You would probably want to know what kind of weather to expect. Such information would help as you selected 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 vacation.

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) was established by the United Nations to coordinate scientific activity related to weather and climate. It consists of 185 countries and territories representing all parts of the globe. Its World Weather Watch provides up-to-the-minute standardized observations through member-operated observation systems. This global system involves 10 satellites, 10,000 land-observation and 7,000 ship stations, as well as hundreds of automated data buoys and thousands of aircraft.

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 you are seeking is information about the climate, the conditions that are typical for 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.

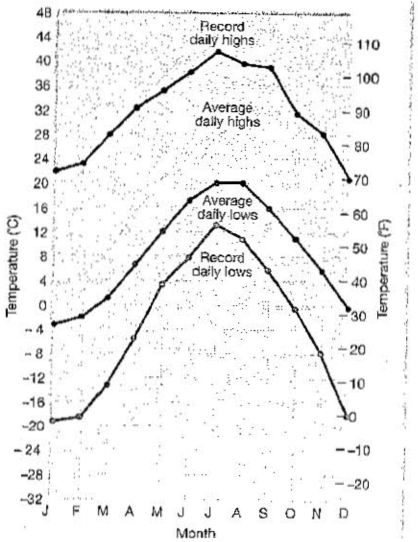


FIGURE 16.3 Graph showing daily temperature data for New York City. In addition to the average daily maximum and minimum temperatures for each month, extremes are also shown. As this graph shows, there can be significant departures from average.

Such information could no 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 climate types are deciphered. 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

Earth's Dynamic 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 to time and from place to place (Box 16.1). If the water vapor, dust, and other variable components were removed from the atmosphere, we would find that its makeup is very stable worldwide up to an altitude of about 80 kilometers (50 miles).

BOX 16.1 ▸ PEOPLE AND THE ENVIRONMENT

Altering the Atmosphere's Composition—Sources and Types of Air Pollution

Air pollutants are airborne particles and gases that occur in concentrations that endanger the health and well-being of organisms or disrupt the orderly functioning of the environment. One category of pollutants, the *primary pollutants*, are emitted directly from identifiable sources. They pollute the air immediately upon being emitted. The most significant primary pollutants are carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOC), and particulate matter (PM). Figure 16.A shows percentages calculated on the basis of weight. Important sources include industrial processes, electrical generation, solid waste disposal, and transportation (cars, trucks, trains, airplanes, etc.). In the United States the tens of millions of cars and trucks on the roads are the greatest contributors.

Sometimes the direct impact of primary pollutants on human health and the environment is less severe than the effects of the secondary pollutants they form. *Secondary pollutants* are not emitted directly into the air, but form in the atmosphere when reactions take place among primary pollutants. The chemicals that make up smog are important examples, as is the sulfuric acid that falls as acid precipitation. After the primary pollutant, sulfur dioxide, is emitted into the atmosphere, it combines with oxygen to produce sulfur trioxide, which then combines with water to create this irritating and corrosive acid.

Many reactions that produce secondary pollutants are triggered by strong sunlight and so are called *photochemical reactions*. One common example occurs when nitrogen oxides absorb solar radiation, initiating a chain of complex reactions. When certain volatile organic compounds are present, the result is the formation of a number of undesirable secondary products that are very reactive, irritating, and toxic. Collectively, this noxious mixture of gases and particles is called *photochemical smog*.

Between 1980 and 2006, emissions of the five major primary pollutants dropped significantly (Figure 16.B). The aggregate decrease amounted to about 49 percent. During that same span, U.S. population increased by nearly one-third, energy consumption was up by 29 percent, and vehicle miles traveled doubled (Figure 16.C). Despite this progress, about 139 million tons of pollutants were emitted into U.S. skies in 2006 and approximately 105 million people lived in counties where monitored air quality was unhealthy at times because of high levels of at least one of the principal air pollutants.

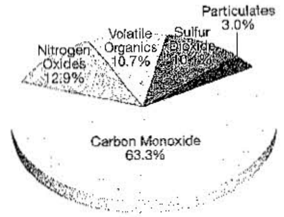


FIGURE 16.A Major primary pollutants. Percentages are calculated on the basis of weight. (Data from the U.S. Environmental Protection Agency)

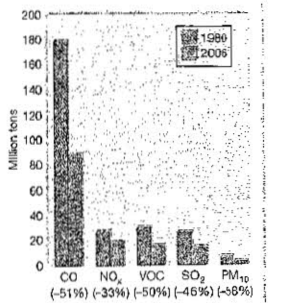


FIGURE 16.B Comparison of 1980 and 2006 emissions. The 2006 total is about 49 percent lower than 1980.

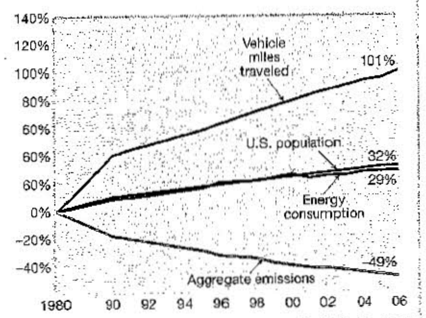


FIGURE 16.C Between 1980 and 2006 vehicle miles traveled increased 101 percent, energy consumption increased 29 percent, and U.S. population increased 32 percent. During that same time span, total emissions of the principal pollutants decreased 49 percent. (After U.S. Environmental Protection Agency)

BOX 16.2 ▸ PEOPLE AND THE ENVIRONMENT

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.D). 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 offending chemicals are known as chlorofluorocarbons (CFCs for short). They are versatile compounds that are chemically stable, odorless, nontoxic, noncorrosive, 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—studied the relationship. In 1974 they alerted the world when they reported that CFCs were probably reducing the average concentration of ozone in the stratosphere. 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 chemicals into their constituent atoms. The chlorine atoms released this way, through a complicated series of reactions, have 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 the *Montreal Protocol on Substances that Deplete the Ozone Layer* was concluded under the 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 not 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 promise a 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 has started to decrease in recent years. If the nations of the world continue to follow the provisions of the protocol, the decreases are expected to continue throughout the twenty-first century. Some offending chemicals are still increasing but will begin to decrease in coming decades. By mid-century, the abundance of ozone-depleting gases should fall to values that existed before the Antarctic ozone hole began to form in the 1980s. Figure 16.E shows global ozone recovery predictions to the year 2050.

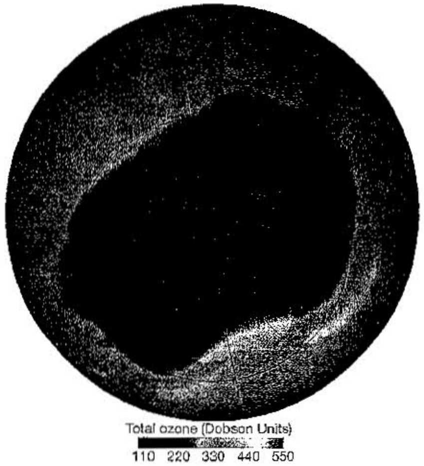


FIGURE 16.D This satellite image shows ozone distribution in the Southern Hemisphere on September 24, 2006. The area of greatest depletion is called the "ozone hole." Dark blue colors correspond to the region with the sparsest ozone. Average values are about 300 Dobson Units. Any area below 220 Dobson Units is considered part of the hole. The ozone hole forms over Antarctica during the Southern Hemisphere spring. In 2006, it extended over about 29 million square kilometers (11.4 million square miles), an area slightly larger than all of North America. It tied the record for the largest ozone hole yet recorded. (NASA)

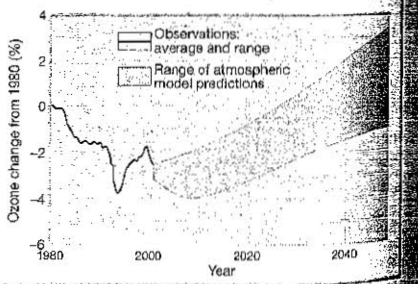


FIGURE 16.E Global ozone recovery predictions. Observed values of global total ozone decreased beginning about 1980. As emissions of ozone-depleting gases decrease in the early twenty-first century, computer models indicate that ozone values will increase. Model results show that recovery is expected to be significant by 2050 or perhaps sooner.

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
▸ Introduction to the 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), 90 percent of the atmosphere has been traversed, and above 100 kilometers (62 miles), only 0.00003 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 partly 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 and is obvious in pictures of snowcapped mountaintops rising above snow-free lowlands (Figure 16.7). We divide the atmosphere vertically into four layers on the basis of temperature (Figure 16.8).

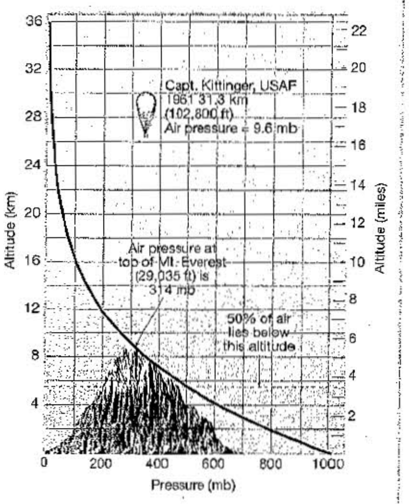


FIGURE 16.6 Atmospheric pressure variation with altitude. The rate of pressure decrease with an increase in altitude is not constant. Rather, pressure decreases rapidly near Earth's surface and more gradually at greater heights.

Troposphere The bottom layer in which we live, where temperature decreases with an increase in altitude, is the **troposphere**. The term literally means the region where air "turns over," a reference to the appreciable vertical mixing of air in this lowermost zone. The troposphere is the chief focus of meteorologists, because it is in this layer that essentially all important weather phenomena occur.

The temperature decrease in the troposphere is called the **environmental lapse rate.** Its average value is 6.5°C per kilometer (3.5°F per 1,000 feet), a figure known as the *normal lapse rate*. It should be emphasized, however, that the environmental lapse rate is not a constant, but rather can be highly variable, and must be regularly measured. To determine the actual environmental lapse rate as well as gather information about vertical changes in pressure, wind, and humidity, radiosondes are used. The *radiosonde* is an instrument package that is attached to a balloon and transmits data by radio as it ascends through the atmosphere (Figure 16.9).

The thickness of the troposphere 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 troposphere is the *tropopause*.

Stratosphere Beyond the tropopause is the **stratosphere.** In the stratosphere, the temperature remains constant to a height of about 20 kilometers (12 miles) and then begins a gradual

BOX 17.1 ▶ PEOPLE AND THE ENVIRONMENT

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 this well-known phrase: "The solution to pollution is dilution." To a significant degree this is true. If the air into 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 polluted air 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 pollution 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 dilute rapidly. When the mixing depth is shallow, 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, an unstable atmosphere promotes vertical air movements and greater mixing depths. Because heating of Earth's surface by the Sun enhances convectional 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 restricted. Warm air overlying cooler air acts as a lid and prevents upward movement, leaving the pollutants trapped in a relatively narrow zone near the ground (Figure 17.A).

Inversions are generally classified into one of two categories—those that form near the ground and those that form aloft. A *surface inversion* develops close to the ground on clear and relatively calm nights. It forms because the ground is a more effective radiator than the air above. This being the case, radiation from the ground to the clear night sky causes more rapid cooling at the surface than higher in the atmosphere. The result is that the air close to the ground is cooled more than the air above, yielding a temperature profile similar to the one shown in Figure 17.B. After sunrise the ground is heated and the inversion disappears.

Although surface inversions are usually shallow, they may be quite thick in regions where the land surface is uneven. Because cold air is denser (heavier) than warm air, the chilled air near the surface gradually drains from the uplands and slopes into adjacent lowlands and valleys. As might be expected, these thicker surface inversions will not dissipate as quickly after sunrise.

Many extensive and long-lived air-pollution episodes are linked to temperature inversions that develop in association with the sinking air that characterizes slow-moving centers of high pressure (Figure 17.C). As the air sinks to lower altitudes, it is compressed and so its temperature rises. Because turbulence is almost always present near the ground, this lower-most portion of the atmosphere is generally prevented from participating in the general subsidence. Thus, an inversion develops aloft between the lower turbulent zone and the subsiding warmed layers above.

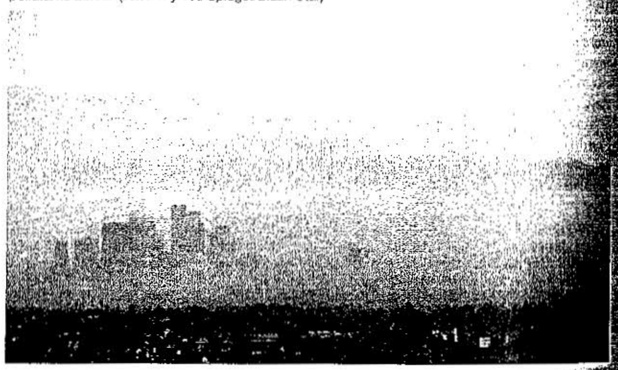


FIGURE 17.A Air pollution in downtown Los Angeles. Temperature inversions act as lids to trap pollutants below. (Photo by Ted Spiegel/Black Star)

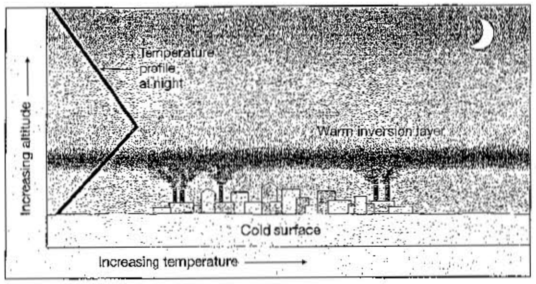
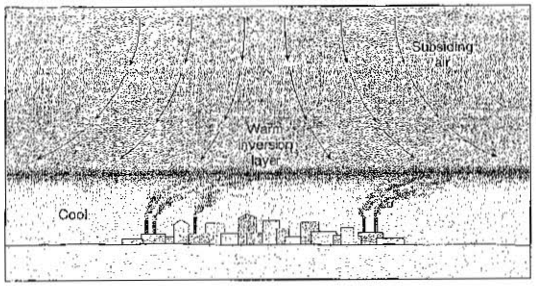


FIGURE 17.B Generalized temperature profile for a surface inversion.

FIGURE 17.C Inversions aloft frequently develop in association with slow-moving centers of high pressure where the air aloft subsides and warms by compression. The turbulent surface zone does not subside as much. Thus, an inversion often forms between the lower turbulent zone and the subsiding layers above.



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 thickness when 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 dreary, overcast day with light drizzle, stable air has been forced aloft. On the other hand, during a day when cauliflower-shaped clouds appear to be growing as if bubbles of hot air are surging upward, we can be fairly certain 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 will come 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 dew, fog, or clouds. For any of these forms of condensation to occur, the air must be saturated. Saturation occurs most commonly when air is cooled to its dew point, or less often when water vapor is added to the air.

Generally, there must be a surface on which the water vapor can condense. When dew occurs, objects at or near the ground such as grass and car windows serve this purpose. But when condensation occurs in the air above the ground, tiny bits of particulate matter, known as **condensation nuclei**, serve as surfaces for water-vapor condensation. These nuclei are very important, for in their absence a relative humidity well in excess of 100 percent is needed to produce clouds.

Condensation nuclei such as microscopic dust, smoke, and salt particles (from the ocean) are profuse in the lower atmosphere. Because of this abundance of particles, relative humidity rarely exceeds 101 percent. Some particles, such as ocean salt, are particularly good nuclei because they absorb water. These particles are termed **hygroscopic** (*hygro* = moisture, *scopic* = to seek) **nuclei**. When condensation takes place, the initial growth rate of cloud droplets is rapid. It diminishes quickly because the excess water vapor is quickly absorbed by the numerous competing particles. This results in the formation of a cloud consisting of millions upon millions of tiny water droplets, all so fine that they remain suspended in air. When cloud formation occurs at below-freezing temperatures, tiny ice crystals form. Thus, a 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 suggest that condensation alone is not responsible for the formation of drops large enough to fall as rain. We first examine clouds and then return to the questions 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

BOX 17.2 ▸ UNDERSTANDING EARTH

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 in this accident a new and meaningful discovery, then you have experienced serendipity. Most nonscientists, 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 health resort at an altitude of 430 meters (1,400 feet) on a hill near Oslo, Norway. During his stay, Bergeron noted that this hill was often "fogged-in" by a layer of supercooled clouds. As he walked along a narrow road in the fir forest along the hillside, he noticed that the "fog" did not enter the "road tunnel" at temperatures below −5°C, but did enter it when the temperature was warmer than 0°C. (Profiles of the hill, trees, and fog for the two temperature regimes is shown in Figure 17.D.)

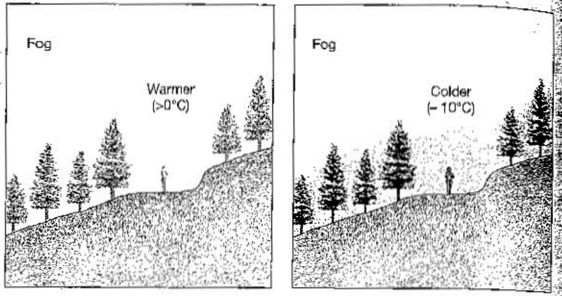


FIGURE 17.D Distribution of fog when the temperature is above freezing and when the temperature falls to −10 °C.

Bergeron immediately concluded that at temperatures below about −5°C the branches of the firs 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.D). The result was the growth of ice crystals (rime) on the branches of the firs accompanied by a "clearing-off" between the trees and along the "road-tunnel."

From this experience, Bergeron realized that, if ice crystals somehow were to appear in the midst of a cloud of supercooled droplets, they would grow rapidly as water molecules diffused toward them from the evaporating cloud droplets. This rapid growth forms snow crystals that, depending on the air temperature beneath the cloud, fall to the ground as snow or rain. Bergeron had thus discovered one way that minuscule cloud droplets can grow large enough to fall as precipitation (see the discussion titled "Precipitation from Cold Clouds: The Bergeron Process," p. 501–503).

Serendipity influences the entire realm of science. Can we conclude that anyone who makes observations will necessarily make a major discovery? Not at all. A perceptive and inquiring mind is required; a mind that has been searching for order in a labyrinth of facts. As Langmuir said, the unexpected occurrence is not enough; you must know how to profit from it. Louis Pasteur observed that "In the field of observation, chance favors only the prepared mind." The discoverer of vitamin C, Nobel Laureat Albert Szent-Gyorgyi, remarked that discoveries are made by those who "see what everybody else has seen, and think what nobody else has thought." Serendipity is at the heart of science itself.

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*Based on material prepared by Duncan C. Blanchard.

freeze until it reaches a temperature of nearly −40°C (−40°F). Water in the liquid state below 0°C is referred to as **supercooled**. Supercooled water will readily freeze if it impacts an object. This explains why airplanes collect ice when they pass through a cloud composed of supercooled droplets.

In addition, supercooled water droplets will freeze upon contact with solid particles that have a crystal form closely resembling that of ice. Such materials are termed **freezing nuclei**. The need for freezing nuclei to initiate the freezing process is similar to the requirement for condensation nuclei in the process of condensation.

In contrast to condensation nuclei, freezing nuclei are very sparse in the atmosphere and do not generally become active until the temperature reaches −10°C (14°F) or less. Only at temperatures well below freezing will ice crystals begin to form in clouds, and even at that, they will be few and far between. Once ice crystals form, they are in direct competition with the supercooled droplets for the available water vapor.

Students Sometimes Ask . . .

What is the snowiest city in the United States?

According to National Weather Service records, Rochester, New York, which averages nearly 239 centimeters (94 inches) of snow annually, is the snowiest city in the United States. However, Buffalo, New York, is a close runner-up.

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

Temperature (°C)	Relative Humidity with Respect to: Water (%)	Ice (%)
0	100	100
−5	100	105
−10	100	110
−15	100	116
−20	100	121

Supersaturation When air is saturated (100 percent relative humidity) with respect to water, it is **supersaturated** (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 110 percent. Thus, ice crystals cannot coexist with water droplets, because the air always "appears" supersaturated to the ice crystals. 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 17.26).

Because the level of supersaturation with respect to ice can be quite great, the growth of ice crystals is generally rapid enough to generate crystals large enough to fall. During their descent, these ice crystals enlarge as they intercept cloud drops, 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**.

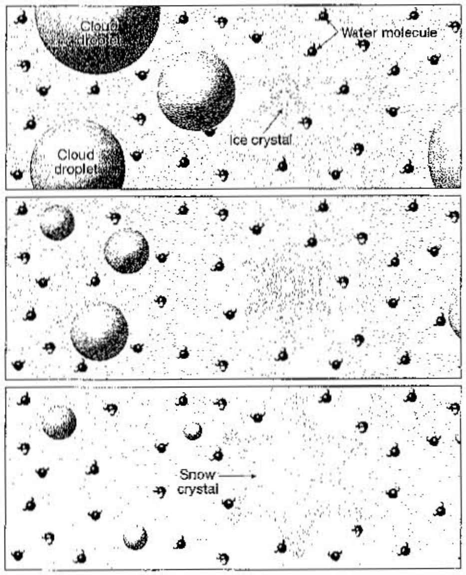
In summary, the Bergeron process can produce precipitation throughout the year in the middle latitudes, provided at least the upper portions of clouds are cold enough to generate ice crystals. The type of precipitation (snow, sleet, rain, or freezing rain) that reaches the ground depends on the temperature profile in the lower few kilometers of the atmosphere. When the surface temperature is above 4°C (39°F), snowflakes usually melt before they reach 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.

Precipitation from Warm Clouds: The Collision–Coalescence Process

A few decades ago, meteorologists believed that the Bergeron process was responsible for the formation of most precipitation. However, it was discovered that copious rainfall can be associated with clouds located well below the freezing level (*warm clouds*), particularly in the tropics. This led to the proposal of a second mechanism thought to produce precipitation—the **collision–coalescence process**.

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-

FIGURE 17.26 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.



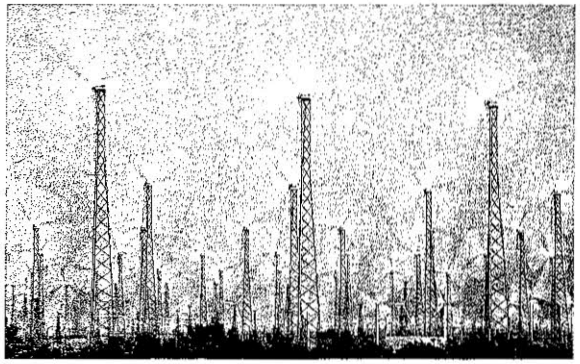
BOX 18.1 ▸ PEOPLE AND THE ENVIRONMENT

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.A).

Mechanical energy from wind is commonly used for pumping water in rural or remote places. The "farm 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 sawing logs, grinding grain, and propelling sailboats. By contrast, wind-powered electric turbines generate electricity for homes, businesses, and for sale to utilities.

FIGURE 18.A These wind turbines are operating near Palm Springs, California. California is second to Texas among the states in wind-power development. As of January 2007, California had a total of 2,361 megawatts of installed capacity. Texas is the leading state with 2,768 megawatts of capacity in January 2007. (Photo by John Mead/Science Photo Library/Photo Researchers, Inc.)



Approximately 0.25 percent (one quarter of 1 percent) of the solar energy that reaches the lower atmosphere is transformed into wind. Although it is just a minuscule percentage, the absolute amount of energy is enormous. According to one estimate, North Dakota alone is theoretically capable of producing enough wind-generated power to meet more than one-third of U.S. electricity demand. Wind speed is a crucial element in determining whether a place is a suitable site for installing a wind-energy facility. Generally a minimum, annual 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 mph could in theory generate about 33 percent more electricity than one at an 11-mph site, because the cube of 12 (1,768) is 33 percent larger than the cube of 11 (1,331). (In the real world, the turbine will not produce quite that much electricity, but it will still generate much more than the 9 percent difference in wind speed.) The important thing to understand is that what seems like a small difference in wind speed can mean a large difference in available energy and in electricity produced, and therefore a large difference in the cost of the electricity generated. Also, there is little energy to be harvested at very low wind speeds (6-mph winds contain less than one-eighth the energy of 12-mph winds).[*]

As technology has improved, efficiency has increased and the costs of wind-generated electricity have become more competitive. Since 1983, technological advances have substantially cut the cost of wind power. As a result, the growth of installed capacity has grown dramatically (Table 18.A). Worldwide, the total amount of installed wind power grew from 7,636 megawatts in 1997 to 74,223 megawatts at the close of 2006. That is enough to supply more than 16 million average American households. By the end of 2006, U.S. capacity exceeded 11,600 megawatts and in 2007 an additional 3,000 megawatts of capacity were expected to be added (Figure 18.B).

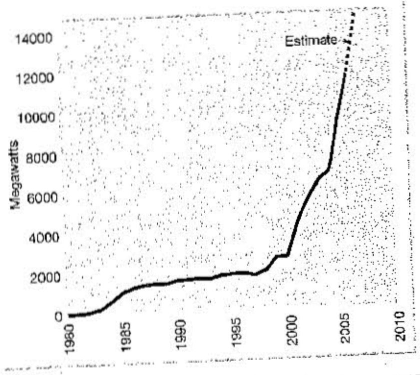
The U.S. Department of Energy has announced a goal of obtaining 5 percent of U.S. electricity from wind by the year 2020—a goal that seems consistent with the current growth rate of wind energy nationwide. Thus, wind-generated electricity seems to be shifting from being an "alternative" to being a "mainstream" energy source.

TABLE 18.A World Leaders in Wind Energy Capacity (January 2007)

Country	Capacity (megawatts*)
Germany	20,622
Spain	11,615
United States	11,603
India	6,270
Denmark	3,136
China	2,604
Italy	2,123
United Kingdom	1,963
Portugal	1,716
France	1,567
Rest of world	11,004
World total	74,263

*1 megawatt is enough electricity to supply 250–300 average American households.
Source: Global Wind Energy Council.

FIGURE 18.B U.S.-installed wind-power capacity (in megawatts). Growth in recent years has been dramatic. By January 2007, U.S. capacity reached 11,603 megawatts. That is enough electricity to serve the equivalent of 3 million average U.S. households. Utility wind-power projects planned for 2007 will add an additional 3,000 megawatts of wind capacity. (Data from U.S. Department of Energy and American Wind Energy Association)



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[*] American Wind Energy Association, "Wind Energy Basics" http://www.awea.org/faq/wwt_basics.html

to Pacific storms, which move toward Alaska during the warm months, thus producing an extended dry season for much of the West Coast. The number of cyclones generated is seasonal as well, with the largest number occurring in the cooler months when the temperature gradients are greatest. This fact is in agreement with the role of cyclonic storms in the distribution of heat across the midlatitudes.

Local Winds

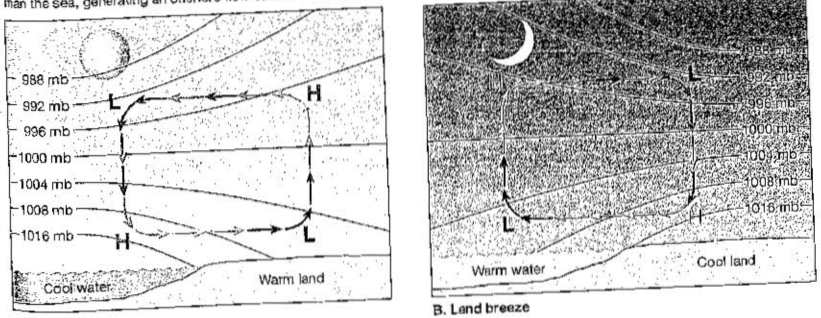
Having examined Earth's large-scale circulation, let us turn briefly to winds that influence much smaller areas. Remember that all winds are produced for the same reason: pressure differences that arise because of temperature differences that are caused by unequal heating of Earth's surface. *Local winds* 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 daylight hours than is 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 cooler air over the water (higher pressure) moves toward the warmer land (lower pressure) (Figure 18.18A). The sea breeze begins to develop shortly before 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 18.18B). Small-scale sea breezes can also develop along the shores of large lakes. People who live in a city near the Great Lakes, such as Chicago, recognize this lake effect, especially in the summer. They are reminded daily by weather reports

FIGURE 18.18 Illustration of a sea breeze and a land breeze. **A.** During the daylight hours the air above the land heats and expands, creating an area of lower pressure. Cooler and denser air over the water moves onto the land, generating a sea breeze. **B.** At night the land cools more rapidly than the sea, generating an offshore flow called a *land breeze*.



A. Sea breeze

B. Land breeze

TABLE 19.1 Enhanced Fujita Intensity Scale*

	Wind Speed		
Scale	Km/Hr	Mi/Hr	Damage
EF-0	105–137	65–85	*Light*. Some damage to siding and shingles.
EF-1	138–177	86–110	*Moderate*. Considerable roof damage. Winds can uproot trees and overturn single-wide mobile homes. Flagpoles bend.
EF-2	178–217	111–135	*Considerable*. Most single-wide homes destroyed. Permanent homes can shift off foundations. Flagpoles collapse. Softwood trees debarked.
EF-3	218–265	136–165	*Severe*. Hardwood trees debarked. All but small portions of houses destroyed.
EF-4	266–322	166–200	*Devastating*. Complete destruction of well-built residences, large sections of school buildings.
EF-5	>322	>200	*Incredible*. Significant structural deformation of mid- and high-rise buildings.

*The original Fujita scale was developed by T. Theodore Fujita in 1971 and put into use in 1973. The Enhanced Fujita Scale is a revision that was put into use in February 2007. Wind speeds are estimates (not measurements) based on damage.

Students Sometimes Ask . . .

Someone told me that my house could explode if I don't open windows when a tornado is approaching. Is that true?

No. The drop in atmospheric pressure associated with the passage of a tornado plays a minor role in the damage process. Most structures have sufficient venting to allow for the sudden drop in pressure. Opening windows, once thought to be a way of minimizing damage by allowing inside and outside atmospheric pressure to equalize, is no longer recommended. In fact, if a tornado gets close enough to a structure for the pressure drop to be experienced, the strong winds will have already caused significant damage.

some question as to the causes of tornadoes, there certainly is no question about the destructive effects of these violent storms (Figure 19.22B).

Tornado Forecasting

Because severe thunderstorms and tornadoes are small and relatively short-lived phenomena, they are among the most difficult weather features to forecast precisely. Nevertheless, the prediction, the detection, and the monitoring of such storms are among the most important services provided by professional meteorologists. The timely issuance and dissemination of watches and warnings are both critical to the protection of life and property (Box 19.2).

The Storm Prediction Center (SPC) located in Norman, Oklahoma, is part of the National Weather Service (NWS) and the National Centers for Environmental Prediction (NCEP). Its mission is to provide timely and accurate forecasts and watches for severe thunderstorms and tornadoes.

Severe thunderstorm outlooks are issued several times daily. *Day 1* outlooks identify those areas likely to be affected by severe thunderstorms during the next 6–30 hours, and *day 2* outlooks extend the forecast through the following day. Both outlooks describe the type, coverage, and intensity of the severe weather expected. Many local NWS field offices also issue severe weather outlooks that provide a more local description of the severe weather potential for the next 12–24 hours.

Tornado Watches and Warnings **Tornado watches** alert the public to the possibility of tornadoes over a specified area for a particular time interval. Watches serve to fine-tune forecast areas already identified in severe weather outlooks. A typical watch covers an area of about 65,000 square kilometers (25,000 square miles) for a four- to six-hour period. A tornado watch is an important part of the tornado alert system because it sets in motion the procedures necessary to deal adequately with detection, tracking, warning, and response. Watches are generally reserved for organized severe weather events where the tornado threat will affect at least 26,000 square kilometers (10,000 square miles) and/or persist for at least three hours. Watches typically are not issued when the threat is thought to be isolated and/or short-lived.

Whereas a tornado watch is designed to alert people to the possibility of tornadoes, a **tornado warning** is issued by local offices of the National Weather Service when a tornado has actually been sighted in an area or is indicated by weather radar. It warns of a high probability of imminent danger. Warnings are issued for much smaller areas than watches, usually covering portions of a county or counties. In addition, they are in effect for much shorter periods, typically 30–60 minutes. Because a tornado warning may be based on an actual sighting, warnings are occasionally issued after a tornado has already developed. However, most warnings are issued prior to tornado formation, sometimes by several tens of minutes, based on Doppler radar data and/or spotter reports of funnel clouds.

If the direction and the approximate speed of the storm are known, an estimate of its most probable path can be made. Because tornadoes often move erratically, the warning area is fan-shaped downwind from the point where the tornado has been spotted. Improved forecasts and advances in technology have contributed to a significant decline in tornado deaths over the past 50 years.

Doppler Radar Many of the difficulties that once limited the accuracy of tornado warnings have been reduced or eliminated by an advancement in radar technology called **Doppler radar**. Doppler radar not only performs the same tasks as conventional radar but also has the ability to detect motion directly (Figure 19.23). Doppler radar can detect the initial formation and subsequent development of a *mesocyclone*. Almost all mesocyclones produce damaging hail, severe winds, or tornadoes. Those that produce tornadoes (about 50 percent) can sometimes be distinguished by their stronger wind speeds and their sharper gradients of wind speeds.

It should also be pointed out that not all tornado-bearing storms have clear-cut radar signatures and that other storms can give false signatures. Detection, therefore, is sometimes a subjective process and a given display could be interpreted

Students Sometimes Ask . . .

What is the most destructive tornado on record?

One tornado easily ranks above all others as the single most dangerous and destructive. Known as the Tri-state tornado, it occurred on March 18, 1925. Its path is labeled on Figure 19.21. Starting in southeastern Missouri, the tornado remained on the ground for 352 kilometers (219 miles), finally ending in Indiana. The losses included 695 dead and 2,027 injured. Property losses were also great, with several small towns almost totally destroyed.

BOX 19.2 ▸ PEOPLE AND THE ENVIRONMENT

Surviving a Violent Tornado

About 11:00 A.M. on Tuesday, July 13, 2004, much of northern and central Illinois was put on a tornado watch. A large supercell had developed in the northwestern part of the state and was moving southeast into a very unstable environment (Figure 19.B). A few hours later, as the supercell entered Woodford County, rain began to fall and the storm showed signs of becoming severe. The National Weather Service (NWS) issued a *severe thunderstorm warning* at 2:29 P.M. CDT. Minutes afterward a tornado developed. Twenty-three minutes later, the quarter-mile-wide twister had carved a 9.6-mile-long path across the rural Illinois countryside.

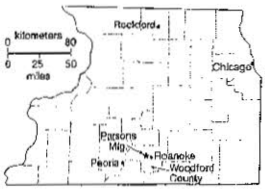


FIGURE 19.B On July 13, 2004, an EF4 tornado cut a 23-mile path through the rural Illinois countryside near the Woodford County town of Roanoke. The Parsons Manufacturing plant was just west of town.

What, if anything, made this storm special or unique? After all, it was just one of a record-high 1,819 tornadoes that were reported in the United States in 2004. For one, this tornado attained EF4 status for a portion of its life. The NWS estimated that maximum winds reached 240 miles per hour. Fewer than 1 percent of tornadoes attain this level of severity. However, what was most remarkable is that no one was killed or injured when the Parsons Manufacturing facility west of the small town of Roanoke took a direct hit while the storm was most intense. At the time, 150 people were in three buildings that comprised the plant. The 250,000-square-foot facility was flattened, cars were twisted into gnarled masses, and debris was strewn for miles (Figure 19.C).

How did 150 people escape death or injury? The answer is foresight and planning. More than 30 years earlier, company owner Bob Parsons was inside his first factory when a small tornado passed close enough to blow windows out. Later, when he built a new plant, he made sure that the restrooms were constructed to double as tornado shelters with steel-reinforced concrete walls and eight-inch-thick concrete ceilings. In addition, the company developed a severe weather plan. When the severe thunderstorm warning was issued at 2:29 P.M. on July 13, the emergency response team leader at the Parsons plant was immediately notified. A few moments later he went outside and observed a rotating wall cloud with a developing funnel cloud. He radioed back to the office to institute the company's severe weather plan. Employees were told to immediately go to their designated storm shelter. Everyone knew where to go and what to do because the plant conducted semi-annual tornado drills. All 150 people reached a shelter in less than four minutes. The emergency response team leader was the last person to reach shelter, less than two minutes before the tornado destroyed the plant at 2:41 P.M.

The total number of tornado deaths in 2004 for the entire United States was just 36. The toll could have been much higher. The building of tornado shelters and the development of an effective severe storm plan made the difference between life and death for 150 people at Parsons Manufacturing.

FIGURE 19.C The quarter-mile-wide tornado had wind speeds reaching 240 miles per hour. The destruction at Parsons Manufacturing was devastating. (Photos courtesy of NOAA)