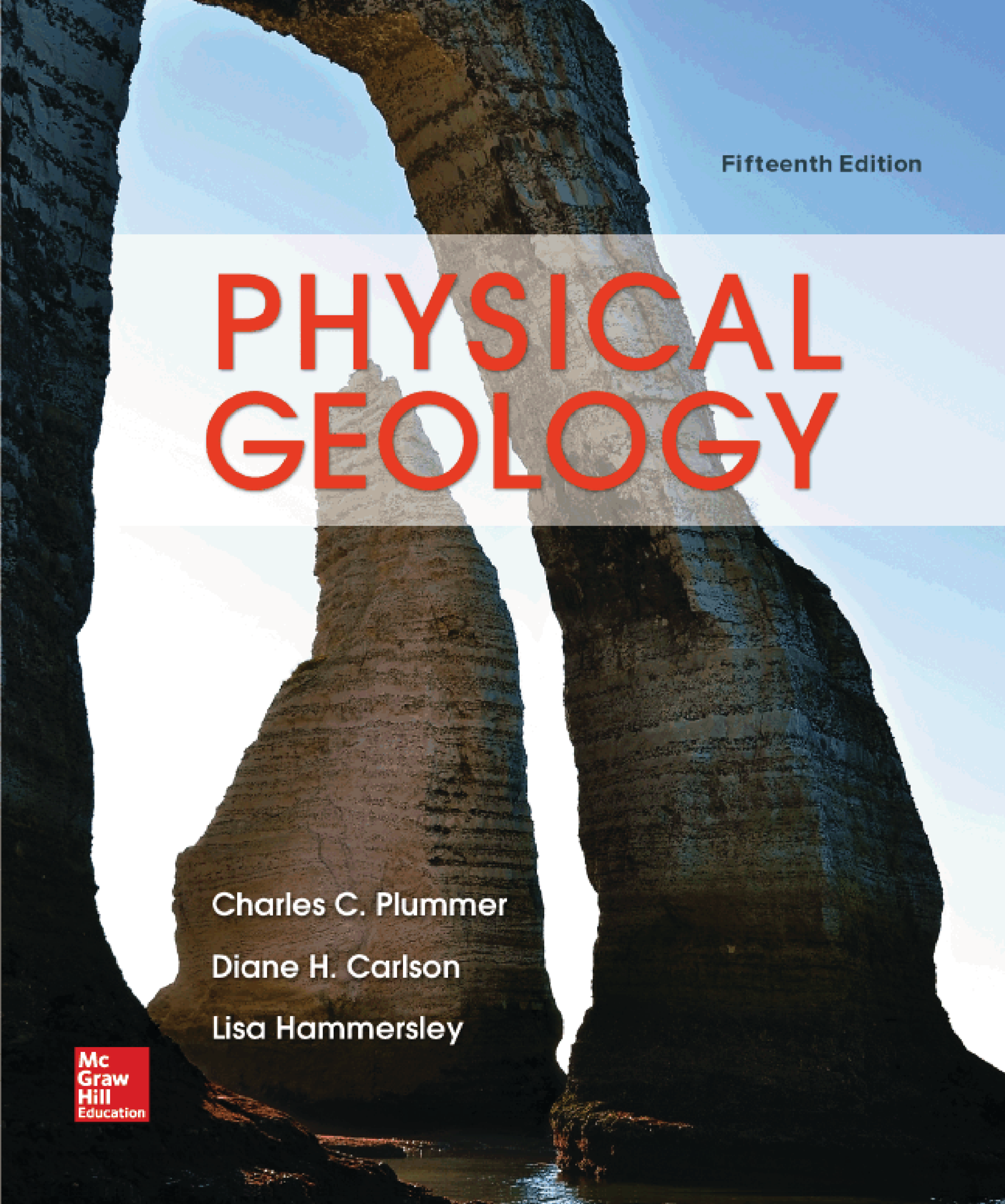


Fifteenth Edition

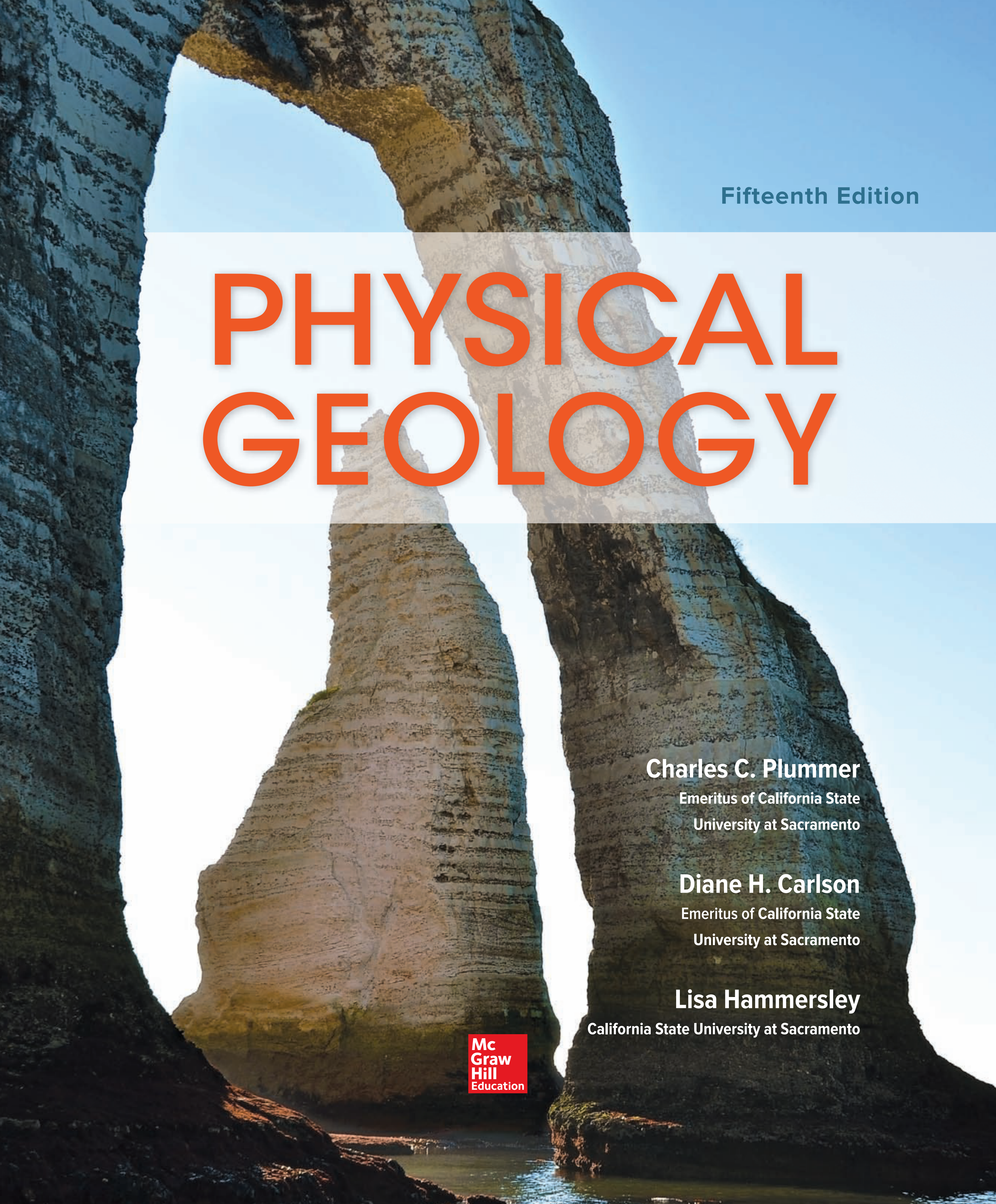
PHYSICAL GEOLOGY

Charles C. Plummer

Diane H. Carlson

Lisa Hammersley

McGraw Hill Education



Fifteenth Edition

PHYSICAL GEOLOGY

Charles C. Plummer
Emeritus of California State University at Sacramento

Diane H. Carlson
Emeritus of California State University at Sacramento

Lisa Hammersley
California State University at Sacramento

Mc Graw Hill Education

PHYSICAL GEOLOGY, FIFTEENTH EDITION

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 DOW/DOW 1 0 9 8 7 6 5

ISBN 978-0-07809610-5
MHID 0-07-809610-3

Senior Vice President, Products & Markets: *Kurt L. Strand*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Kimberly Meriwether David*
Managing Director: *Thomas Timp*
Brand Manager: *Michelle Vogler*
Director, Product Development: *Rose Koos*
Digital Product Developer: *Daniel Wallace*
Director, Content Design & Delivery: *Linda Avenarius*
Program Manager: *Lora Neyens*
Content Project Managers: *Laura Bies & Tammy Juran*
Buyer: *Jennifer Pickel*
Design: *Tara McDermott*
Content Licensing Specialists: *Carrie Burger & Shirley Lanners*
Cover Image: ©*Musat/Getty Images*
Compositor: *Laserwords Private Limited*
Typeface: *10.5/12 TimesLTSTD Roman*
Printer: *R. R. Donnelley*

Library of Congress Cataloging-in-Publication Data

Plummer, Charles C., 1937- author.
Physical geology. — Fifteenth edition / Charles C. Plummer, Emeritus of California State University at Sacramento, Diane H. Carlson, California State University at Sacramento, Lisa Hammersley, California State University at Sacramento.
pages cm
ISBN 978-0-07-809610-5 (acid-free paper) 1. Physical geology—Textbooks. I. Carlson, Diane H. II. Hammersley, Lisa. III. Title.
QE28.2.P58 2016
551—dc23

2014021840

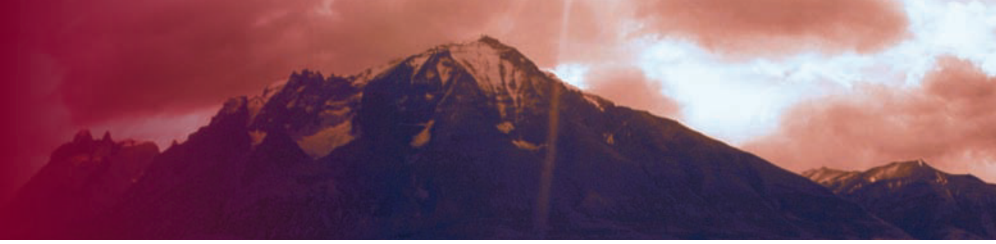
www.mhhe.com

About the Cover

The cover photo is of a portion of France's western coastline in the province of Normandy. The sea is the English Channel, the portion of the Atlantic Ocean between France and England.

The layered bedrock exposed on the cliffs is sedimentary rock (see chapter 6). Originally, layers of sediment settled on the floor of a shallow sea. In time, the loose sediment solidified into sedimentary rock. Most of the white layers are chalk, a variety of limestone made up of tiny fossils that require a microscope to be seen. Fossils in the rocks indicate that deposition of sediment took place during the Cretaceous period, which ended around 65 million years ago (see chapter 8).

Later, the region was uplifted above sea level and erosion of the rock began and continues to take place. Wave action along the new shoreline carved the coast into sea cliffs, arches and stacks, as explained in chapter 14. The steep, rugged island seen through the arch is a sea stack.



BRIEF CONTENTS

CHAPTER 4

Volcanism and Extrusive Rocks

Volcanic lightning generated during the eruption of Chaitén volcano in Chile, May 2008. *Photo © Carlos Gutierrez/UPI/Landov*

LEARNING OBJECTIVES

- Differentiate between effusive and explosive eruptions, and describe the eruptive products associated with them.
- Explain the relationship between magma composition, temperature, dissolved gas, and viscosity and relate them to eruptive violence.
- Describe the five major types of volcanoes in terms of shape and eruptive style.
- Know the major hazards associated with volcanic eruptions.
- Describe the three components of volcanic hazard mitigation.
- Explain the role of plate tectonics in determining the location and eruptive style of volcanoes.

On May 2, 2008, Chaitén volcano, located in a remote and sparsely populated part of Chile, suddenly burst into violent eruption, sending a plume of volcanic ash more than 20 kilometers into the air. By the next day, a plume of ash had spread across Chile and Argentina to the Atlantic Ocean, affecting water supplies, ground transport, and airline traffic. The eruption continued for almost three years, causing extensive damage to the nearby town of Chaitén and coating large areas of Argentina and Chile with ash. The opening photo for this chapter, which shows volcanic lightning generated in the ash cloud from Chaitén, demonstrates the combination of deadliness and beauty that makes volcanoes so compelling.

Volcanic eruptions are some of the most spectacular and deadly geologic phenomena. Not surprisingly, myths and religions relating gods to volcanoes flourish in cultures that live with volcanoes. In Iceland, Loki, of Norse mythology, is regarded as imprisoned underground, blowing steam and lava up through fissures. Pacific Northwest Indians regarded the Cascade volcanoes as warrior gods who would sometimes throw red-hot boulders at each other. In Hawaii, Madame Pele is regarded as a goddess who controls eruptions. According to legend, Pele and her sister tore up the ocean floor to produce the Hawaiian island chain. Today, many fervently believe that Pele dictates when and where an eruption will take place. In the 1970s, when Kilauea began erupting near a village, residents chartered an airplane and dropped flowers and a bottle of gin into the lava vent to appease Pele.

While awesome natural spectacles, volcanic eruptions also provide important information about the workings of Earth's interior. Eruptions vary in terms of eruptive style and degree of explosive violence. A strong correlation exists between the chemical composition of magma (or lava), its physical properties, and the violence of an eruption. The size and shape of volcanoes and lava flows and their pattern of distribution on Earth's surface also correlate with the composition of their lavas. Our observations of volcanic activity fit nicely into plate tectonic theory. Understanding volcanism also provides a background for theories relating to mountain building and the development and evolution of continental and oceanic crust (topics covered in later chapters). Landforms are created through volcanic activity, and portions of Earth's surface are built up. Less commonly, as at Mount St. Helens, landforms are destroyed by violent eruptions (box 4.1). As you learned in chapter 3, by studying the magma, gases, and rocks from eruptions, we can infer the chemical conditions as well as the temperatures and pressures within Earth's crust or underlying mantle.

In chapter 3 you learned about the origin of magma, igneous rock classification, and intrusive structures. In this chapter we will concentrate on extrusive (volcanic) igneous activity. We will begin by broadly defining eruptions into two categories: explosive and effusive. We will explore how the nature of volcanic eruptions is controlled by the physical properties of magma. We will then discuss the products of volcanic eruptions and describe different types of volcanoes. Following this we will examine volcanic hazards and the types of volcano monitoring that are used to mitigate these hazards. Finally, we will examine the link between the types of volcanoes (and their eruptive styles) and plate-tectonic settings.

WHAT ARE VOLCANOES AND WHY SHOULD WE STUDY THEM?

Volcanism occurs when magma makes its way to the Earth's surface. **Volcanoes** are landforms formed by the extrusion of lava or the ejection of rock fragments from a vent. Volcanoes come in many shapes and sizes, and eruptions can vary widely in their duration, violence, and the type of material erupted.

On October 25, 2010, after a short period of intense seismic unrest, Mount Merapi, Indonesia's most active volcano, erupted violently (figure 4.1*A*). The eruptions that occurred over the next few weeks sent eruption columns several kilometers up into the atmosphere, generating *pyroclastic flows* (fast-moving flows of hot ash and pyroclastic debris) that flowed down the slopes of the volcano. Over 350,000 people were evacuated from the affected area, and volcanic ash caused major disruption to air travel across Java. By early December, when the volcanic activity had subsided, 353 people had been reported killed. These were mostly people who had refused to evacuate or who had returned to their homes while the volcanic activity continued. In addition to the destruction of villages located on the slopes of Merapi, crops in the vicinity were ruined, and many livestock were killed. **Explosive eruptions,** also called *pyroclastic eruptions*, such as the eruption of Merapi, are dominated by the generation of solid volcanic fragments. Explosive eruptions vary enormously in size. Box 4.1 discusses the 1980 eruption of Mount St. Helens, a relatively large explosive eruption. A smaller explosive eruption of Eyjafjallajökull in Iceland in 2010 caused major disruption to European air traffic (see box 1.2).

Kilauea on the island of Hawaii has been erupting constantly since 1983. The style of eruption is very different from

A B

FIGURE 4.1

Contrasting styles of volcanic eruptions. (*A*) Explosive eruption from Mount Merapi, Indonesia, in November 2010. A pyroclastic flow can be seen descending the slopes in the foreground. *Photo © Dwi Oblo/Reuters/Landov* (*B*) Effusive eruption of lava from a fissure that opened on the flanks of Kilauea volcano, Hawaii, in March 2011. *Photo by U.S. Geological Survey, Hawaiian Volcano Observatory*

that seen at Mount Merapi or Mount St. Helens. In Hawaii, lava extrudes out of vents and fissures in the ground as lava flows. In March 2011, a new fissure, almost 500 meters long, opened on the eastern side of Kilauea (figure 4.1*B*). Lava spewed out of the fissure, in places fountaining 65 feet into the air. Eruptions dominated by lava flows are called **effusive eruptions** and are typically less dangerous than explosive eruptions. While the lava flows from Kilauea have destroyed some homes and roadways, very few people have been killed or injured.

While the dangers associated with volcanoes provide a compelling reason to study them, there are many other reasons. Volcanoes provide geologists with information on processes occurring within the Earth's mantle. Volcanic eruptions can affect the Earth's climate. Volcanoes can also be beneficial.

Creation of New Land

Although occasionally a highway or village is overrun by outpourings of lava, the overall effects of volcanism have been favorable to humans in Hawaii. Lava flowing into the sea and solidifying adds real estate to the island of Hawaii. Kilauea volcano has been erupting since 1983, spewing out an average of 325,000 cubic meters of lava a day. This is the equivalent of 40,000 dump truckloads of material. In twenty years, 2.5 billion cubic meters of lava were produced—enough to build a highway that circles the world over five times. Were it not for volcanic activity, Hawaii would not exist. The islands are the crests of a series of volcanoes that have been built up from the bottom of the Pacific Ocean over millions of years (the vertical distance from the summit of Mauna Loa volcano to the ocean floor greatly exceeds the height above sea level of Mount Everest). When lava flows into the sea and solidifies, more land is added to the islands. Hawaii is, quite literally, growing.

In addition to gaining more land, Hawaii benefits in other ways from its volcanoes. Weathered volcanic ash and lava produce excellent, fertile soils (think pineapples and papayas). Moreover, Hawaii's periodically erupting volcanoes (which are relatively safe to watch) are great spectacles that attract both tourists and scientists, benefiting the island's economy.

Geothermal Energy

In other areas of recent volcanic activity, underground heat generated by igneous activity is harnessed for human needs. Steam or superheated water trapped in layers of hot volcanic rock is tapped by drilling and then piped out of the ground to power turbines that generate electricity. The United States is the biggest producer of geothermal power, followed by the Philippines, Indonesia, Mexico, and Italy. Naturally heated geothermal fluids can also be tapped for space or domestic water heating or industrial use, as in paper manufacturing. (For more information, go to http://geothermal.marin.org/, chapter 11 on groundwater, or chapter 22 on geologic resources.)

Effect on Climate

The atmosphere was created by degassing magma during the time following Earth's formation. Even now, gases and dust given off by major volcanic eruptions can profoundly alter worldwide climate. Occasionally, a volcano will spew large amounts of fine volcanic dust and gas into the high atmosphere. Winds can keep fine particles suspended over the Earth for years. The 1991 eruption of Mount Pinatubo in the Philippines produced noticeably more colorful sunsets worldwide. More significantly, it reduced solar radiation that penetrates the atmosphere. Measurements indicated that the worldwide average

ENVIRONMENTAL GEOLOGY 4.1

Mount St. Helens Blows Up

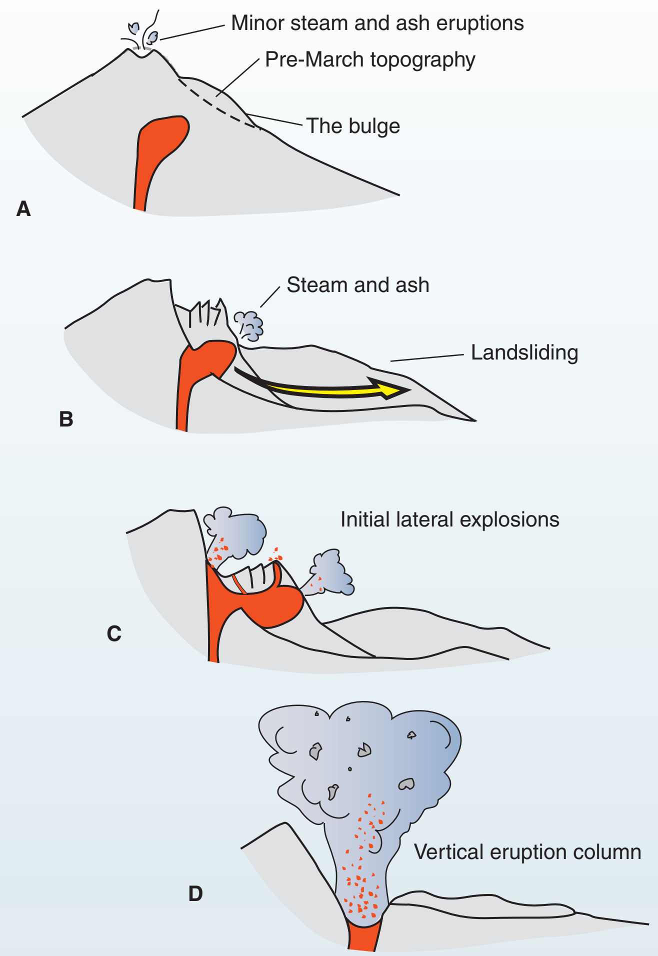
Before 1980, Mount St. Helens, in southern Washington, had not erupted since 1857. On March 27, 1980, ash and steam eruptions began and continued for the next six weeks. These were minor eruptions in which magma was not erupted. Rather, they were due to exploding gas blasting out the volcano's previously formed rock. However, the steam and the pattern of earthquakes indicated that magma was working its way upward beneath the volcano.

After several weeks, the peak began swelling—like a balloon being inflated—indicating that magma was now inside the volcano. The northern flank of the volcano bulged outward at a rate of 1.5 meters per day. Bulging continued until the surface of the northern slope was displaced outward over a hundred meters from its original position. The bulge was too steep to be stable, and the U.S. Geological Survey warned of another hazard—a mammoth landslide.

On May 18, a monumental blast destroyed the summit and north flank of Mount St. Helens. Seconds after the eruption began, an area extending northward 10 kilometers was stripped of all vegetation and soil.

Although the sequence of events was exceedingly rapid, it is now clear what happened (box figure 1). A fairly strong earthquake loosened the bulging north slope, triggering a landslide. The landslide, known as a *debris avalanche,* moved at speeds of over 160 kilometers per hour (100 mph). It was one of the largest landslides ever to occur, but it was eclipsed by the huge eruption that followed. The landslide stripped away the lid on the magma chamber, and because of the reduced pressure, the previously dissolved gases in the magma exploded (box figure 1*C*). The violent froth of gas and magma blasted away the mountain's north flank and roared outward at up to 1,000 kilometers per hour (600 mph). The huge lateral blast of hot gas and volcanic rock debris killed everything near the volcano and, beyond the 10-kilometer scorched zone, knocked down every tree in the forest.

For the next 30 hours, exploding gases propelled frothing magma and volcanic ash vertically into the high atmosphere. The mushroom-shaped cloud of ash was blown northeastward by winds.



BOX 4.1 ■ FIGURE 1

Sequence of events at Mount St. Helens, May 18, 1980. (*A*) Just before the eruption. (*B*) The landslide relieves the pressure on the underlying magma. (*C*) Magma blasts outward. (*D*) Full vertical eruption.

temperature dropped approximately one degree Celsius for a couple of years. While this may not seem like much, it was enough to temporarily offset the global warming trend of the past 100 years.

The 1815 eruption of Tambora in Indonesia was the largest single eruption in a millennium—40 cubic kilometers of material were blasted out of a volcanic island, leaving a 6-kilometer-wide depression. The following year, 1816, became known as "the year without summer." In New England, snow in June was widespread, and frosts throughout the summer ruined crops. Parts of Europe suffered famine because of the cold weather effects on agriculture. (See chapter 21 for more information on the impact of volcanoes on the climate.)

ERUPTIVE VIOLENCE AND PHYSICAL CHARACTERISTICS OF LAVA

Box 4.2 describes the Volcanic Explosivity Index (VEI), which is used to indicate how powerful volcanic eruptions are. The scale goes from nonexplosive and gentle eruptions to mega-colossal eruptions. What determines the degree of violence associated with volcanic activity? Whether an eruption is effusive or explosive? Why can we state confidently that active volcanism in Hawaii poses only slight danger to humans, but we expect violent eruptions to occur around the margins of the

A rain of ash went on for days, causing damage as far away as Montana. Volcanic mudflows caused enormous damage during and after the eruption. The mudflows resulted when water from melted snow and glacier ice mixed with volcanic debris to form a slurry with the consistency of wet cement. Mudflows flowed down river valleys, carrying away steel bridges and other structures (see chapter 9, notably figure 9.13).

Damage was in the hundreds of millions of dollars, and 63 people were killed. The death toll might have been much worse had not scientists warned public officials about the potential hazards, causing them to evacuate the danger zone before the eruption. For comparison, 29,000 people were killed during an eruption of Mount Pelée (described later in this chapter), and 23,000 lives were lost in a 1985 volcanic mudflow in Colombia.

Mount St. Helens is still active. Lava oozing into the crater is continuing to build domes (described later in this chapter). But there is no indication that the volcano will erupt violently in the near future. Other volcanoes in the Pacific Northwest, however, could erupt and be disastrous to nearby cities. Seattle and Tacoma are close to Mount Rainier. Mount Hood is practically in Portland, Oregon's suburbs. Vancouver, British Columbia, could be in danger if either Mount Garibaldi to the north or Mount Baker in Washington to the south erupts.

BOX 4.1 ■ FIGURE 2

Mount St. Helens, May 18, 1980. Looking north, we can see the last of the huge lateral explosion from the far side of the volcano. This was followed by vertical eruption of gases and pyroclasts from the top of the volcano. *Photo by Robert Krimmel, U.S. Geological Survey*

Additional Resource

USGS Cascade Volcano Observatory—Mount St. Helens

- http://volcanoes.usgs.gov/volcanoes/st_helens/

This website provides a wealth of information, maps, and photos of Mt. St. Helens as well as current monitoring data.

USDA Forest Service—Mt. St. Helens volcano cams

- http://www.fs.fed.us/gpnf/volcanocams/msh/

This website shows live images of Mt. St. Helens and includes information on the current status of the volcano.

Pacific Ocean? Whether eruptions are violently explosive or relatively "quiet" is largely determined by two factors: (1) the amount of gas in the lava or magma and (2) the ease or difficulty with which the gas can escape to the atmosphere. The **viscosity,** or resistance to flow, of a lava determines how easily the gas escapes. The more viscous the lava and the greater the volume of gas trying to escape, the more violent the eruption. Later we will show how these factors not only determine the degree of violence of an eruption but also influence the shape and height of a volcano.

Lava is a mixture of molten silicate rock, crystals, and gas. When we look at a volcanic rock, we commonly see these components. For example, examine the rock shown in figure 4.2. This basalt contains small *phenocrysts* of white plagioclase feldspar held in a finer-grained *groundmass.* The phenocrysts represent crystals held in molten lava. The *vesicles* in the rock represent gases expanding and escaping from the lava as it erupted. From active volcanoes we have learned that most of the gas released during eruptions is water vapor, which condenses as steam. Other gases, such as carbon dioxide, sulfur dioxide, hydrogen sulfide (which smells like rotten eggs), and hydrochloric acid, are given off in lesser amounts with the steam. If a lava is too viscous to allow the gas bubbles to form easily, it will fragment, causing large, explosive eruptions that can blast ash and rock debris kilometers into the atmosphere. The three factors

FIGURE 4.2

Vesicular basalt with phenocrysts of plagioclase feldspar. *Photo © Parvinder Sethi*

that influence the viscosity of lava are (1) the silica (SiO_2) content of the lava; (2) the temperature of the lava; and (3) the amount of gas dissolved in magma. Although explosive eruptions are driven by the expansion of dissolved gases, the greater the dissolved gas content in a magma, the more fluid it is. If the lava being extruded is considerably hotter than its solidification temperature, the lava is less viscous (more fluid) than when its temperature is near its solidification point. Temperatures at which lavas solidify range from about 700°C for felsic rocks to 1,200°C for mafic rocks.

The silica content of magma is a major factor in determining viscosity. As described in chapter 3, volcanic rocks, and the magma from which they formed, have silica contents that range from 45% to 75% by weight. **Felsic rocks** are silica-rich (65% or more SiO_2). *Rhyolite* is the most abundant felsic volcanic rock. **Mafic rocks** are *silica-deficient.* Their silica content is close to 50%. *Basalt* is the most common mafic rock. **Intermediate rocks** have a silica content between that of felsic and mafic rocks. The most common intermediate rock is *andesite.* Table 4.1 provides a review of the common extrusive rock types and their characteristics.

Mafic lavas, which are relatively low in SiO_2, tend to flow easily. Conversely, felsic lavas are much more viscous and flow sluggishly. Mafic lava is around 10,000 times as viscous as water, whereas felsic magma is around 100 million times the viscosity of water. Why are felsic lavas more viscous than mafic lavas? In chapter 2 you learned that the silicate minerals form when silica-oxygen tetrahedra bond together with other cations to form different crystal structures. Lavas rich in silica are more viscous because even before they have cooled enough to allow crystallization of minerals, silicon-oxygen tetrahedra have linked to form small, framework structures in the lava. Although too few atoms are involved for the structures to be considered crystals, the total effect of these silicate structures is to make the liquid lava more viscous, much the way that flour or cornstarch thickens gravy.

TABLE 4.1 Names for Extrusive Rocks

Names for Finely Crystalline Rocks Based on Chemical or Mineralogical Composition (See chapter 3 for pictures)

Rock Name	Chemical Composition	Description
Rhyolite	Silicic	Light colored. Usually cream-colored, tan, or pink. Mostly finely crystalline white or pink feldspar and quartz.
Andesite	Intermediate	Moderately gray or green color. A little over half of rock is light- to medium-gray plagioclase feldspar, while the rest is ferromagnesian minerals (usually *pyroxene* or *amphibole*).
Basalt	Mafic	Black or dark gray. The rock is made up mostly of ferromagnesian minerals (notably *olivine* and *pyroxene*) and calcium-rich *plagioclase feldspar.*

Adjectives Used to Modify Rock Names

Porphyritic (e.g. porphyritic andesite)	Some crystals (phenocrysts) are larger than 1 millimeter (usually considerably larger). Most grains are smaller than 1 millimeter. Or phenocrysts are enclosed in glass.
Vesicular (e.g. vesicular basalt)	Holes (vesicles) in rock due to gas trapped in solidifying lava.

Names for Rocks Based on Texture

Obsidian	Volcanic glass that is usually silicic. Black or reddish with a conchoidal fracture.
Pumice	Frothy volcanic glass.
Scoria	Vesicular basalt in which the volume of vesicles is greater than that of the solid rock.
Tuff	Consolidated, fine pyroclastic material.
Volcanic breccia	Consolidated, pyroclastic debris that includes coarse material (lapilli, blocks, or bombs).

IN GREATER DEPTH 4.2

Volcanic Explosivity Index

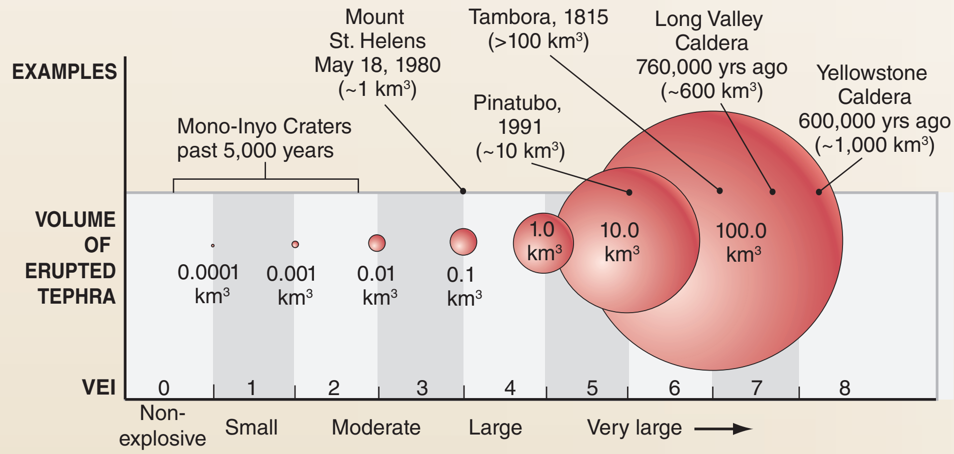
To indicate how powerful volcanic eruptions are, scientists use the **Volcanic Explosivity Index** or **VEI**. The index is on a scale of 0 to 8 (box table 1) and is based on a number of factors, including the volume of erupted pyroclastic material, the height of the eruption column, and how long the eruption lasts. Like the Richter magnitude scale for earthquakes (discussed in chapter 16), the VEI is logarithmic, meaning that each interval on the scale represents a tenfold increase in the size of the eruption. An eruption of VEI 3 is ten times bigger than a 2 and one hundred times smaller than a 5 (box figure 1).

BOX 4.2 ■ TABLE 1

The Volcanic Explosivity Index

VEI	Description	Plume Height	Volume	Classification	How Often	Example
0	nonexplosive	< 100 m	1,000s m^3	Hawaiian	daily	Kilauea
1	gentle	100-1,000 m	10,000s m^3	Haw/Strombolian	daily	Stromboli
2	explosive	1–5 km	1,000,000s m^3	Strom/Vulcanian	weekly	Galeras, 1992
3	severe	3–15 km	10,000,000s m^3	Vulcanian	yearly	Ruiz, 1985
4	cataclysmic	10–25 km	100,000,000s m^3	Vulcanian/Plinian	10s of years	Galunggung, 1982
5	paroxysmal	>25 km	1 km^3	Plinian	100s of years	St. Helens, 1980
6	colossal	>25 km	10s km^3	Plinian/Ultra-Plinian	100s of years	Krakatau, 1883
7	super-colossal	>25 km	100s km^3	Ultra-Plinian	1,000s of years	Tambora, 1815
8	mega-colossal	>25 km	1,000s km^3	Ultra-Plinian	10,000s of years	Yellowstone, 2 Ma

Source: Volcano World (http://volcano.oregonstate.edu/vwdocs/eruption_scale.html)



BOX 4.2 ■ FIGURE 1

VEI of past explosive eruptions. The volume for each eruption is given in parentheses. The relative increase in volume for each step on the scale is represented by the red circles. Note that the increase in volume is tenfold for each step. *Source: USGS Volcano Hazards Program (http://volcanoes.usgs.gov/images/pglossary/vei.php)*

Because felsic magmas are the most viscous, they are associated with the most violent, explosive eruptions. Mafic magmas are the least viscous and commonly erupt as lava flows in effusive eruptions (such as in Hawaii). Eruptions associated with intermediate magma can be violent or can produce lava flows, depending on the amount of dissolved gas in the magma.

Surface water introduced into a volcanic system can greatly increase the explosivity of an eruption, as exemplified by the 2010 eruption of Eyjafjallajökull volcano in Iceland (described in box 1.2).

THE ERUPTIVE PRODUCTS OF VOLCANOES

A volcano is an opening in the earth's crust through which molten lava, ash, and gases are ejected. Volcanic material that is ejected from and deposited around a central vent produces the conical shape typical of volcanoes. The **vent** is the opening through which an eruption takes place. The **crater** of a volcano is a basin-like depression over a vent at the summit of the cone

FIGURE 4.3

Volcanic crater (200 meter diameter) on Karymsky volcano, Kamchatka, Russia. The lake in the background fills a large crater known as a caldera. *Photo by C. Dan Miller, U.S. Geological Survey*

(figure 4.3). Material is not always ejected from the central vent. In a **flank eruption,** lava pours from a vent on the side of a volcano.

Effusive Eruptions

Effusive eruptions are characterized by lava flows. As described previously, the nature of an eruption is controlled by the characteristics of the lava, in particular the gas content and viscosity. Effusive eruptions are most commonly basaltic in composition because mafic basalts are less viscous, and gases can escape easily. Intermediate and felsic lava can erupt effusively if the gas content is quite low.

Mafic Lava Flows

Due to its low silica content, basaltic lava is typically low viscosity and flows easily. Volcanic activity in Hawaii is dominantly basaltic in composition, and Hawaiian names have been given to two distinctive surfaces of basalt lava flows. **Pahoehoe** (pronounced *pah-hoy-hoy*) is characterized by a ropy or billowy surface (figure 4.4). Pahoehoe is formed by the rapid cooling and solidification of the surface of the lava flow, rather like the skin that forms on the top of a cup of hot chocolate. As the lava below the solidified surface continues to flow, the "skin" is dragged along and becomes folded and rumpled, rather like what happens to the skin on the top of your hot chocolate when you tip the cup. **A′a** (pronounced *ah-ah*) is a flow that has a jagged, rubbly surface (figure 4.5). It forms when basalt is cool enough to have partially solidified and moves slowly as a pasty mass. Its largely solidified front is shoved forward as a pile of rubble. Pahoehoe flows often change into a′a flows farther from the vent as the lava cools and becomes more viscous.

FIGURE 4.4

Flow of lava solidifying to pahoehoe in Hawaii. *Photo by J.D. Griggs, U.S. Geological Survey*

FIGURE 4.5

An *a′a* flow in Hawaii, 1983. *Photo by J. D. Griggs, U.S. Geological Survey*

A (usually) minor feature called a *spatter cone,* a small, steep-sided cone built from lava sputtering out of a vent (figure 4.6), will occasionally develop on a solidifying lava flow. When a small concentration of gas is trapped in a cooling lava flow, lava is belched out of a vent through the solidified surface of the flow. Falling lava plasters itself onto the developing cone and solidifies. The sides of a spatter cone can be very steep, but they are rarely over 10 meters high. An exception to this is Pu′u O′o, the 250-meter-high, combined spatter and cinder cone on the eastern flank of Kilauea shield volcano. It is located at the vent for the ongoing (1983–onward) lava eruptions.

A **lava tube** is a tunnel-like conduit for lava that develops after most of a fluid, pahoehoe-type flow has solidified (figure 4.7*A*). The tube's roof and walls solidified along with the earlier, broader flow. The tube provides insulation so that the rapidly flowing lava loses little heat and remains fluid. Much of the lava in the ongoing Hawaiian eruptions flows underground in a lava tube, traveling about 7 kilometers from Pu′u O′o, the currently erupting vent, to the sea. Lava Beds National Monument in northeastern California (figure 4.7*B*) contains many lava tubes that formed within basaltic lava flows erupted 30,000 to 40,000 years ago from Medicine Lake volcano. When the eruption ended, lava drained from the tubes, leaving them hollow.

Flood Basalts

Lava that is very nonviscous and flows almost as easily as water does not build a cone around a vent. Rather, it flows out of long fissures that extend through Earth's crust. **Flood basalts** are vast outpourings of mafic lava from fissures that can cover wide areas with multiple lava flows, building thick *lava plateaus.*

The Columbia Plateau area of Washington, Idaho, and Oregon (see inside front cover), for example, is constructed of layer upon layer of basalt (figure 4.8), in places as thick as 3,000 meters. The area covered is over 400,000 square kilometers. Each individual flood of lava added a layer, usually between 15 and 100 meters thick and sometimes thousands of square kilometers in extent. The outpourings of lava that built the Columbia Plateau took place from 17.5 to 6 million years ago, but 95% erupted between 17 and 15.5 million years ago. Similar huge, lava plateau–building events have not occurred since then. (The hypothesis that these are due to the arrival of huge mantle plumes beneath the lithosphere is described in chapter 3.) Even relatively small basaltic floods not associated with shield volcanoes are a rarity (see box 4.3).

Even larger basalt plateaus are found in India and Siberia. Their times of eruption coincide with the two largest mass extinctions of life on Earth. The one in Siberia occurred about 250 million years ago, around the time of the largest mass

FIGURE 4.6

A spatter cone (approximately 1 meter high) erupting in Hawaii. *Photo by J. B. Judd, U.S. Geological Survey*

A

B

FIGURE 4.7

(*A*) Lava stream seen through a collapsed roof of a lava tube during a 1970 eruption of Kilauea volcano, Hawaii. Note the ledges within the tube, indicating different levels of flows. (*B*) Lava tube at Lava Beds National Monument, California. The narrow, dark shelf on either side of the tube marks the level of the lava stream, indicating where lava solidified against the walls of the tube. *Photo A by J. B. Judd, U.S. Geological Survey; photo B by C. C. Plummer*

EARTH SYSTEMS 4.3

The Largest Humanly Observed Fissure Eruption and Collateral Deadly Gases

Huge eruptions from fissures, such as those of the Columbia Plateau, have not occurred in historical time. The largest fissure eruption and basaltic flood documented by humans took place in Iceland in 1783. Eruptions began when 130 cinder cones built up along a 25-kilometer-long fissure when rising magma encountered groundwater. Eventually pyroclastic activity yielded to Hawaiian-type lava flows, creating the Laki flow. Fluid basalt flowed out of the fissure for several months. Over that time some 12 cubic kilometers of basalt lava covered 565 square kilometers of land.

Along with the lava, a tremendous amount of gases were released. These had a devastating effect on Iceland's biosphere. A blue haze of gas, called a "dry fog" or "vog," hung over Iceland and parts of northern Europe for months. Fluorine in the gas contaminated grass, and over 200,000 sheep, cattle, and horses died of fluoridosis. The resulting famine was made worse because fishermen couldn't get out to sea due to the "vog." Some 10,000 Icelanders died because of the famine. That represents one-fifth of Iceland's population at that time.

In Europe the "vog" was more of an irritant to people than a danger. The winter of 1783–84 was exceptionally severe. Ben Franklin, who was the American envoy to France at the time, became the first person to link volcanic eruptions to climate changes. He suggested that the gases and dust from the eruptions may have blocked enough sunshine to result in the severe cold.

Additional Resource

The Laki and Grimsvotn Eruptions of 1883–1885 (Volcano World site)

- http://volcano.oregonstate.edu/vwdocs/volc_images/europe_west_asia/laki.html

FIGURE 4.8

Flood basalt layers in the Columbia Plateau, Dry Falls State Park, Washington. *Photo by Cynthia Shaw* extinction, when over 90% of living species were wiped out. The eruptions are a prime suspect because of the enormous amount of gases that must have been emitted. These would have changed the atmosphere and worldwide climate. The Indian eruptions occurred about 65 million years ago and coincided with the mass extinction in which the last of the dinosaurs died. Although this mass extinction is generally blamed on a large asteroid hitting Earth (see chapter 8), the intense volcanic activity may have been a contributing factor.

Basalt plateaus have their counterparts in the oceans. These were unknown until they were discovered through deep-ocean drilling a couple of decades ago. The largest of these *oceanic plateaus* is the Ontang Java Plateau in the western Pacific ocean. This plateau is larger in area than Alaska. A thick sequence of sedimentary rocks covers the huge volume of basalt that formed the plateau around 90 million years ago.

Columnar Jointing

Some basaltic lava flows show a distinctive feature formed of parallel, mostly six-sided, vertical columns. This characteristic is called **columnar jointing** (figure 4.9). The columns can be explained by the way in which basalt contracts as it cools *after* solidifying. Basalt solidifies completely at temperatures below about 1,200°C. The hot layer of rock then continues to cool to temperatures normal for the Earth's surface. Like most solids, basalt contracts as it cools. The layer of basalt is easily able to accommodate the shrinkage in the narrow vertical dimension; but the cooling rock cannot "pull in" its edges, which may be many kilometers away. Instead, the rock contracts toward evenly spaced centers of contraction. Tension cracks develop halfway between neighboring centers. A hexagonal fracture pattern is the most efficient way in which a set of contraction centers can share fractures. Although most columns are six-sided, some are five- or seven-sided.

Submarine Lava Flows

When lava erupts into water it cools rapidly, forming a distinctive feature known as **pillow structure**—rocks, generally basalt, occurring as pillow-shaped, rounded masses closely fitted together (figure 4.10). From observations of submarine eruptions by divers, we know how these **pillow basalts** are produced: Fluid, pahoehoe-type lava flows into water. Elongate

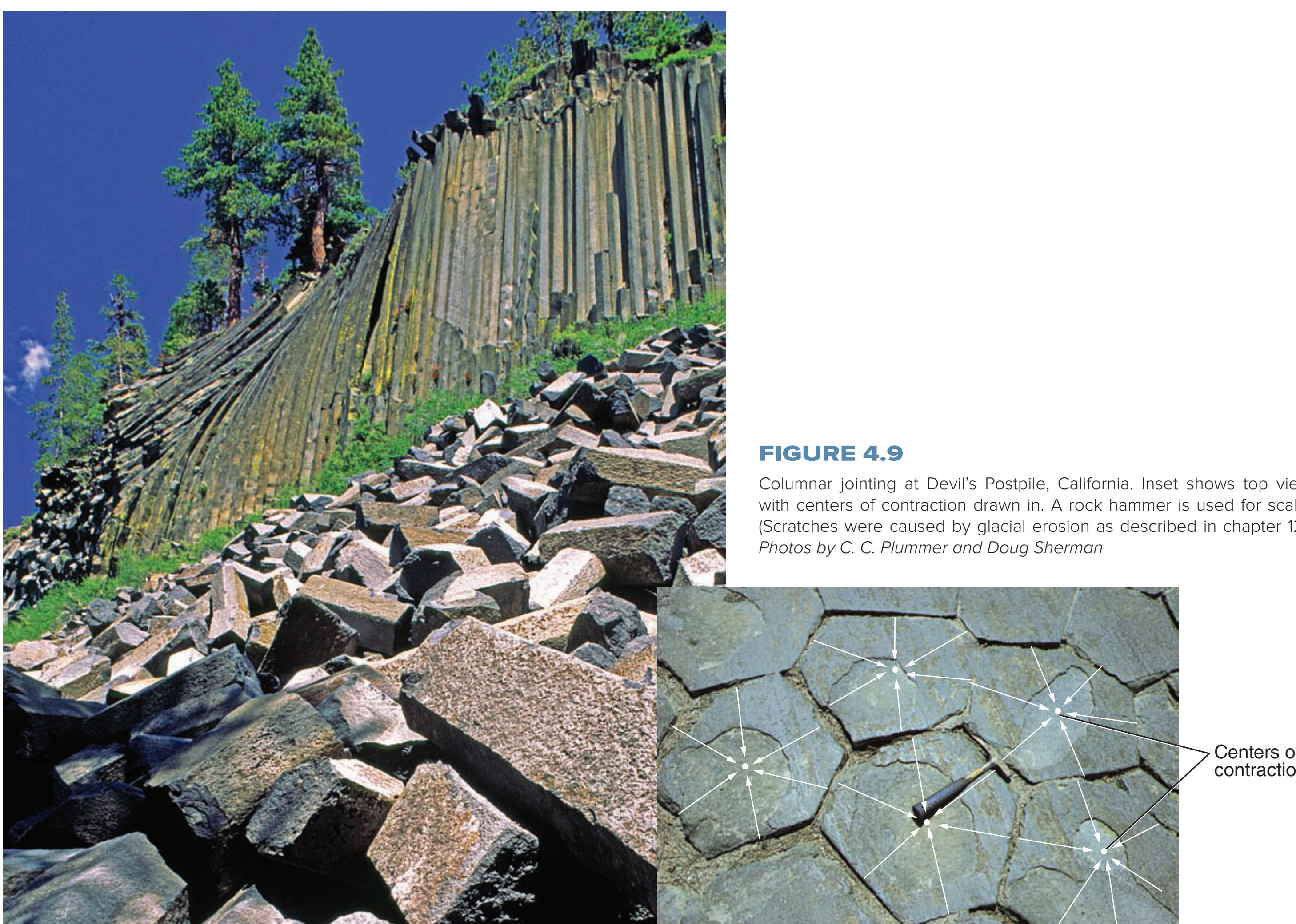


FIGURE 4.9

Columnar jointing at Devil's Postpile, California. Inset shows top view with centers of contraction drawn in. A rock hammer is used for scale. (Scratches were caused by glacial erosion as described in chapter 12.) *Photos by C. C. Plummer and Doug Sherman*

FIGURE 4.10

Pillow basalt, Lillooet glacier, British Columbia, Canada. *Photo by John J. Clague, Simon Fraser University*

FIGURE 4.11

Pillow basalt erupted from the Galapagos Rift. Photo taken from a submersible vessel. *Image courtesy of the Galapagos Rift 2005 Expedition/NOAA Ocean Explorer*

blobs of lava break out of a thin skin of solid basalt over the top of a flow that is submerged in water. Each blob is squeezed out like toothpaste, and its surface is chilled to rock within seconds. A new blob forms as more lava inside breaks out. Each new pillow settles down on the pile, with little space left in between. Some pillow basalt forms in lakes and rivers or where lava flows from land into the sea (as in Hawaii). However, most pillow basalt forms at mid-oceanic ridge crests.

According to plate-tectonic theory, basalt magma flows up the fracture that develops at a divergent boundary (explained in chapter 3). The magma that reaches the sea floor solidifies as pillow basalt (figure 4.11). The rest solidifies in the fracture as a dike. Pillow basalt that is overlying a series of dikes is sometimes found in mountain ranges. These probably formed during seafloor spreading in the distant past followed, much later, by uplift.

Intermediate and Felsic Lava Flows

Because intermediate and felsic lavas are much more viscous than mafic lava, flows tend to be thicker and flow over much shorter distances. Sometimes the lava is too viscous to flow and will build up into a lava dome (described later in this chapter). Intermediate lava, having intermediate viscosity, forms lava flows of intermediate thickness. Occasionally, more felsic lavas can flow over greater distances if they are very hot when they erupt.

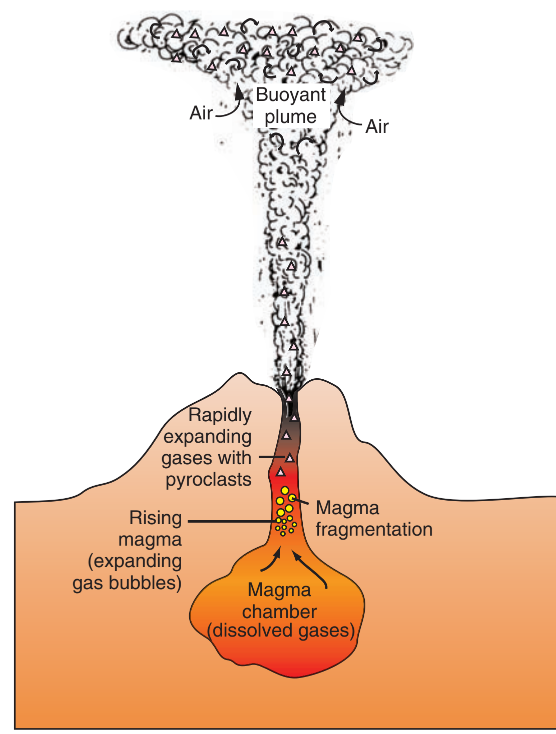


FIGURE 4.12

Generation of an explosive eruption. Gases dissolved in magma come out of solution and expand as magma rises from the magma chamber toward the surface. The expanding gases fragment the viscous magma, generating an upward blast of hot gas and pyroclasts. The jet draws in air as it rises, expanding to form a buoyant plume.

Explosive Eruptions

Explosive eruptions are driven by the expansion of gases in viscous magma (figure 4.12). When the magma is deep underground, the gases are kept dissolved by the pressure. When the magma rises toward the surface, the decrease in pressure causes the gas to come out of solution and expand. Imagine a bottle of soda. Before opening it, you see very few bubbles in the liquid because the gas (carbon dioxide) is under pressure. When you open the bottle, you release the pressure and gas comes out of solution and expands, forming bubbles. If you release the pressure too quickly, the bubbles expand so much that the mixture of soda and bubbles spills out of the bottle. During an explosive eruption, expanding, hot gases fragment the rapidly cooling magma into pieces and blast them into the air. These fragments are know as **pyroclasts** (from the Greek *pyro* "fire" and *klastos* "broken"). The hot gas and pyroclasts are blasted upward as a plume, which draws in air as it rises.

Pyroclastic Materials

Also known as *tephra,* pyroclastic material can range in size from fine **dust** and **ash** (figures 4.13*A* and *B*) to blocks six meters or more in diameter (20 feet, the size of a recreational vehicle).

Pyroclastic fragments are named according to their size:

Dust	<1/8 millimeter
Ash	1/8–2 millimeters
Cinder or lapilli	2–64 millimeters
Blocks and bombs	>64 millimeters

Cinder is often used as a less-restricted, general term for smaller pyroclasts. **Lapilli** is used for the 2–64 millimeter particles—a size range that extends from that of a grain of rice to a peach. When solid rock has been blasted apart by a volcanic explosion, the pyroclastic fragments are *angular,* with no rounded edges or corners, and are called **blocks.** If lava is ejected into the air, a molten blob becomes streamlined during flight, solidifies, and falls to the ground as a **bomb,** a spindle or lens-shaped pyroclast (figures 4.13*C* and 4.13*D*).

During an eruption, expanding hot gases can propel pyroclasts high into the atmosphere as a column rising from a volcano. At high altitudes, the pyroclasts often spread out into a dark mushroom cloud. The fine particles are transported by high atmospheric winds. Eventually, debris settles back to Earth under gravity's influence as *pyroclastic fall* (often called *ashfall* or *pumice fall*) deposits.

Pyroclastic Flows

A **pyroclastic flow** is a mixture of gas and pyroclastic debris that is so dense that it hugs the ground as it flows rapidly into low areas (figure 4.14). Pyroclastic flows develop in several

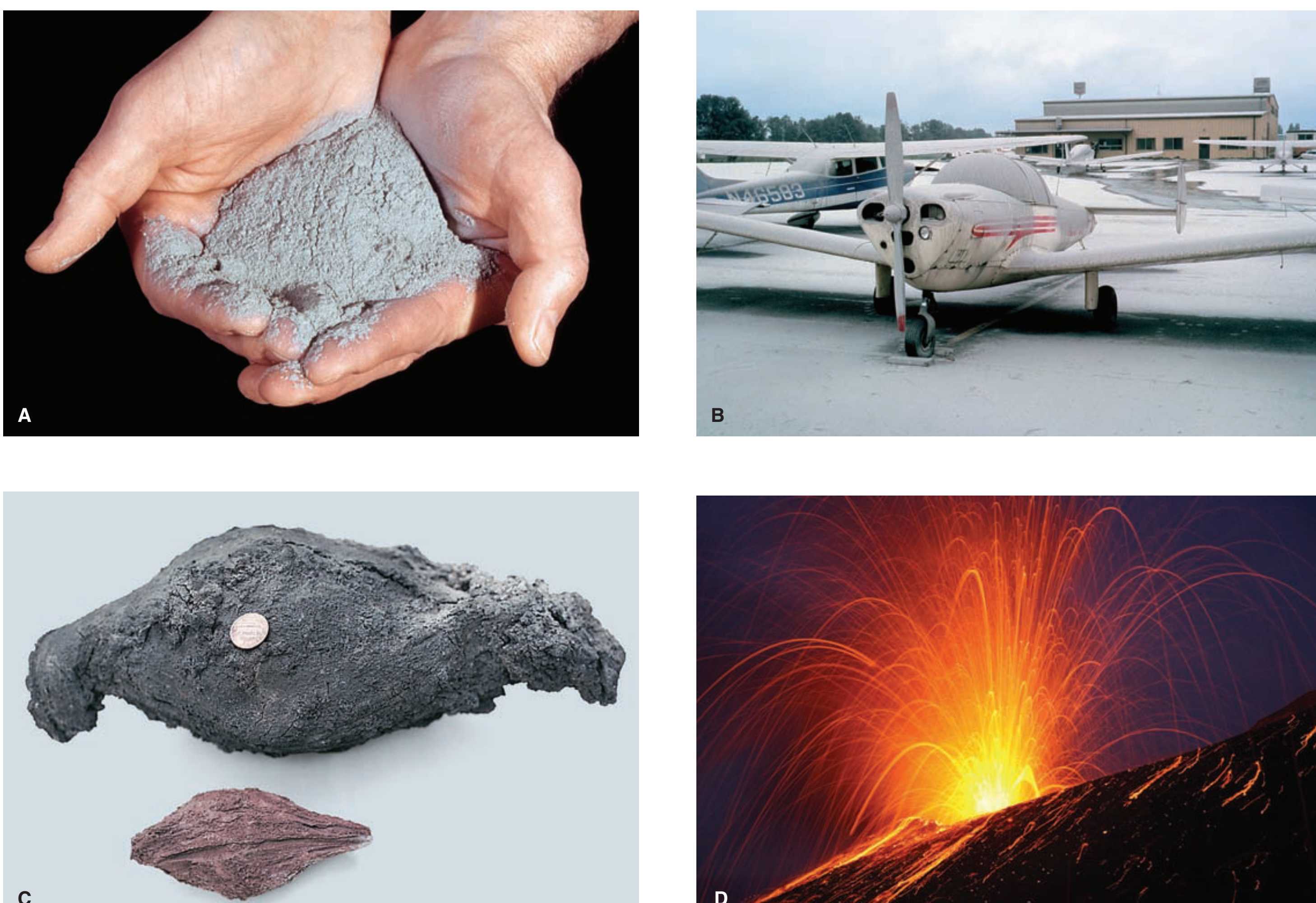


FIGURE 4.13

Pyroclastic material (*A*) Ash. (*B*) Planes covered with ash from the 1980 eruption of Mt. St. Helens. (*C*) Volcanic bombs. (*D*) Lava bomb trajectories are visible during a May 2008 nighttime eruption of Anak Kraktau volcano in Indonesia. Magma blobs that solidify in the air will land as bombs. If they are still molten upon landing, they will spatter. *Photo A by D. Wieprecht, U.S. Geological Survey; photo B by P. W. Lipman, U.S. Geological Survey; photo C by C. C. Plummer; Photo D © Stocktrek Images/Richard Roscoe RF*

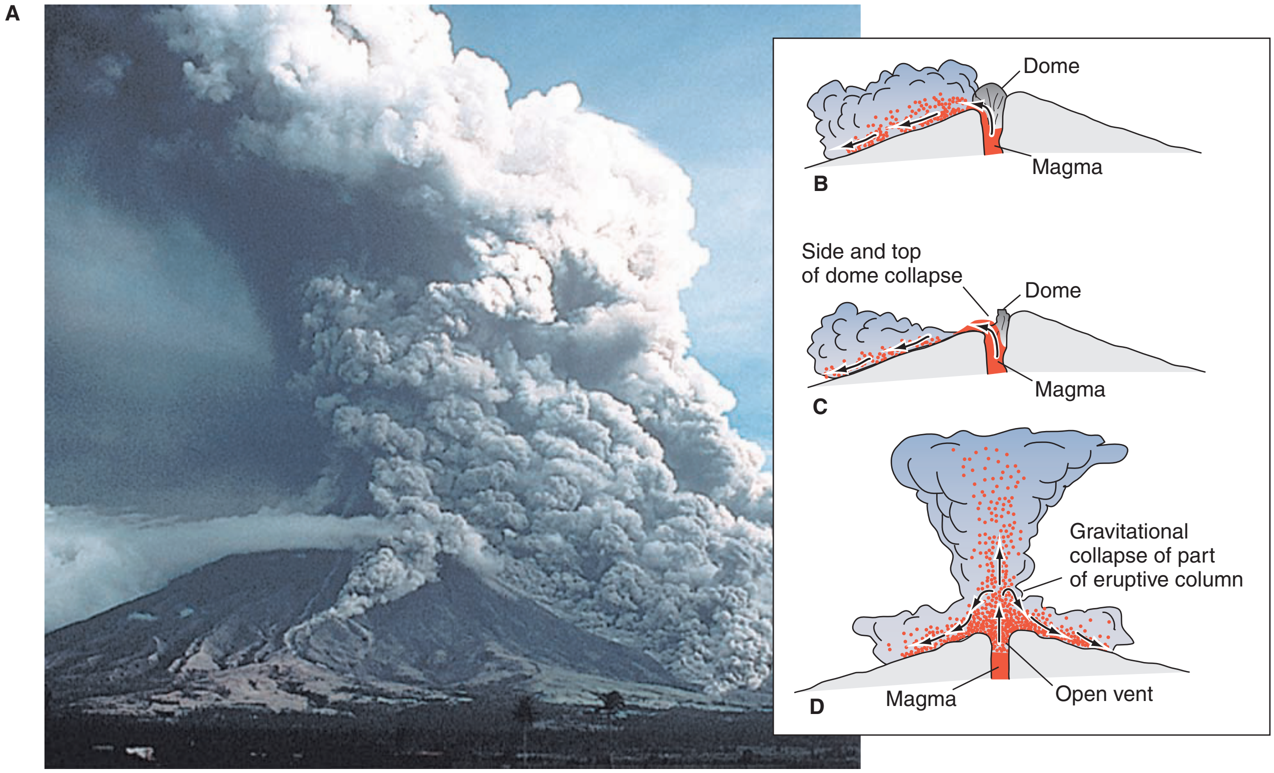


FIGURE 4.14

(*A*) Pyroclastic flow descending Mayon volcano, Philippines (elevation 2,460 meters), in 1984. Ways in which pyroclastic flows can form: (*B*) Blasting out from under a plug capping a volcano. (*C*) Collapse of part of a steep-sided dome. (*D*) Gravitational collapse of an eruptive column. *Photo by Chris Newhall, U.S. Geological Survey*

ways. Some are associated with volcanic domes (discussed later). An exploding froth of gas and magma can blast out of the side of the dome or viscous plug capping a volcano. A steep-sided dome might collapse, allowing violent release of magma and its gases. For some volcanoes, a pyroclastic flow results from gravitational collapse of a column of gas and pyroclastic debris that was initially blasted vertically into the air. These turbulent masses can travel up to 200 kilometers per hour and are extremely dangerous. In 1991, a pyroclastic flow at Japan's Mount Unzen killed 43 people, including three geologists and famous volcano photographers Maurice and Katia Krafft. Far worse was the destruction of St. Pierre on the Caribbean island of Martinique, where about 29,000 people were killed by a pyroclastic flow in 1902 (see box 4.4).

TYPES OF VOLCANOES

The major types of volcanoes (shield, cinder cone, composite, lava dome, and caldera) are markedly distinct from one another in size, shape, and, usually, composition. Table 4.2 provides a comparison of shield volcanoes, cinder cones, and composite volcanoes. Note from the scales that the shield volcano shown is vastly bigger than the other two, and the composite volcano is much bigger than the cinder cone.

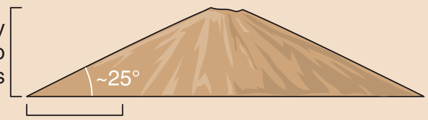
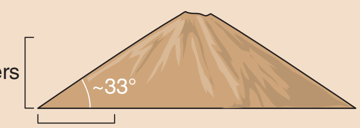
Shield Volcanoes

Shield volcanoes are broad, gently sloping volcanoes constructed of solidified lava flows. Eruptive activity at shield volcanoes is dominated by effusive eruption of low viscosity, mostly basaltic lava. During eruptions, the lava spreads widely and thinly due to its low viscosity. Because the lava flows from a central vent, without building up much near the vent, the slopes are usually between 2 degrees and 10 degrees from the horizontal, producing a volcano in the shape of a flattened dome or "shield" (figure 4.15).

The islands of Hawaii are essentially a series of shield volcanoes, built upward from the ocean floor by intermittent eruptions over millions of years (figure 4.15*B*). Although spectacular to observe, the effusive eruptions are relatively nonviolent because the lavas are fairly fluid (low viscosity). The features associated with effusive eruption described earlier in the section on the eruptive products of volcanoes (pahoehoe, a′a, spatter cones, lava tubes, etc.) are all common on the islands of Hawaii. In fact, the names pahoehoe and a′a are Hawaiian names, and shield volcanoes got their name from their resemblance to Hawaiian warriors' shields.

Measuring nearly 22 km (14 miles) in height and 600 km (370 miles) across, the largest shield volcano in the solar system is Olympus Mons on Mars. For more information on extraterrestrial volcanic activity, see box 4.5.

TABLE 4.2 Comparison of the Three Types of Volcanoes

Profile of Volcano	Description	Composition
 10 km; ~4°; 100 km; Shield Volcano	**Shield Volcano** Gentle slopes—between 2 and 10 degrees. The Hawaiian example rises 10 kilometers from the sea floor.	Basalt. Layers of solidified lava flows
 Typically 1,000 to 4,000 meters; ~25°; 1,000 – 4,000 m; Composite Volcano	**Composite Volcano** Slopes less than 33 degrees. Considerably larger than cinder cones.	Layers of pyroclastic fragments and lava flows. Mostly andesite
 < 500 meters; ~33°; < 500 m; Cinder Cone	**Cinder Cone** Steep slopes—33 degrees. Smallest of the three types.	Pyroclastic fragments of any composition. Basalt is most common.

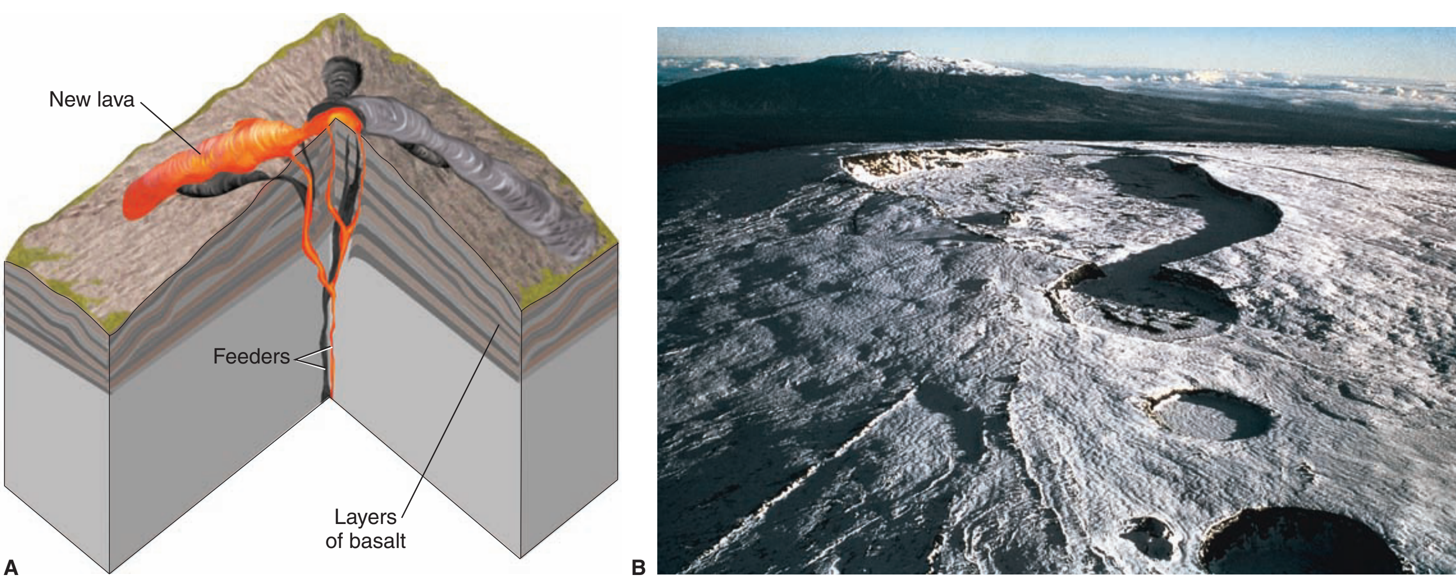


FIGURE 4.15

(*A*) Cutaway view of a shield volcano. (*B*) The top of Mauna Loa, a shield volcano in Hawaii, and its summit caldera, which is approximately 2 kilometers wide. The smaller depressions are pit craters. *Photo US Geological Survey, HVO*

Cinder Cones

A **cinder cone** (less commonly called a *pyroclastic cone*) is a volcano constructed of pyroclastic fragments ejected from a central vent (figure 4.16). Unlike a shield volcano, which is made up of lava flows, a cinder cone is formed exclusively of pyroclasts. In contrast to the gentle slopes of shield volcanoes, cinder cones commonly have slopes of about 30 degrees. Most of the ejected material lands near the vent during an eruption, building up the cone to a peak. The steepness of slopes of accumulating loose material is limited by gravity to about 33 degrees. Cinder cones tend to be very much smaller than shield volcanoes. In fact, cinder cones are commonly found on the flanks and in the calderas of Hawaii's shield volcanoes. Few cinder cones exceed a height of 500 meters.

Cinder cones form by pyroclastic material accumulating around a vent. They form because of a buildup of gases and are independent of composition. Most cinder cones are associated with mafic or intermediate lava. Felsic cinder cones, which are made of fragments of pumice, are also known as pumice cones.

FIGURE 4.16

Cerro Negro, a 230-meter-high cinder cone in Nicaragua, erupting. Figure 4.13*D* shows a nighttime eruption of Cerro Negro. *Photo by Mark Hurd Aerial Surveys Corp., courtesy of California Division of Mines and Geology*

The life span of an active cinder cone tends to be short. The local concentration of gas is depleted rather quickly during the eruptive periods. Moreover, as landforms, cinder cones are temporary features in terms of geologic time. The unconsolidated pyroclasts are eroded relatively easily.

Composite Volcanoes

A **composite volcano** (also called a **stratovolcano**) is one constructed of alternating layers of pyroclastic fragments and solidified lava flows (figure 4.17). The slopes are intermediate in steepness compared with cinder cones and shield volcanoes. Pyroclastic layers build steep slopes as debris collects near the vent, just as in cinder cones. However, subsequent lava flows partially flatten the profile of the cone as the downward flow

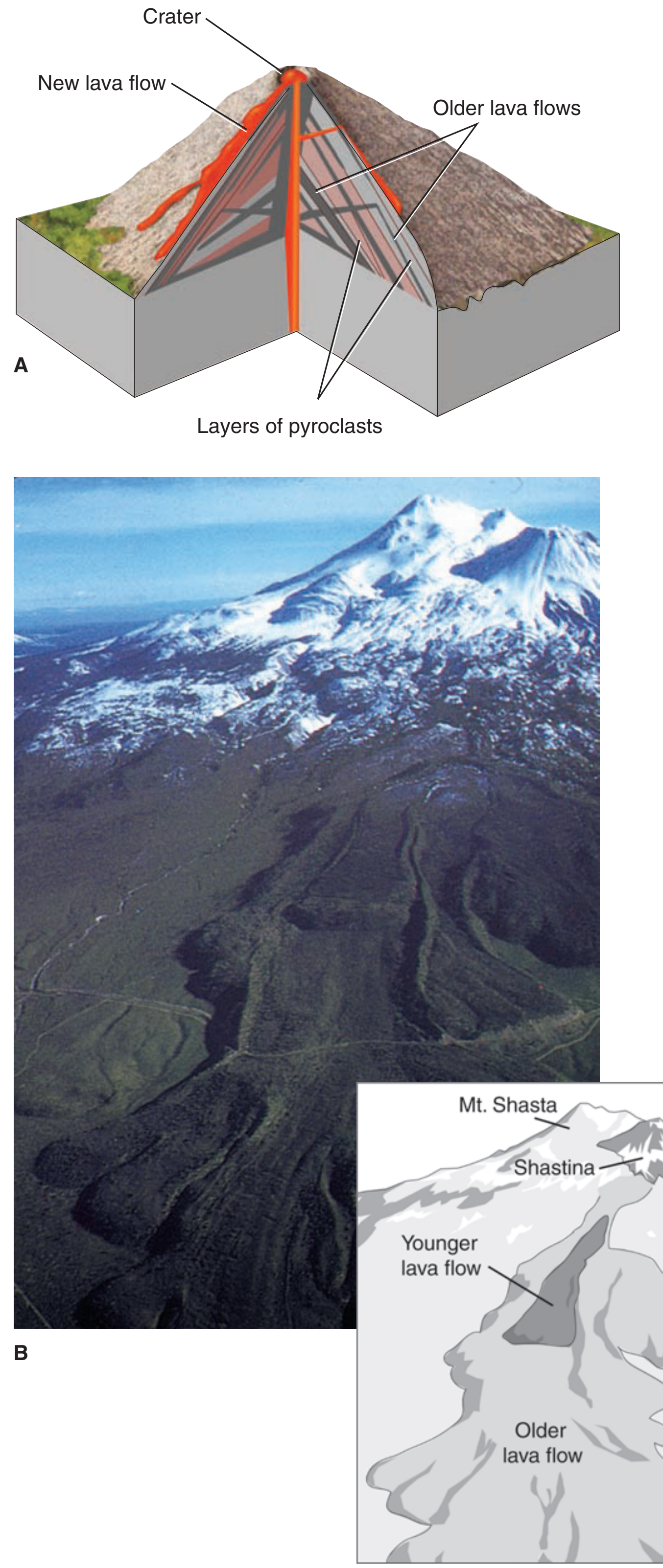


FIGURE 4.17

(*A*) Cutaway view of a composite volcano. Light-colored layers are pyroclasts. (*B*) Mount Shasta, a composite volcano in California. Shastina on Mount Shasta's flanks is a subsidiary cone, largely made of pyroclasts. Note the lava flow that originated on Shasta and extends beyond the volcano's base. *Photo by B. Amundson* builds up the height of the flanks more than the summit area. The solidified lava acts as a protective cover over the loose pyroclastic layers, making composite volcanoes less vulnerable to erosion than cinder cones.

Composite volcanoes are built over long spans of time. Eruption is intermittent, with hundreds or thousands of years of inactivity separating a few years of intense activity. During the quiet intervals between eruptions, composite volcanoes may be eroded by running water, landslides, or glaciers. These surficial processes tend to alter the surface, shape, and form of the cone. But because of their long lives and relative resistance to erosion, composite cones can become very large.

The extrusive material that builds composite cones is predominantly of intermediate composition, although there may be some felsic and mafic eruptions. Therefore, *andesite* is the rock most associated with composite volcanoes. If the lava is especially hot, the relatively low viscosity fluid flows easily from the crater down the slopes. On the other hand, if enough gas pressure exists, an explosive eruption may litter the slopes with pyroclastic andesite, particularly if the lava has fully or partially solidified and clogged the volcano's vent.

The composition as well as the eruptive history of individual volcanoes can vary considerably, even within a single volcanic arc. Take for instance the Cascade volcanoes (figure 4.18) of Washington, Oregon, and northern California. Mount Rainier is composed of 90% lava flows and only 10% pyroclastic layers. Conversely, Mount St. Helens was built mostly from pyroclastic eruptions—reflecting a more violent history. As would be expected, the composition of the rocks formed during the 1980 eruptions of Mount St. Helens is somewhat higher in silica than average for Cascade volcanoes.

FIGURE 4.18

The Cascade volcanoes. The named volcanoes are ones that have erupted in geologically recent time. *Adapted from U.S. Geological Survey*

Distribution of Composite Volcanoes

Nearly all the larger and better-known volcanoes of the world are composite volcanoes. They tend to align along two major belts (figure 4.19). The **circum-Pacific belt,** or "Ring of Fire," is the larger. The Cascade Range volcanoes (figure 4.18), including Mount St. Helens, Crater Lake, and Lassen Peak, make up a small segment of the circum-Pacific belt.

Further south, the Mexican Volcanic Belt has several composite volcanoes, some that rise higher than 5,000 meters, including Orizaba (third-highest peak in North America) and Popocatépetl. Popocatépetl (affectionately called "Popo"), at 5,484 meters (17,991 feet) above sea level, is one of North America's highest mountains. It is 55 kilometers east of Mexico City, one of the world's most populous cities. Popo awakened from a long period of dormancy in 1994. In December 2000, Popo had its largest eruption in over 1,000 years, and 50,000 people near its flanks were evacuated to shelters. On January 31, 2001, a pyroclastic flow descended the volcano to within 8 kilometers of a town.

The circum-Pacific belt includes many volcanoes in Central America, western South America, and Antarctica. Mount Erebus, in Antarctica, is the southernmost active volcano in the world.

The western portion of the Pacific belt includes volcanoes in New Zealand, Indonesia (including Mount Merapi), the Philippines (with Pinatubo, whose 1991 caldera-forming eruption was the second-largest eruption of the twentieth century), and Japan. The beautifully symmetrical Fujiyama, in Japan, is probably the most frequently photographed and painted volcano in the world, as well as its most-climbed mountain. The northernmost part of the circum-Pacific belt includes active volcanoes in Russia (see figure 4.3) and on Alaska's Aleutian Islands. The 1912 eruption of Katmai in Alaska was the world's largest in the twentieth century.

The second major volcanic belt is the **Mediterranean belt,** which includes Mount Vesuvius. An exceptionally violent eruption of Mount Thera, an island in the Mediterranean, may have destroyed an important site of early Greek civilization. (Some archaeologists consider Thera the original "lost continent" of Atlantis.) Mount Etna, on the island of Sicily, is

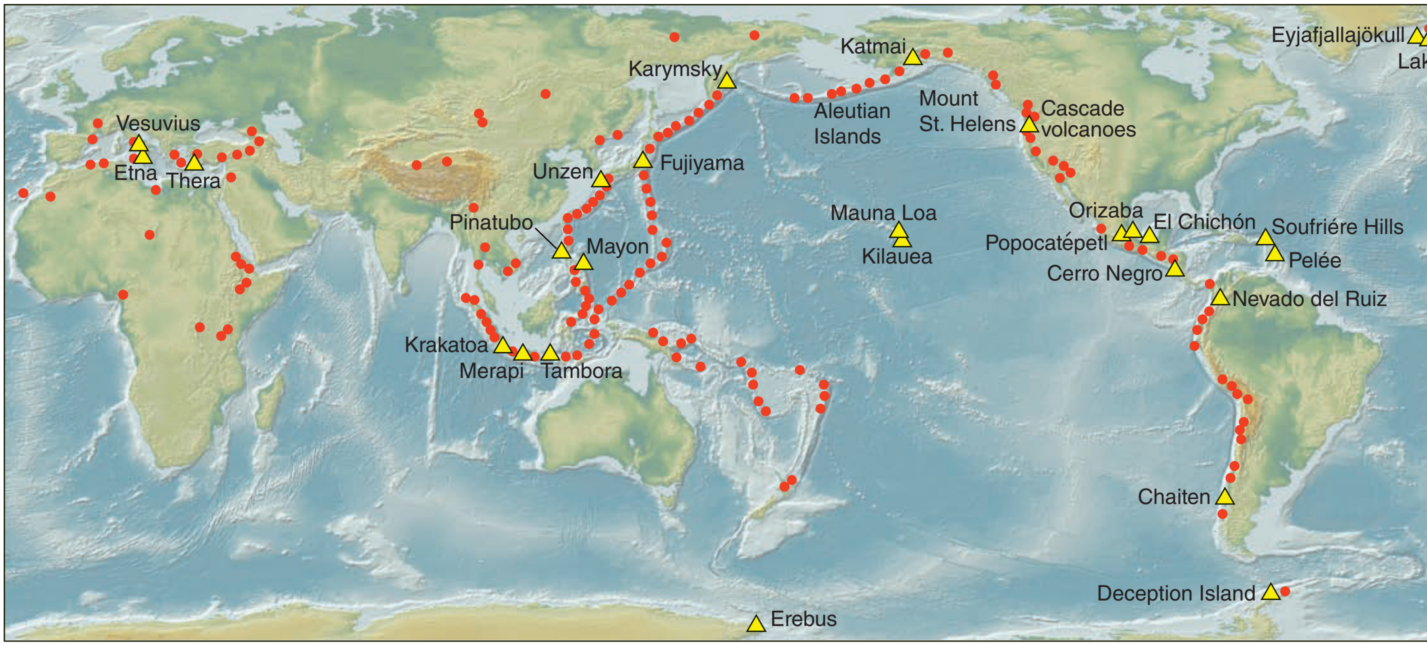


FIGURE 4.19

Map of the world showing recently active major volcanoes. Red dots represent individual volcanoes. Yellow triangles represent volcanoes mentioned in this chapter.

Europe's largest volcano and one of the world's most active volcanoes. Its largest eruption in 300 years began in 1991 and lasted for 473 days. Some 250 million cubic meters of lava covered 7 square kilometers of land. A town was saved from the lava by heroic efforts that included building a dam to retain the lava (the lava quickly overtopped it), plugging some natural channels, and diverting the lava into other, newly constructed channels.

Lava Domes

Lava domes are steep-sided, dome- or spine-shaped masses of volcanic rock formed from viscous lava that solidifies in or immediately above a volcanic vent. Lassen Peak, the southernmost of the Cascade volcanoes, is a lava dome. Most of the viscous lavas that form volcanic domes are high in silica. They commonly solidify as obsidian that is the chemical equivalent of rhyolite (or, less commonly, andesite). If minerals do crystallize, the rock is rhyolite if it is from a felsic magma, or andesite if it is from an intermediate magma.

Volcanic domes often form within the craters of composite volcanoes. A volcanic dome grew within the crater of Mount St. Helens after the climactic eruption of May 1980. This was expected because of the high viscosity of the lava from the eruptions. In 1983 alone, the dome increased its elevation by 200 meters. After years of quiescence, dome growth resumed in October 2004. At that time, lava extrusion shifted, and a new dome began growing adjacent to the original dome. In 2005, 70 million cubic meters of lava were extruded to build seven domes in the crater. Lava extruded at a rate of one large pickup truck load per second. The volcano has been quiet again since January 2008. Go to http://volcanoes.usgs.gov/volcanoes/st_helens/st_helens_multimedia_11.html and scroll to the bottom of the page to find time-lapse movies of the dome growth activity.

Because the thick, pasty lava that squeezes from a vent is too viscous to flow, it builds up a steep-sided dome or spine (figure 4.20). Some volcanic domes act like champagne corks, keeping gases from escaping. If the plug is removed or broken, the gas and magma escape suddenly and violently, usually as a pyroclastic flow. Some of the most destructive volcanic explosions known have been associated with volcanic domes (see box 4.4).

Calderas

A **caldera** is a volcanic depression much larger than the original crater, having a diameter of at least 1 kilometer. A caldera can be created when a volcano's summit is blown off by exploding gases or when a volcano (or several volcanoes) collapses into a partially emptied magma chamber (see figure 4.21). Caldera-forming eruptions are extremely violent, blasting huge volumes of pyroclastic material into the atmosphere and generating pyroclastic flows that can blanket vast areas in sometimes hundreds of meters of hot volcanic debris.

The most famous caldera in the United States is misnamed "Crater Lake." A series of eruptions in prehistoric time (about 7,700 years ago) created the depression now occupied by Crater Lake in Oregon (figure 4.21). Approximately 50 cubic kilometers of volcanic debris was erupted and now covers more than a million square kilometers in Oregon and neighboring states. The original volcano, named Mount Mazama (now regarded as a cluster of overlapping volcanoes), is estimated to have been

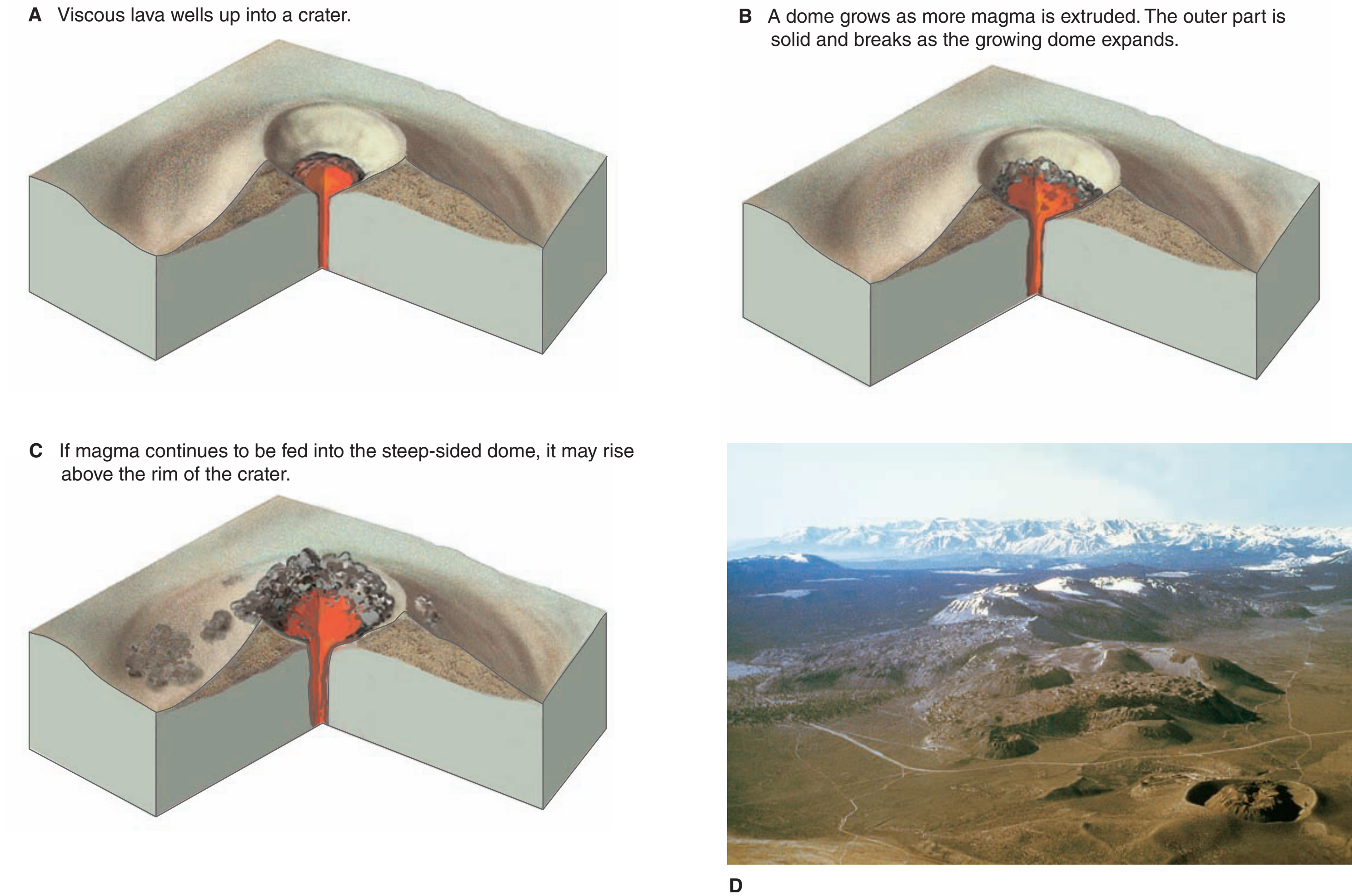


FIGURE 4.20

A volcanic dome forming in the crater of a pumice cone (*A, B, C*). (*D*) Mono Craters, eastern California, is a line of craters with lava domes. The dome in the crater in the foreground has not grown above the level of the crater's rim (like *B*). Some in the background have overtopped their rims. You can also see some short and steep lava flows, reflecting the very viscous silicic lava that erupted. The photo of pumice in figure 3.10*A* was taken on the flanks of the cinder cone in the foreground. A two-lane highway provides a scale for the photo. The Sierra Nevada range is on the skyline. *Photo by C. Dan Miller, U.S. Geologic Survey*

about 2,000 meters higher than the present rim of Crater Lake. For more on Crater Lake and Mount Mazama, go to http://pubs.usgs.gov/fs/2002/fs092-02/.

The eruptions that formed Crater Lake were relatively small when compared to two other calderas in the United States. About 640,000 years ago a massive eruption at Yellowstone formed a caldera 70 by 50 kilometers across. The eruption blasted 1,000 cubic kilometers of pyroclastic material into the atmosphere. For comparison, the 1980 eruption of Mount St. Helens erupted only about 1 cubic kilometer of lava. Enormous pyroclastic flows buried the surrounding area with thick deposits of hot pyroclastic material. Ash from the eruption covers much of central North America. The Long Valley caldera in California formed 760,000 years ago with the eruption of 600 cubic kilometers of material. Ash from this eruption is found as far away as Nebraska. Figure 4.22 shows the areas covered in at least 2 centimeters of ash from the Crater Lake, Yellowstone, and Long Valley eruptions. Ash from the 1980 eruption of Mount St. Helens is shown for comparison. Both Yellowstone and Long Valley are considered to be active, and while eruptions of the scale that formed the calderas are not believed to be imminent, volcanologists monitor them carefully.

LIVING WITH VOLCANOES

Volcanic eruptions present a number of challenges to human beings. Hazards include ash clouds, pyroclastic flows, and mudflows. Reducing the impact of volcanic eruptions (called *mitigation*) involves monitoring, hazard mapping, and alerting the population about a potential eruption.

Volcanic Hazards

Figure 4.23 shows the results of research at the Smithsonian Institute and Macquarie University, Australia. Note the dramatic increase in fatalities during the recent centuries

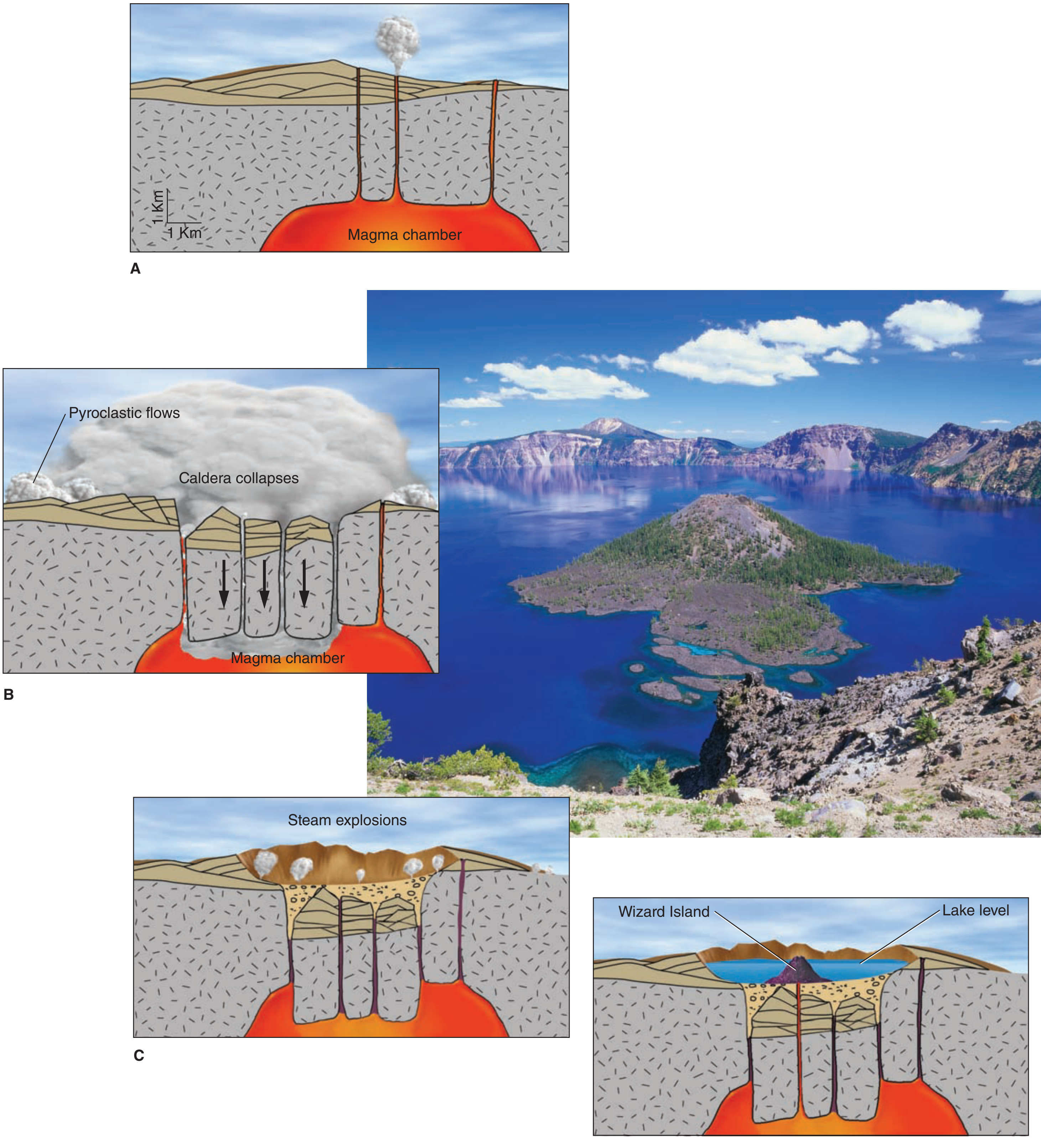


FIGURE 4.21

Crater Lake, Oregon. The lake is approximately 10 kilometers (6 miles) across. Its development and geologic history: (*A*) Cluster of overlapping volcanoes form. (*B*) Collapse into the partially emptied magma chamber is accompanied by violent eruptions. (*C*) Volcanic activity ceases, but steam explosions take place in the caldera. (*D*) Water fills the caldera to become Crater Lake, and minor renewed volcanism builds a cinder cone (Wizard Island). *Photo © Robert Glusic/Corbis; Illustration after C. Bacon, U.S. Geological Survey*

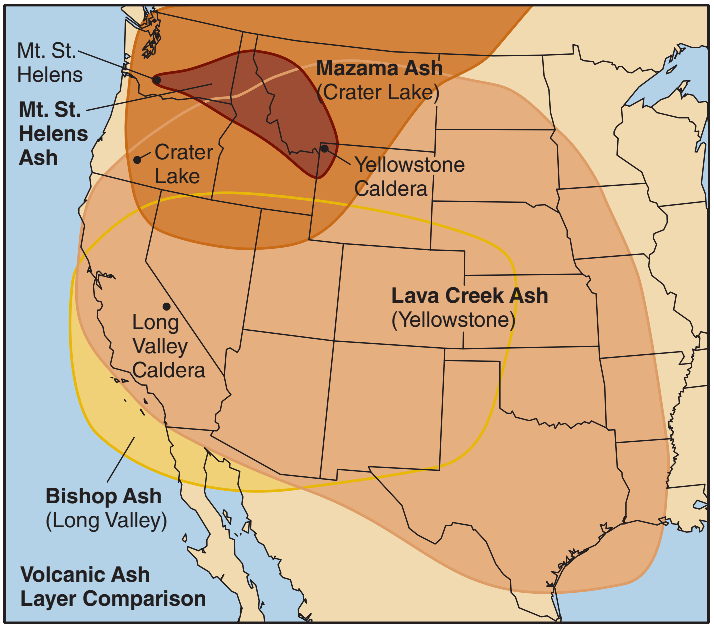


FIGURE 4.22

Volcanic ash deposits (>2 centimeters) from caldera eruptions at Crater Lake, Yellowstone, and Long Valley. Ash from the 1980 eruption of Mount St. Helens is shown for comparison.

(figure 4.23*A*). This is not due to increasing volcanic activity but to increasing population and more people living near volcanoes. Figure 4.23*B*, which shows the cumulative number of deaths during the last seven centuries, also shows that most of the fatalities have been caused by seven major eruptions.

Volcanoes can kill in a number of ways (figure 4.23*C*). Some, like pyroclastic flows, are directly related to the eruption; others, like famine, are secondary effects.

Pyroclastic flows, already described in detail earlier in this chapter, are the most deadly volcanic hazards, accounting for approximately 30% of all volcano fatalities. *Pyroclastic fall* accounts for the largest number of deadly events; however, few people die in each event, so the total number of deaths is not great. Most of the deaths due to pyroclastic fall are caused by the collapse of ash-covered roofs or by being hit by falling rock fragments. The Roman city of Pompeii and at least four other towns near Naples in Italy were destroyed in A.D. 79 when Mount Vesuvius erupted (figure 4.24). Before the eruption, vineyards on the flanks of the apparently "dead" volcano extended to the summit. After Vesuvius erupted without warning, Pompeii was buried under 5 to 8 meters of hot ash. Seventeen centuries later, the town was rediscovered. Excavation revealed molds of people, many with facial expressions of terror. Initially it was believed that the people had been suffocated by ashfall, but recent studies suggest that while 38% of the deaths were due to buildings collapsing under the weight of ash, it was exposure to high temperatures in hot pyroclastic surges that killed the majority of the victims.

Volcanic eruptions are often accompanied by the release of large amounts of gas such as water vapor, carbon dioxide, and sulfur dioxide. As you've learned, it is the expansion of gas, primarily water vapor, that drives explosive eruptions. Sometimes the gas itself can be a deadly hazard. Lake Nyos, Cameroon, in western Africa is an example of this type of event. Carbon dioxide seeped into the lake within

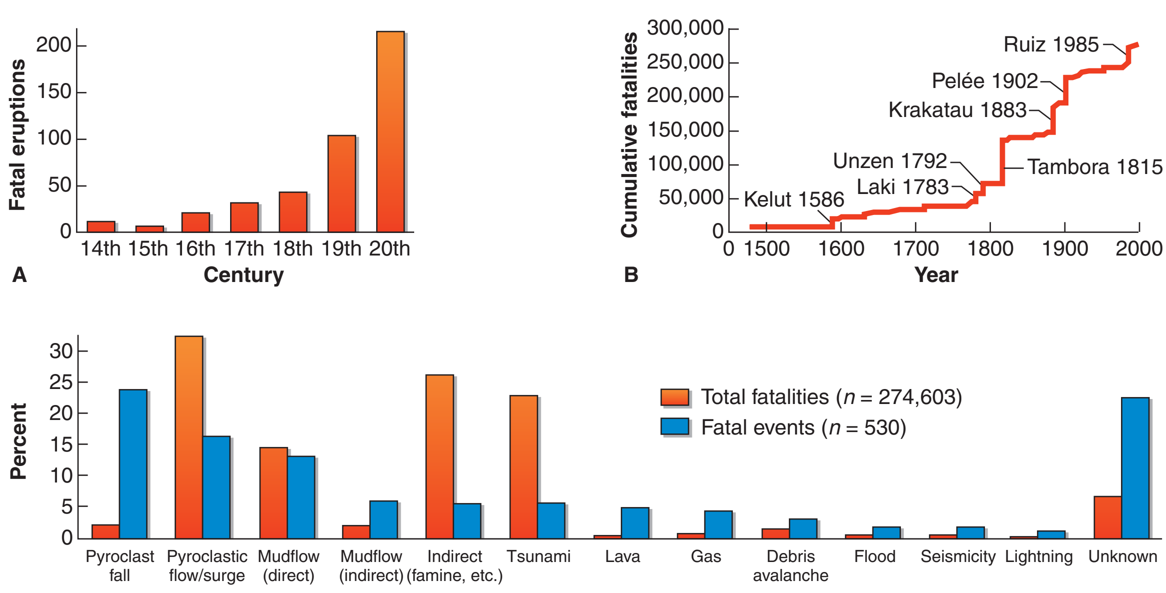


FIGURE 4.23

Volcano fatalities. (*A*) Fatal volcanic eruptions per century. (*B*) Cumulative volcano fatalities. Note the big jumps with the seven most deadly eruptions. These were eruptions that killed over 10,000 people and account for two-thirds of the total. (*C*) The causes of volcano fatalities. *Reprinted with permission from "Volcano Fatalities" by T. Simkin, L. Siebert, and R. Blong,* Science, *v. 291: p. 255. Copyright © 2001 American Association for the Advancement of Science*

ENVIRONMENTAL GEOLOGY 4.4

A Tale of Two Volcanoes—Lives Lost and Lives Saved in the Caribbean

Montserrat and Martinique are two of the tropical islands that are part of a volcanic island arc (box figure 1). During the twentieth century, both islands had major eruptions that destroyed towns. Violent and deadly pyroclastic flows associated with the growth of volcanic domes caused most of the destruction. For one island, the death toll was huge, and for the other, it was minimal.

In 1902, the port city of St. Pierre on the island of Martinique was destroyed after a period of dome growth and pyroclastic flows on Mount Pelée (no relationship to Pele, Hawaii's goddess of volcanoes). A series of pyroclastic flows broke out of a volcanic dome and flowed down the sides of the volcano. Searingly hot pyroclastic flows can travel at up to 200 kilometers per hour and will destroy any living things in their paths. After the pyroclastic flows began, the residents of St. Pierre became fearful, and many wanted to leave the island. The authorities claimed there was no danger and prevented evacuation. There was an election coming up, and the governor felt that most of his supporters lived in the city. He did not want to lose their votes, but neither the governor nor any of the city's residents would ever vote. The climax came on the morning of May 8, when great fiery, exploding clouds descended like an avalanche down the mountainside, raced down a stream valley, through the port city and into the harbor. St. Pierre and the ships anchored in the harbor were incinerated. Temperatures within the pyroclastic flow were estimated at 700°C. Some of the dead had faces that appeared unaffected by the incinerating storm. However, the backs of their skulls were blasted open by their boiling brains. About 29,000 people were burned to death or suffocated (of the two survivors in St. Pierre, one was a condemned prisoner in a poorly ventilated dungeon).

Ninety-three years later, in July 1995, small steam-ash eruptions began at Soufriére Hills volcano on the neighboring island of Montserrat. As a major eruption looked increasingly likely, teams of volcanologists from France, the United Kingdom, the United States (including members of the U.S. Geological Survey's Volcano Disaster Assistance Team that had successfully predicted the eruption of Mount Pinatubo in the Philippines, as described in chapter 1), and elsewhere flew in to study the volcano and help assess the hazards. An unprecedented array of modern instruments (including seismographs, tiltmeters, and gas analyzers) were deployed around the volcano. In November 1995, viscous, andesitic lava built a dome over the vent. Pyroclastic flows began when the dome collapsed in March 1996. Pyroclastic flows continued with more dome building and collapsing. By 1997, nearly all of the people in the southern part of the island were evacuated, following advice from the scientific teams. In June 1997, large eruptions took place, and pyroclastic flows destroyed the evacuated capital city of Plymouth. In contrast to the tragedy of St. Pierre, only nineteen people were killed in the region.

In August 1997, major eruptions resumed. This time, the northern part of the island, previously considered safe, was faced with pyroclastic flows (box figure 1), and more people were evacuated from the island. Activity continued, at least into the mid-2000s, but with decreasing intensity. In May 2004, a volcanic mudflow went through the already uninhabitable town of Plymouth. Up to 6 meters of debris were deposited, partially burying buildings still left in the town.

Additional Resources

Mount Pelée, West Indies (Volcano World site)

This site contains some excellent photos from the 1902 eruptions. The second page has photos of the famous spine that grew in Mount Pelée after the tragic eruption.

- http://volcano.oregonstate.edu/pelee

Montserrat Volcano Observatory

Includes up-to-date reports on volcanic activity.

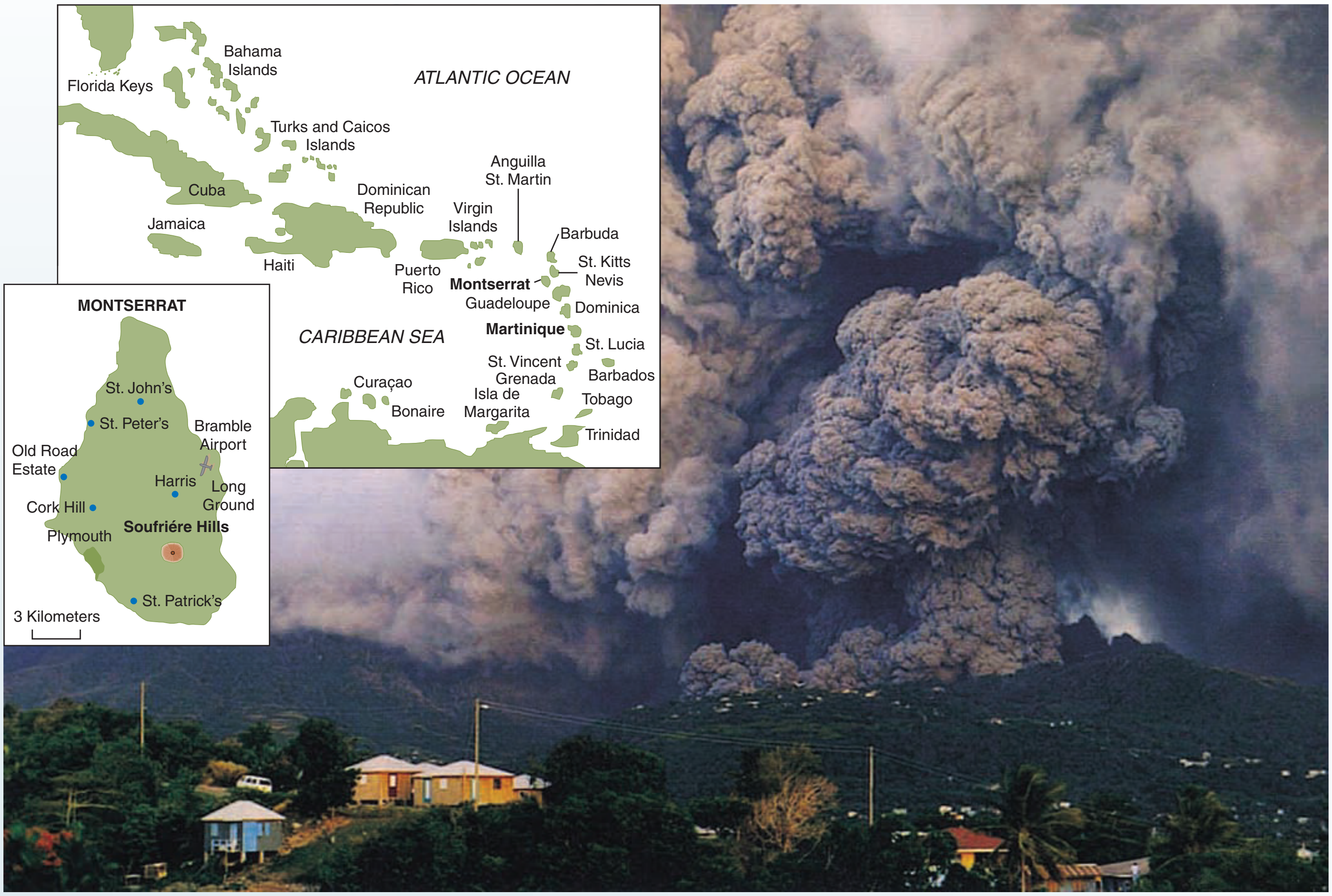
- http://www.mvo.ms/

the crater of an active volcano. The gas dissolved into the cold water at the bottom of the lake, slowly saturating the water with carbon dioxide. On August 21, 1986, the lake suddenly released a large cloud of carbon dioxide. Being heavier than air, the carbon dioxide flowed down the slopes of the volcano, engulfing nearby villages. About 1,700 people living within 25 kilometers (16 miles) of the lake were suffocated; at least 3,500 head of cattle also died.

Volcanic mudflows, called **lahars,** are responsible for 15% of volcano-related fatalities. Explosive eruptions deposit large amounts of loose pyroclastic material over the slopes of a volcano and the surrounding area. When this material mixes with rainwater or snowmelt, it forms a dense slurry of water, ash, and even large boulders that flows rapidly down the steep slopes of the volcano. In 1985, 23,000 people in the town of Armero, Colombia, were killed when hot volcanic debris blasted from Nevado del Ruiz in Colombia melted ice and snow capping the peak. The meltwater mixed with the pyroclastic material, forming a lahar that buried the town.

Famine and other indirect causes account for 23% of fatalities. Widespread destruction of crops and farm animals can cause regional famine (as occurred with the eruption of Tambora in 1815). Note the large number of deaths attributable to famine were the result of relatively few events.

Lightning is a spectacular and sometimes deadly effect of volcanic eruptions. Volcanic lightning (see the image of



BOX 4.4 ■ FIGURE 1

Eruption of Soufriére Hills volcano on Montserrat, August 4, 1997. An ash cloud billows upward above a ground-hugging pyroclastic flow. Map of the West Indies showing location of Montserrat, Martinique, and Soufriére Hills volcano. *Photo by AP/Kevin West*

Chaitén volcano in Chile at the beginning of this chapter) is generated by tiny particles of ash thrown out by the volcano. The ash is believed to cause friction that generates an electrical charge. During the eruption of Parícutin in Mexico that destroyed two villages, the only three fatalities were due to volcanic lightning.

Monitoring Volcanoes

A volcano is considered **active** if it is currently erupting or has erupted recently. Volcanoes that have not erupted in many thousands of years but that are expected to at some point in the future are considered **dormant**. **Extinct** volcanoes are those that have not erupted for a very long time and show no signs of ever erupting again. Volcanoes can lie dormant for very long periods of time, making the distinction between extinct and dormant difficult to make. For example, the Soufriére Hills volcano on Montserrat (see box 4.4) was thought to be extinct before waking up in 1995.

There are approximately 500 active volcanoes in the world, 50 of which are in the United States. There are more than 1,500 potentially active volcanoes. With an estimated 500 million people living near active volcanoes, volcanic monitoring is essential for reducing loss of life. The active U.S. volcanoes are monitored by the USGS through a series of volcano observatories, including the Hawaiian Volcano Observatory and the Cascade Volcano Observatory.

A

B

FIGURE 4.24

(*A*) Pompeii with Mount Vesuvius in the background. (*B*) Casts of bodies of people who died in Pompeii, buried by ash from the eruption of Vesuvius, AD 79. The casts were made by pouring plaster into voids in the ash left by the dead. *Photo A © Oliver Goujon/Robert Harding World Imagery/Getty Images; Photo B © Bettmann/Corbis*

Volcanic hazard mitigation has three important components: hazard mapping, monitoring, and alerts.

Hazard mapping involves the study of deposits from past eruptions of a volcano. This provides information on the frequency of eruptions of the volcano and the typical size and style of eruptive activity. Hazard maps allow populations living near a volcano to create evacuation plans in case of an eruption. Unlike earthquakes, which occur without warning, volcanoes often show signs of unrest weeks or even months prior to an eruption. The earliest sign that a volcano is entering an eruptive phase is often increased seismic activity beneath the volcano as magma makes its way toward the surface. Seismographs, described in detail in chapter 16, are used to monitor seismic activity beneath volcanoes that are thought likely to erupt in the future. As magma gets closer to the surface, it may cause the ground surface to bulge upward. Volcanologists use instruments on the ground such as tiltmeters as well as satellites to measure changes in the ground surface (figure 4.25). Volcanic gases may escape as magma moves closer to the surface. Volcanologists measure the amount of gas emitted from a volcano, looking for sudden rises or drops that may indicate an imminent eruption. Heat from magma can be measured at the surface and may produce visible signs such as increased

FIGURE 4.25

U.S. Geological Survey scientist at a Global Positioning System (GPS) station on the east flank of Mount St. Helens. Mount Adams, another Cascade Range volcano, is visible in the distance. More than a dozen GPS stations were installed on or around Mount St. Helens to measure deformation of the ground surface when activity at the volcano resumed in 2004. *Photo by Mike Poland, U.S. Geological Survey.*

PLANETARY GEOLOGY 4.5

Extraterrestrial Volcanic Activity

Volcanic activity has been a common geologic process operating on the Moon and several other bodies in the solar system. Approximately one-sixth of the Moon's surface consists of nearly circular, dark-colored, smooth, relatively flat lava plains. The lava plains, found mostly on the near side of the Moon, are called *maria* (singular, *mare;* literally, "seas"). They are believed to be huge meteorite impact craters that were flooded with basaltic lava during the Moon's early history. There are also a few extinct shield volcanoes on the Moon.

Elongate trenches or cracklike valleys called *rilles* are found mainly in the smoother portions of the lunar maria. They range in length from a few kilometers to hundreds of kilometers. Some are arc-shaped or crooked and are regarded as drained basaltic lava channels.

Mercury, the innermost planet, also has areas of smooth plains, suspected to be volcanic in origin.

Radar images of Venus show a surface that is young and probably still volcanically active. More than three-fourths of that surface is covered by continuous plains formed by enormous floods of lava. Close examination of these plains reveals extensive networks of lava channels and individual lava flows thousands of kilometers long.

Large shield volcanoes, some in chains along a great fault, have been identified on Venus, and molten lava lakes may exist. In other places, thick lavas have oozed out to form kilometer-high, pancake-shaped domes. Radar studies have shown that some of these domes are composed of a glassy substance mixed with bubbles of trapped gas. Fan-shaped deposits adjacent to some volcanoes may be pyroclastic debris.

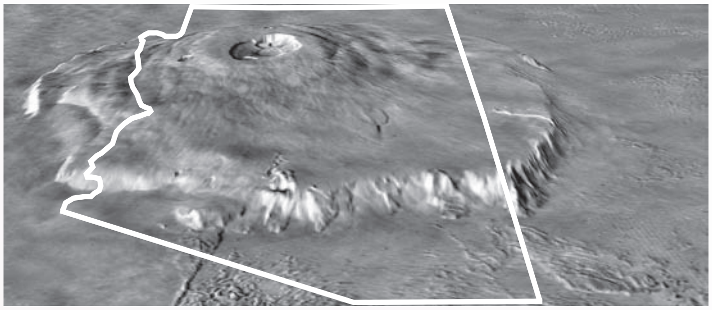
Several of Venus's volcanoes emit large amounts of sulfur gases, causing the almost continuous lightning that has been observed by spacecraft.

Nearly half of the planet Mars may be covered with volcanic material. There are areas of extensive lava flows similar to the lunar maria and a number of volcanoes, some with associated lava flows.

Mars has at least nineteen large shield volcanoes, probably composed of basalt. The largest one, Olympus Mons (box figure 1), is three times the height of Mount Everest and wider than Arizona. Its caldera is more than 90 kilometers across.

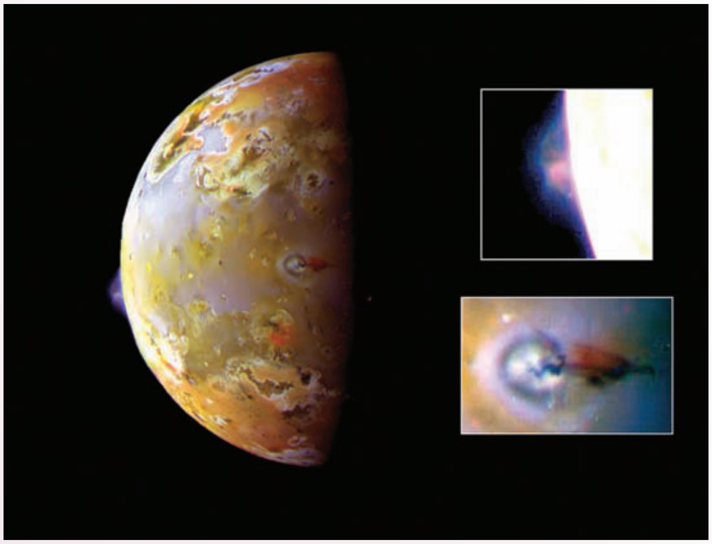
Hundreds of volcanoes have been discovered on Jupiter's moon Io (box figure 2), and some of those have erupted for periods of at least four months. Material rich in sulfur compounds is thrown at least 500 kilometers into space at speeds of up to 3,200 kilometers per hour. This material often forms umbrella-shaped clouds as it spreads out and falls back to the surface. Lakes of very hot silicate lava, perhaps mafic or ultramafic, are common. More than 100 calderas larger than 25 kilometers across have been observed, including one that vents sulfur gases. The energy source for Io's volcanoes may be the gravitational pulls of Jupiter and two of its other larger satellites, causing Io to heat up much as a piece of wire will do if it is flexed continuously.

Neptune's moon Triton is the third object in the solar system that has active volcanoes. There, "ice volcanoes" erupt what is probably nitrogen frost.



BOX 4.5 ■ FIGURE 1

Perspective view of Olympus Mons, the largest volcano and tallest mountain in the solar system. This Martian volcano is over 650 km wide and 24 km high. Note the outline of the state of Arizona for size comparison. *Photo by NASA/MOLA Science Team*



BOX 4.5 ■ FIGURE 2

Two volcanic plumes on Jupiter's moon Io. The plume on left horizon (and upper inset) is 140 kilometers high; the one in the center (and lower inset) is 75 kilometers high. For details go to photojournal.jpl.nasa.gov/catalog/PIA00703. *Photo by JPL/NASA*

Additional Resource

The Nine Planets

- www.nineplanets.org/

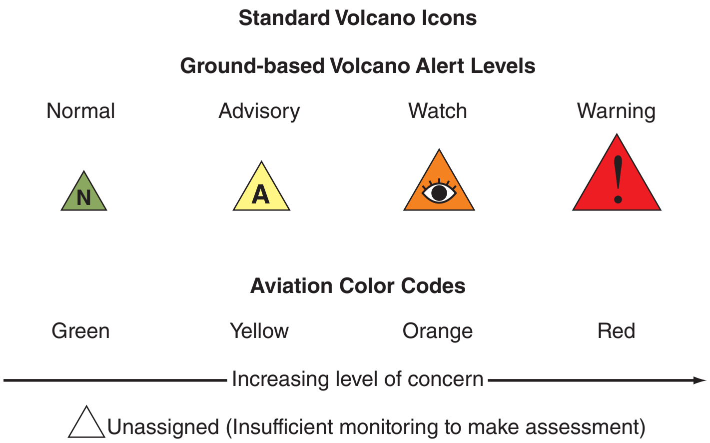


FIGURE 4.26

Icons for the U.S. Geological Survey Volcanic Activity Alert-Notification System.

hydrothermal springs activity or melting snow. Using all of this information, volcanologists can alert populations living close to a volcano that an eruption is about to occur. Alerts are also released to the aviation industry so that planes can avoid hazardous ash clouds (figure 4.26).

For more information on volcanic hazards and monitoring, visit the website of the USGS volcano hazards program at http://volcanoes.usgs.gov/.

PLATE TECTONICS AND VOLCANISM

Earlier in this chapter, we asked why it is that we can state confidently that active volcanism in Hawaii poses only slight danger to humans, but we expect violent eruptions to occur around the margins of the Pacific Ocean. You learned that the composition of a magma and the amount of gas (primarily water vapor) it contains determine whether an eruption will be effusive or explosive. In chapter 3 you learned that most magma originates in the mantle at plate boundaries. Mantle rocks only melt under particular circumstances, primarily as a result of *decompression melting* and *flux melting*. The type of melting, the composition of the magma, the amount of gas it contains, and therefore the style of eruption, are all related to plate-tectonic setting.

Volcanic Activity at Divergent Boundaries

At divergent plate boundaries, decompression melting of the asthenosphere (see figures 3.14*A* and 3.26) generates basaltic magma that contains only small amounts of water. Most of the formation of the sea floor has involved eruptions along mid-oceanic ridges. The eruptions almost always consist of mafic lavas that create basalt. As described in chapter 3, basaltic rock, thought to have been formed from lava erupting along mid-oceanic ridges and forming pillow basalts or solidifying underground beneath the ridges, makes up virtually the entire crust underlying the oceans. Iceland is one of the few places on Earth where a mid-oceanic ridge is exposed above sea level. Volcanism in Iceland is mostly effusive, dominated by eruptions of relatively fluid basaltic magma.

Volcanic Activity at Convergent Boundaries

Nearly all the larger and better-known volcanoes of the world are located on convergent plate boundaries, where oceanic lithosphere is being subducted into the mantle. Most of these volcanoes are composite volcanoes, capable of generating violent explosive eruptions. Why are convergent plate boundaries associated with explosive volcanism? Melting at convergent boundaries occurs when the subducted oceanic crust releases water into the overlying asthenosphere, lowering its melting temperature (flux melting; see figures 3.14*B* and 3.28). When the hydrated asthenosphere partially melts, the magma contains significantly more water than magma generated at divergent margins. The majority of lavas erupted along convergent margins are andesitic in composition. Andesite is more viscous than basalt. In continental volcanic arcs, where the crust is thick, magma can evolve to rhyolite, which is even more viscous than andesite. This combination of viscous lava and large amounts of water vapor is what generates explosive eruptions.

Within-Plate Volcanic Activity

Volcanic activity that occurs away from plate boundaries, within tectonic plates, is related to mantle plumes (hot spots). Mantle plumes are narrow upwellings of hot mantle material, and partial melting occurs as a result of decompression (figure 3.27). Hot spot melting is associated with large volumes of basaltic magma. The eruption of basalt in Hawaii, generating large shield volcanoes, is an example of hot spot volcanism. The large flood basalts of the Columbia Plateau are also believed to be due to a mantle plume. Some continental hot spots generate very large, caldera-forming eruptions of rhyolite (e.g., Yellowstone). This is thought to be due to melting of large amounts of thick continental crust by mafic mantle melts.

Summary

A volcano is an opening in the earth's crust through which molten lava, ash, and gases are ejected. Volcanic eruptions can be *effusive* or *explosive*. Effusive eruptions are dominated by lava flows. Explosive eruptions are dominated by pyroclastic material.

The style of eruption is controlled by the gas content and chemistry of the lava. Lava contains 45% to 75% *silica* (SiO_2). The more silica, the more viscous the lava is. Viscosity is also influenced by the temperature and gas content of the lava. Viscous lavas are associated with more violent eruptions than are fluid lavas.

The main products of effusive eruptions are lava flows. Basaltic lava flows are fluid. *Pahoehoe* lava flows have a ropy surface and *a′a* flows have a rubbly surface. *Flood basalts* are large eruptions of very fluid basalt that form thick sequences of lava flows. *Columnar jointing* develops in solidified basalt flows. Basalt that erupts underwater forms a *pillow structure.* Pillow basalts commonly form along the crests of mid-oceanic ridges. Rhyolite lava is very viscous and unless very hot, cannot flow for great distances. Felsic lava flows are very thick, often forming lava domes. Andesite lava has a viscosity intermediate between basaltic and rhyolitic lava and forms flows of intermediate thickness.

The main products of explosive eruptions are *pyroclasts,* fragments of lava that form as a result of volcanic explosions. Pyroclastic material is classified according to size. *Dust* and *ash* are the finest particles, while *lapilli* and *bombs* are the largest particles. Pyroclastic material can fall as *tephra* or can be deposited by *pyroclastic flows.*

There are five major types of volcanoes: shield, cinder cone, composite cone, lava dome, and caldera. A *shield volcano* is built up by successive eruptions of mafic lava. Its slopes are gentle, but its volume is generally large. A *cinder cone* is composed of loose pyroclastic material that forms steep slopes as it falls from the air back to near the crater. *Composite cones* are made of alternating layers of pyroclastic material and solidified lava flows. They are not as steep as cinder cones, but they are steeper than shield volcanoes. Lava domes are formed from very viscous lava that piles up over a volcanic vent. Calderas are large volcanic craters formed by the collapse of volcanoes into magma chambers.

Volcanic hazards include direct hazards such as *pyroclastic flow, pyroclastic fall,* and *volcanic mudflow* and indirect hazards such as famine. More people have been killed by pyroclastic flows and by famine than by other volcanic hazards. Volcanic hazard mitigation involves mapping of old volcanic deposits; monitoring of volcanic activity such as seismicity, gas emission, ground deformation, and heat flow; and issuing warnings to the public.

Plate tectonics helps us understand why certain types of volcanoes are common in particular regions. At divergent margins, melting of the asthenosphere driven by *decompression melting* produces basalt. Volcanic activity includes eruption of pillow basalts at mid-oceanic ridges and basaltic lava flows in Iceland. At convergent margins, explosive eruptions from composite volcanoes are common. *Flux melting* occurs when water is driven off the subducting plate into the overlying asthenosphere. Lavas erupted at convergent margins contain higher amounts of water and are commonly intermediate or felsic in composition. At hot spots, large volumes of basalt are generated in the asthenosphere. These can erupt at the surface, forming large shield volcanoes and flood basalts, or they can melt thick continental crust, forming large pyroclastic eruptions.

Terms to Remember

a′a 84
active volcano 99
ash 89
block 89
bomb 89
caldera 94
cinder 89
cinder cone 91
circum-Pacific belt 93
columnar jointing 87
composite volcano (stratovolcano) 92
crater 83
dormant volcano 99
dust 89
effusive eruption 79
explosive eruption (pyroclastic eruption) 78
extinct volcano 99
flank eruption 84
flood basalt (plateau basalt) 85
lahar 98
lapilli 89
lava dome 94
lava tube 85
Mediterranean belt 93
pahoehoe 84
pillow basalts (pillow structure) 87
pyroclast 89
pyroclastic flow 89
shield volcano 90
vent 83
viscosity 81
Volcanic Explosivity Index (VEI) 83
volcanism 78
volcano 78

Terms Covered in Chapter 3 that are Useful for Chapter 4

andesite 60
basalt 60
felsic rock 60
intermediate rock 60
lava 53
mafic rock 60
magma 53
obsidian 56
porphyritic 56
pumice 58
rhyolite 60
scoria 58
tuff 59
vesicle 57
volcanic breccia 59

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. Describe the difference between effusive and explosive eruptions in terms of their eruptive products and the hazards they pose to society.
2. What are the three main components of magma? What factors control the viscosity of magma?
3. On examining a basaltic lava flow in Hawaii, you discover that close to the vent, the lava flow has a pahoehoe texture, but further from the vent, it becomes an a′a flow. What can explain this?
4. What do pillow structures indicate about the environment of volcanism?
5. What roles do gases and viscosity play in the generation of explosive eruptions?
6. Consider the eruption of Mount Merapi, described at the beginning of this chapter and shown in figure 4.1. What kind of volcano is

Merapi? What evidence did you use to determine this? Based upon your answer, what do you think the plate tectonic setting is of Mount Merapi? What composition of lava do you think it mostly erupts?

7. Describe how a caldera forms.
8. Compare lava flows, pyroclastic flows, and lahars as volcanic hazards.
9. You are a volcanologist working on a volcano that has been active in the past but is currently quiet. What methods would you use to monitor this volcano, and what would those methods tell you about processes beneath the surface?
10. What are the three components of volcanic hazard mitigation? Provide examples of each.
11. Which of the following is an example of a shield volcano?
    a. Mount St. Helens, Washington State
    b. Mount Merapi, Indonesia
    c. Mauna Loa, Hawaii
    d. Cerro Negro, Nicaragua
12. Volcanic eruptions can affect the climate because
    a. they heat the atmosphere.
    b. volcanic dust and gas can reduce the amount of solar radiation that penetrates the atmosphere.
    c. they change the elevation of the land.
    d. all of the preceding.
13. The gas most commonly released during a volcanic eruption is
    a. water vapor. b. carbon dioxide.
    c. sulfur dioxide. d. hydrogen sulfide.
    e. oxygen.
14. _____ is a rock composed of frothy volcanic glass
    a. Obsidian b. Basalt
    c. Tuff d. Pumice
    e. Volcanic breccia
15. A lava flow with a ropy or billowy surface is called
    a. pahoehoe b. a′a
    c. pillow lava d. lahar
    e. lava tube
16. Which of these is *not* a type of pyroclastic material?
    a. ash b. dust
    c. lapilli d. a′a
    e. bomb
17. Which of these is *not* a major type of volcano?
    a. shield b. cinder cone
    c. composite d. stratovolcano
    e. spatter cone
18. An example of a composite volcano is
    a. Mount Rainier. b. Fujiyama.
    c. Mount Vesuvius. d. all of the preceding.
19. Which volcano is *not* usually made of basalt?
    a. shield b. composite cone
    c. spatter cone d. cinder cone
20. Which of the following is *not* a component of volcanic hazard mitigation?
    a. Mapping older volcanic deposits
    b. Preventing a volcanic eruption
    c. Monitoring earthquake activity around a volcano
    d. Alerting nearby residents of an imminent eruption

Expanding Your Knowledge

1. What might explain the remarkable alignment of the Cascade volcanoes?
2. What would the present-day environmental effects be for an eruption such as that which created Crater Lake?
3. Why are there no active volcanoes in the eastern parts of the United States and Canada?
4. Why are volcanic eruptions at convergent plate boundaries typically more explosive than those at divergent plate boundaries?

Exploring Web Resources

http://volcano.oregonstate.edu/

Volcano World. This is an excellent site to learn about volcanoes. Learn more about the volcanoes of the world by clicking on the Volcanoes tab. Explore volcanoes by clicking on "Fun Stuff" and selecting "Virtual Volcano Fieldtrips."

www.geo.mtu.edu/volcanoes/

Michigan Tech volcanoes page. The focus of this site is on scientific and educational information relative to volcanic hazard mitigation. Clicking on "volcanic humor" will show the lighter side of volcanology.

www.volcanolive.com/contents.html

Volcano Live. This well-organized site is maintained by an Australian volcanologist. You can link to live cameras at most of the volcanoes discussed in this chapter (Mount Fuji, Mount Erebus, Mount Etna, etc.). You can get up-to-date information on what is erupting in the world and much more.

http://hvo.wr.usgs.gov/kilauea/

Hawaii Volcano Observatory's Kilauea Website. You can find information about Kilauea, its past and present activity as well as photos taken today and during the past.

http://volcanoes.usgs.gov/publications/

Products and fact sheets of the U.S. Geological Survey's volcanic hazards program. Lists many of the USGS online fact sheets on volcanoes.

CHAPTER

20

Mountain Belts and the Continental Crust

The setting sun catches the highest peaks of the Himalaya range in Nepal. The three peaks still lit are the first (Mt. Everest, on the left), fourth (Lhotse, just to the right of Everest), and fifth (Makalu, center distance) tallest mountains in the world. In the foreground you can see the surface of the Ngozumba Glacier. *Photo by Alisha Wenzel*

LEARNING OBJECTIVES

- Distinguish between mountain, mountain range, and mountain belt.
- Compare the major features of mountain belts to cratons.
- Describe the major factors that control the growth and development of mountain ranges.
- Define an orogeny, and describe the tectonic settings associated with orogenies.
- Explain the Wilson Cycle, and relate it to the formation of mountain belts and cratons.
- Distinguish between the processes occurring during an orogeny and those believed to be responsible for post-orogenic uplift.

Mountain belts are among the most spectacular of Earth's landforms, inspiring works of art and inviting the intrepid to ascend their lofty peaks for thousands of years. But mountains are not permanent features. Under the enormous forces of plate tectonics, mountain belts can evolve from marine-deposited rocks to towering peaks during periods of tens of millions of years. Ultimately, through the influence of weathering and erosion, towering peaks are worn down to plains and become part of the stable interior of a continent. To appreciate the long and complex process of mountain building, you need to know much of the material covered in previous chapters. For instance, you must understand structural geology to appreciate what a particular pattern of folds and faults can tell us about the history of mountain building in a particular region. To understand how the rocks formed during the various stages of a mountain belt's history, you must know about volcanism, plutonism, sedimentation, and metamorphism. Your earlier study of weathering and erosion will help you understand how mountains are worn away. Plate-tectonic theory has been strikingly effective in helping geologists make sense of often complex aspects of mountain belts and the continental crust. For this reason, you may need to go back to some of the material in chapter 19, in particular the section on convergent boundaries, to appreciate how continents evolve.

In this chapter, we first point out what geologists have observed of mountain belts. Next, we describe how these observations are interpreted, particularly in light of plate-tectonic theory. Finally, we discuss current perceptions of how continents change and grow.

MOUNTAINS AND MOUNTAIN BUILDING

A mountain, as you know, is a large terrain feature that rises more or less abruptly from surrounding levels. Volcanoes are mountains; so are erosional remnants of plateaus (mesas). In this chapter, we will not focus on individual mountains; rather, we are concerned here with Earth's **major mountain belts,** chains thousands of kilometers long composed of numerous mountain ranges. A **mountain range** is a group of closely spaced mountains or parallel ridges (figure 20.1). A mountain range is likely to be composed of tectonically deformed sedimentary, volcanic, or metamorphic rocks. It may also show a history of intrusive igneous activity and volcanism.

The map in figure 20.2 shows that most of the world's mountains are in long mountain belts that extend for thousands of kilometers. The Himalaya, the Andes, the Alps, and the Appalachians are examples of major mountain belts, each comprising numerous mountain ranges.

Geologists find working in mountain ranges to be physically challenging and intellectually stimulating. High mountains have steep faces and broad exposures of bedrock. This is good because they allow a geologist to decipher complex interrelationships between rock units. But the geologist may have to become a proficient mountain climber to access the good exposures. (Conversely, mountain climbers who develop an interest in the rocks they climb sometimes become geologists.) On the other hand, exposures of bedrock critical to interpreting the local geology may be buried beneath glaciers or talus from rockfall. Furthermore, even in the highest and best exposed mountains, we never see bedrock representative of all of a mountain range. Significant amounts of rock (usually thousands of meters) once overlying the rocks we now see have been eroded away. Moreover, the present exposures are like the proverbial tips of icebergs—there is much more rock below the exposed mountain range that we cannot observe. For instance, the Himalaya, Earth's highest mountain range, rise to 8,000 meters above sea level; yet their roots (Earth's crust beneath the mountains) extend downward 65,000 meters. In other words, at best, less than one-eighth of the thickness of a mountain range is exposed to us.

Our models of how major mountain belts evolve use data from over a century of studying the geologic structures and rocks exposed in the world's many mountain ranges. Often, a particular study aims to piece together the geologic history of a single mountain range or part of a range. In other field studies, a geologist focuses on a particular type of rock exposed in a mountain range. For instance, a geologist may study the variations in metamorphic rocks in a mountainous area to determine the temperature, depth of burial, and nature of deformation during metamorphism. Geologists working on the "big picture," developing hypotheses of how major mountain belts evolve, might employ the published results of hundreds or thousands of local studies, using them as pieces of a puzzle. (Science works largely because scientists build on the work of others.) Models that currently are widely accepted regarding the evolution of mountain belts are cast within the broader framework of plate-tectonic theory and will be described later in this chapter.

Mountain belts differ from one another because each has undergone a unique combination of events that contributed to its

FIGURE 20.1

View of glaciated peaks in one of the mountain ranges in the Andes mountain belt. A parallel but much lower range is visible at the extreme right skyline of the picture. *Photo by C. C. Plummer*

FIGURE 20.2

Map of the world showing major mountain belts.

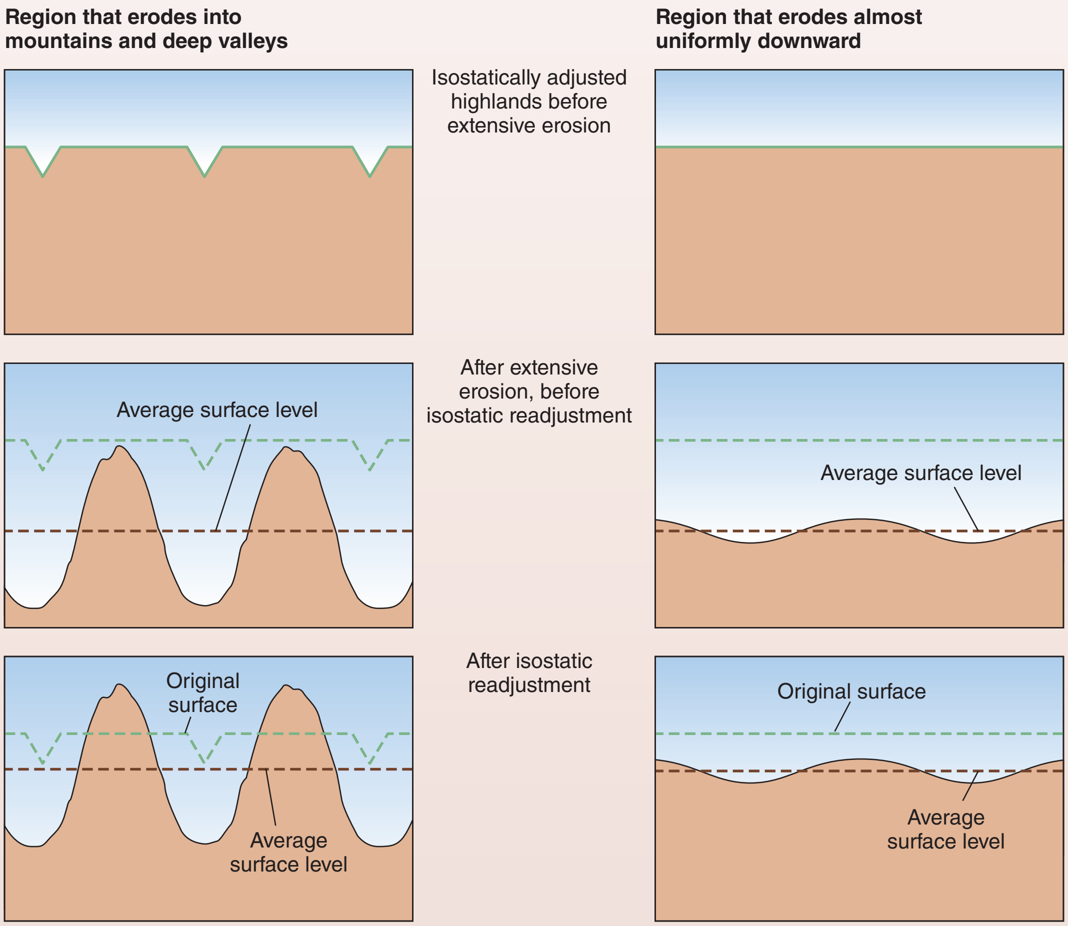
EARTH SYSTEMS 20.1

An Earth Systems Approach to Understanding Mountains

During the last couple decades, geologists have used an Earth systems approach to gain insight into the growth and wearing away of mountains. This approach regards mountains as products of three closely interdependent components: (1) tectonics (plate tectonics and isostasy), (2) climate, and (3) erosion. In other words, the atmosphere, hydrosphere, and geosphere all play a role in mountain building.

The tendency in the past has been to concentrate on tectonics to explain the growth of a mountain belt and to relegate climate and erosion to relatively minor roles. Through mountain system analyses, we gain insight into the extent to which each of the three components interacts with and changes the other two components. Climate influences erosion in obvious ways. For instance, if there is a wet climate, there will be erosion due to abundant running water at lower elevation and heavy glaciation at higher elevation. If the climate is arid, erosion will be much slower. Tectonics affects climate because if a region is uplifted to a high elevation, the climate there will be cold and glaciers can develop. With less uplift and lower mountains, erosion will be mainly due to running water. A moist climate can also result in heavy vegetation at lower elevations, which would tend to retard erosion.

Erosion and climate can influence tectonics as well. For example, the extent and type of erosion can help determine whether a highland grows higher or lower with time. If a high plateau, dissected by only a few valleys, undergoes erosion, the plateau is eroded downward uniformly (box figure 1). Following erosion, isostasy results in the plateau floating upward but not up to its original level. Its average surface, which essentially is its actual surface, is at a lower elevation than before erosion took place. If erosion carves many deep valleys and leaves relatively few mountains between the valleys, the entire regional block will have less mass and will float isostatically upward. As in the case of the plateau, its average surface would rise to a level lower than before erosion; however, its average surface is somewhere between the peaks and bottoms of valleys. Although the average height of the block rises to a level below its previous average height, the mountains rise to heights greater than before.



BOX 20.1 ■ FIGURE 1

Comparison between two regions before extensive erosion, after extensive erosion, and after isostatic readjustment. Region on the left erodes into mountains and deep valleys. Region on the right remains a plateau after approximately uniform erosion. Steepness of mountains is exaggerated.

BOX 20.1 ■ FIGURE 2

Namche Bazaar in the Nepalese Himalaya. Mountain peaks rise thousands of meters above the town. Streams have carved deep valleys below the town. *Photo by C. C. Plummer*

Climate enters the picture because, interacting with tectonics, it helps control the type and extent of weathering that takes place. For instance, heavy precipitation takes place in the Himalaya because of the flow of very humid air from the south during the summer monsoon. At the higher elevations, the precipitation in the form of heavy snowfall contributes to extensive and very active glaciation. As described in chapter 12 on glaciation, glaciers are extremely effective agents of erosion. Sharp peaks are separated by glacially carved valleys. At a lower level, streams fed by meltwater (and rainfall) deepen stream-carved valleys (box figure 2). The mountains will grow higher during isostatic adjustment at the same time the region as a whole is lowered by erosion. The Tibetan Plateau is north of the Himalaya. It is the highest, largest plateau in the world, with an average elevation of around 5 kilometers—higher than any mountain in the United States except in the state of Alaska. The plateau has not been carved into mountains because the climate is quite different from that of the Himalaya. The moist air from the south is blocked by the Himalaya, and the Tibetan Plateau is in its rain shadow (see chapter 13). Without water, there are no glaciers or large rivers to carve the plateau into mountains and deep valleys. So this region is slowly being eroded downward, getting progressively lower as erosion and isostasy balance each other out.

Additional Resource

N. Pinter and M. T. Brandon. How erosion builds mountains. *Scientific American* (April 1997): 74–79.

present characteristics. The major controlling factors that interact with one another during a mountain belt's long history are:

- *Intense deformation.* This is mainly compression and results in intense folding and faulting of sedimentary and volcanic rocks. At depth, deformation results in foliation accompanying metamorphism. Such an episode (usually lasting millions of years) of intense deformation is known as an **orogeny.** We now attribute orogenies mainly to plate convergence.
- *Isostasy.* Vertical movement of mountain belts, both during and after an orogeny, is accounted for by isostasy (described in chapters 1 and 17). Isostatic adjustment means that thicker continental crust tends to "float" higher on the mantle than does thinner crust.
- *Weathering and erosion.* The rate and nature of weathering and erosion are affected by many factors, such as the climate, type of rock, and height of a landmass above sea level. See box 20.1 for a discussion of how the interaction of the geosphere, atmosphere, and hydrosphere plays a role in forming mountains.

CHARACTERISTICS OF MAJOR MOUNTAIN BELTS

Size and Alignment

Major mountain belts are very long compared to their width. Figure 20.3 shows the two major mountain belts of North America, the *Appalachian Mountains* along the East Coast and the *North American Cordillera* in the West. Some of the better known ranges in the North American Cordillera, such as the Sierra Nevada and the Rocky Mountains, are labeled. Note that the mountain belts in North America tend to be parallel to the coastlines. However, some mountain belts elsewhere in the world (most notably the Himalaya) are not parallel to a coastline.

Ages of Mountain Belts and Continents

Although individual ranges within a mountain belt may vary considerably in height, major mountain belts with higher mountain ranges tend to be geologically younger than those where mountains are lower. The two major mountain belts of the North American continent, the Appalachian Mountains and the North American Cordillera (figure 20.3), provide a good example. The Appalachians are topographically much less prominent than the ranges of the North American Cordillera, which have many peaks of over 4,000 meters. Fossils and isotopic ages of rocks indicate that the Appalachian mountains began to evolve much earlier than the North American Cordillera. Other than isostatic adjustment, mountain building in the Appalachians ceased around 250 million years ago, while uplift continues today in some parts of the North American Cordillera.

Mountain regions commonly show evidence that they were once high above sea level during an orogeny, were eroded to

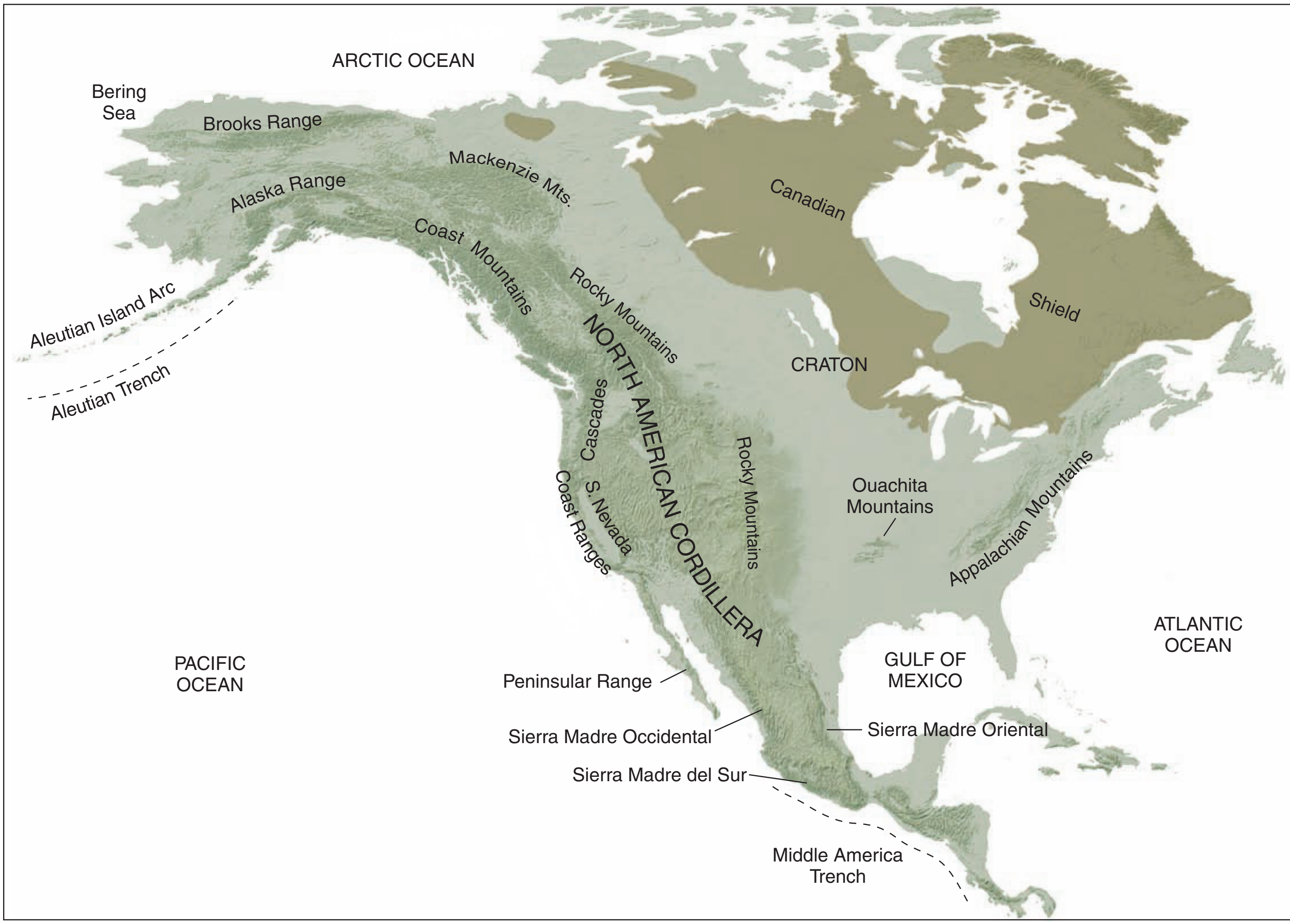


FIGURE 20.3

The mountain belts and craton (including Canadian Shield) of North America. Major ranges in the Cordillera are labeled.

hills or low plains, and then rose again in a later episode of isostatic uplift. Such episodes of uplift and erosion may occur a number of times during the long history of a mountain range. Ultimately, mountain ranges stabilize and are eroded to plains.

The interior plains between the Appalachians and the Cordillera are considered to have evolved from mountain belts in the very distant geologic past (during the Precambrian). The once deep-seated roots of the former Precambrian mountain belts are the *basement* rock for the now stable, central part of the continent. Layers of Paleozoic and younger sedimentary rock cover most of that basement. The great age of the orogenic episodes that preceded the Paleozoic sedimentation is confirmed by isotopically determined dates of over 1 billion years obtained from plutonic and metamorphic rocks in the few scattered locations where the basement is exposed. (The most noteworthy are the Grand Canyon in Arizona, the Ozark dome in Missouri, the Black Hills of South Dakota, some ranges in the Rocky Mountains, and the Adirondacks in New York.) The region of a continent that has been structurally stable for a prolonged period of time is called a **craton** (figures 20.3, 20.4, and 20.5). The central part of the United States and Canada is all part of a craton. Other continents similarly have a craton at their core.

Most of the craton in the central United States has a very thin blanket—only 1,000 to 2,000 meters—of sedimentary rock layers overlying its basement. Sediment was mostly deposited in shallow inland seas during Paleozoic time; however, for the craton in much of eastern and northern Canada, as well as Greenland, no sedimentary rocks cover the eroded remnants of old mountain ranges. This region is a **Precambrian shield**—that is, a complex of Precambrian metamorphic and plutonic rocks exposed over a large area. Such shields and basement complexes of cratons represent the roots of mountain ranges that completed the deformation process more than a billion years ago.

Thickness and Characteristics of Rock Layers

In sharp contrast to the relatively thin cover of sedimentary rock overlying the basement in a craton is the thick sedimentary sequence typical of mountain belts (figure 20.4). In mountain belts, layered sedimentary rock commonly is more than

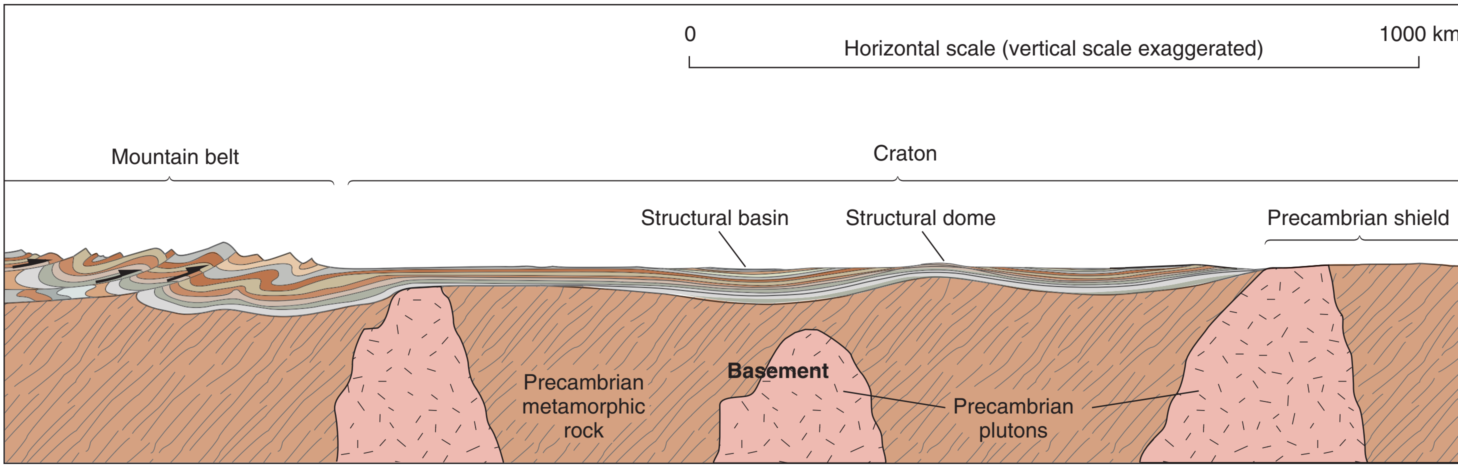


FIGURE 20.4

Schematic cross section through part of a mountain belt (left) and part of a continental interior (craton). Vertical scale is exaggerated.

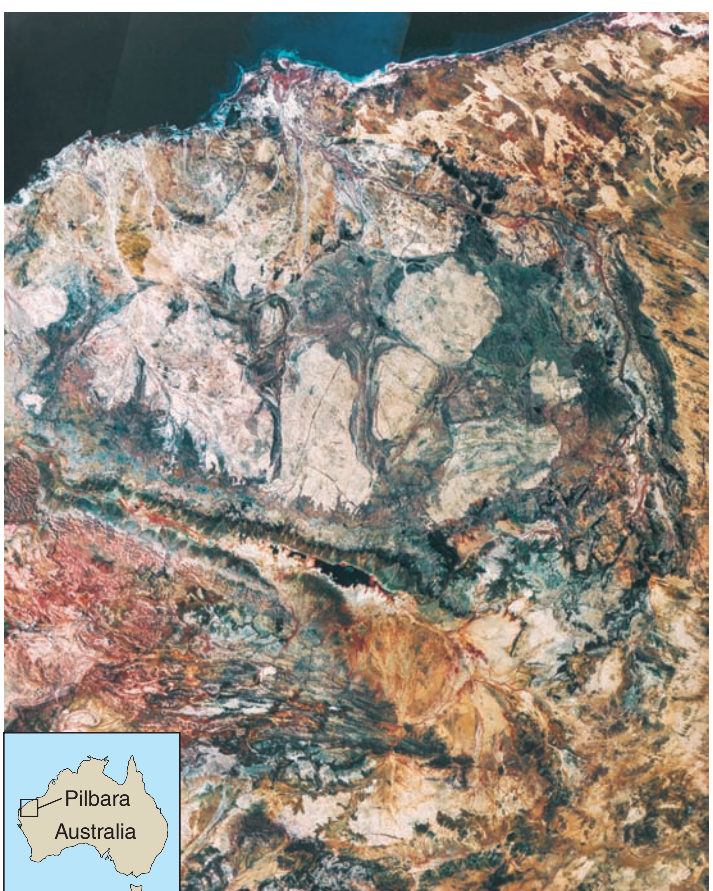


FIGURE 20.5

Satellite image of part of a craton in Western Australia. Metamorphic rock (dark gray) that is 3 billion to 3.5 billion years old surrounds oval-shaped domes of granite and gneiss (white) that are 2.8 billion to 3.3 billion years old. Gently dipping sedimentary and volcanic rocks (tan and reddish) unconformably overlie the granite-metamorphic basement complex. The area is 400 kilometers across. *Landsat mosaic produced by Satellite Remote Sensing Services, Landgate, Western Australia*

10 kilometers thick. We now know that these thick sequences of mostly marine-deposited sedimentary rock were originally deposited on continental margins (continental shelf and continental slope—see chapter 18). If the sedimentary rock is mainly shale, sandstone, and limestone, we can infer that marine deposition was at a passive continental margin. If the sediment has a significant component of volcanic material, the depositional environment was an active continental margin.

The sedimentary rock in cratons may show no deformation, or it may have been gently warped into basins and domes above the basement (figure 20.4). By contrast, mountain belts are characterized by a variety of folds and faults that indicate moderate to very intense orogenic deformation.

Patterns of Folding and Faulting

Reconstructing the original position and determining the original thickness of layers of sedimentary and volcanic rock in mountain belts are complicated because, in most instances, the layered rocks have been folded and faulted after they were deposited. As you learned in chapter 15, geologic structures can be used to interpret the direction and magnitude of the tectonic forces that formed them. (Refer to figure 20.6 as you read through the following paragraphs.) Folds will be open in those parts of a mountain belt where deformation was not very intense. Tighter folds (figure 20.7) indicate greater deformation. Large overturned and recumbent folds (figure 20.8) may be exposed in more intensely deformed portions of mountain belts. Reverse faults are common, particularly in the intensely folded regions. Especially noteworthy are the **fold and thrust belts** found in many mountainous regions. These are characterized by large thrust faults (reverse faults at a low angle to horizontal), stacked one upon another; the intervening rock usually was folded while it was being transported during faulting.

Overall, the folds and thrust faults in a mountain belt suggest tremendous squeezing or *crustal shortening* and *crustal*

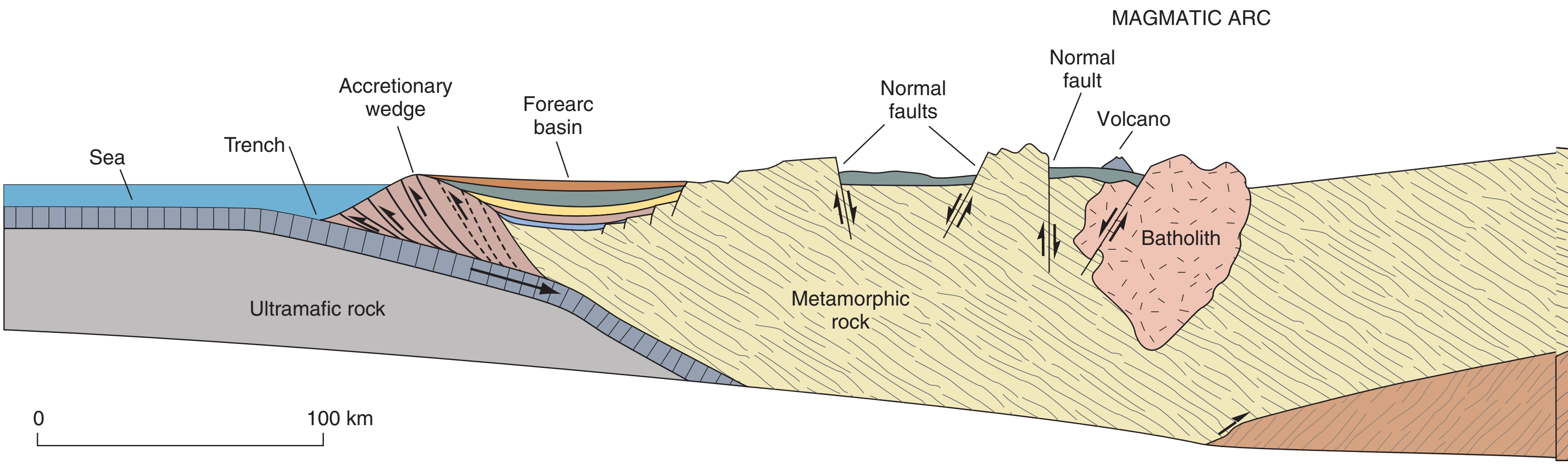


FIGURE 20.6

Cross section of an "Andean type" mountain belt; that is, one whose orogeny is due to oceanic-continental convergence. For simplicity, only a few of the many layers of sedimentary rock are shown. The size of some features is exaggerated for illustrative purposes.

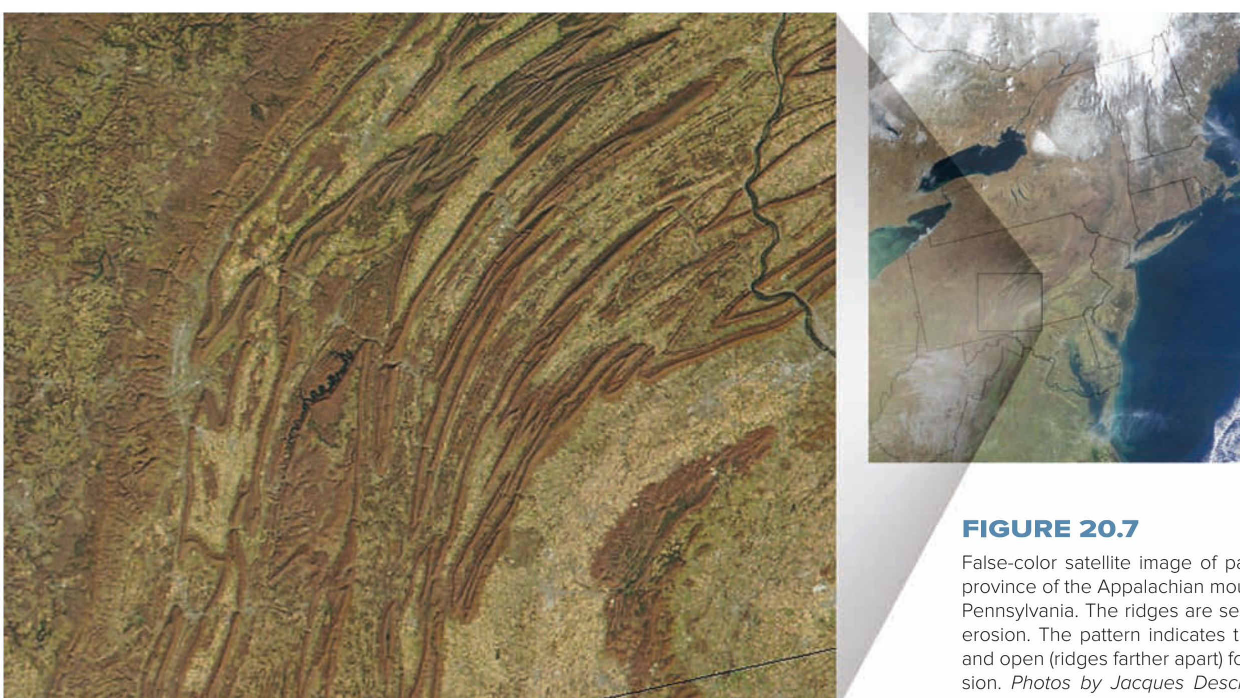


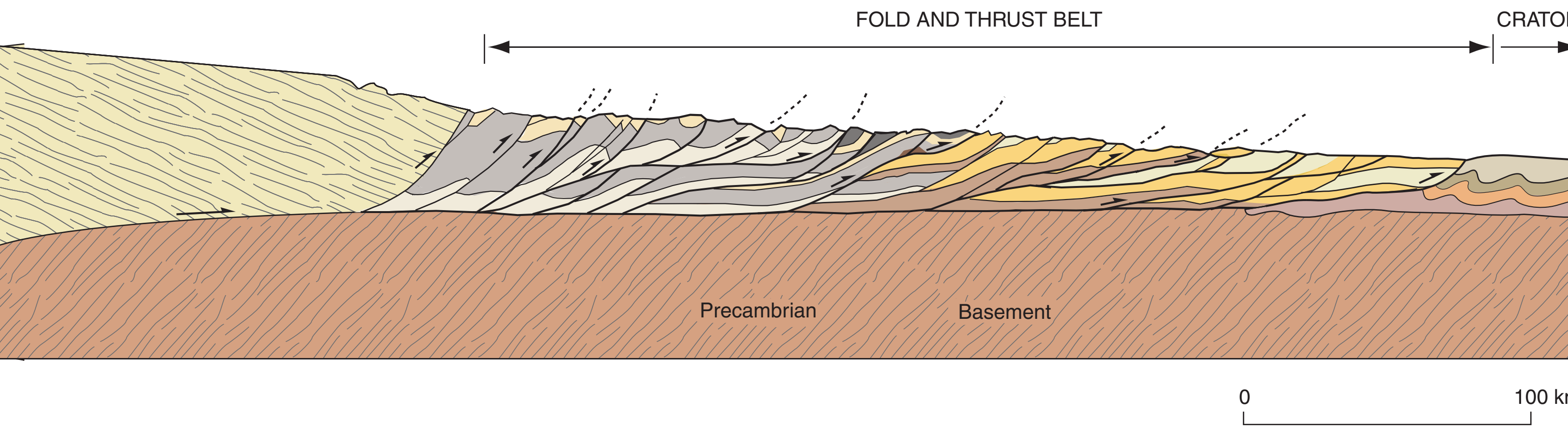
FIGURE 20.7

False-color satellite image of part of the Valley and Ridge province of the Appalachian mountain belt, near Harrisburg, Pennsylvania. The ridges are sedimentary beds resistant to erosion. The pattern indicates tight (ridges close together) and open (ridges farther apart) folding occurred prior to erosion. *Photos by Jacques Descloitres, MODIS Land Rapid Response Team, NASA/GSFC*

thickening. The sedimentary rocks of the Alps, for instance, are estimated to have covered an area of ocean floor about 500 kilometers wide when they were deposited. During the Alpine orogeny, they were compressed into the present width of the Alps, which is less than 200 kilometers (see figure 20.13).

Metamorphism and Plutonism

A complex of regional metamorphic and plutonic rock is generally found in the mountain ranges of the most intensely deformed portions of major mountain belts. Most of the metamorphic rocks were originally sedimentary and volcanic rocks that had been deeply buried and subjected to intense stress and high temperature during an orogeny. *Migmatites* (intermixed granitic and metamorphic rock, such as that shown in figure 7.19) may represent those parts of the mountain belts that were once at even deeper levels in the crust, where higher temperatures caused partial melting of the rocks (as described in chapters 3 and 7). These must have been transported into much higher levels of the crust during and after an orogeny. Batholiths, largely granitic, also have their origin in the lower crust (or uppermost mantle). Rather than remaining behind and forming migmatites, the magma generated from partial melting collects in large blobs (diapirs) that work their way upward into an upper level of Earth's crust.



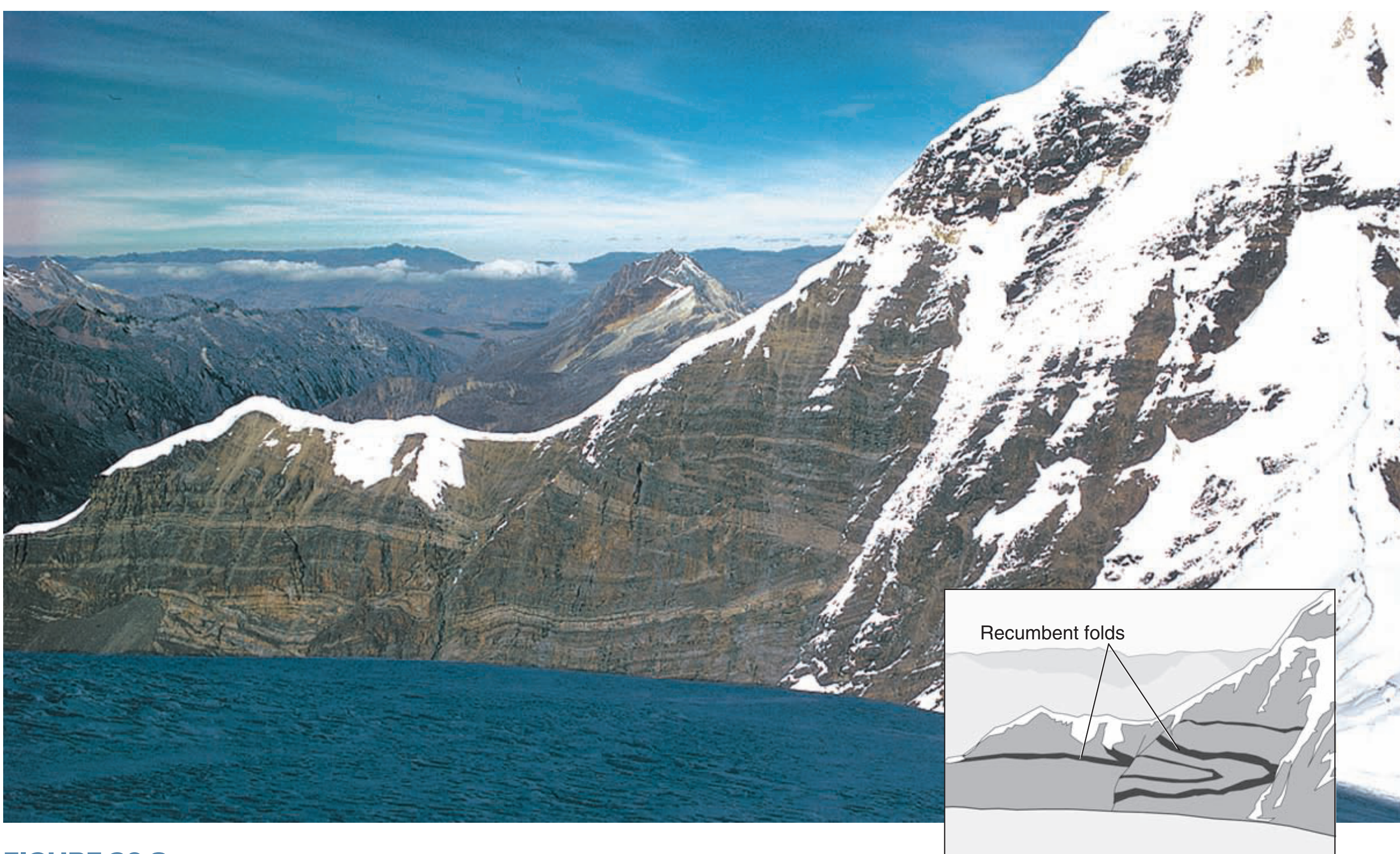


FIGURE 20.8

Recumbent folds exposed on a mountainside in the Andes. *Photo by C. C. Plummer*

Geologist's View

Normal Faulting

Older portions of some major mountain belts have undergone normal faulting (figure 20.9). Cross-cutting relationships show that the normal faulting occurs after the orogeny that resulted in tight folding, thrust faulting, and metamorphism, and after most batholiths had formed. This late stage of normal faulting (described in chapter 15 on geologic structures) is a result of *vertical uplift* or *horizontal extension.* Either of these contrasts with the overall shortening that prevailed during the orogeny.

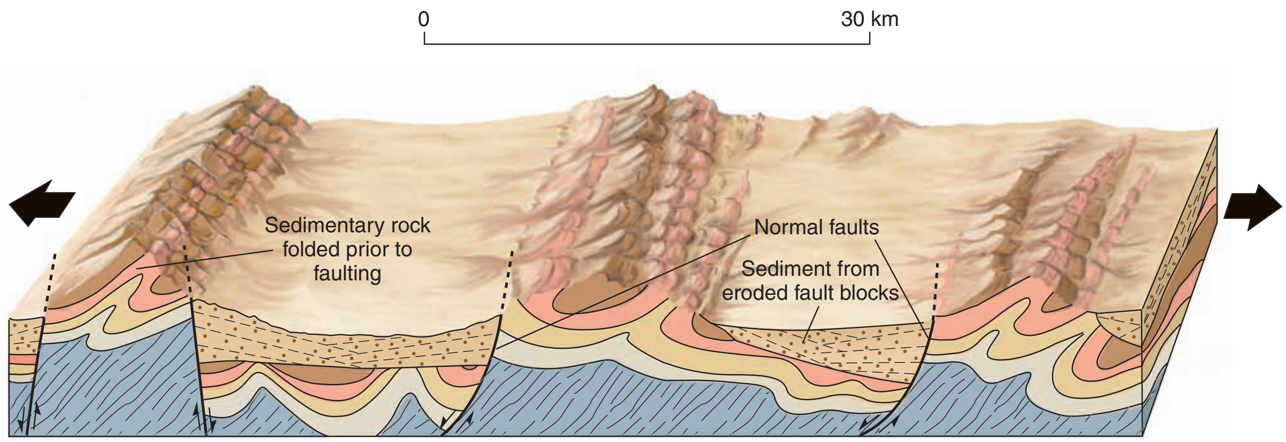


FIGURE 20.9

Fault-block mountains with movement along normal faults.

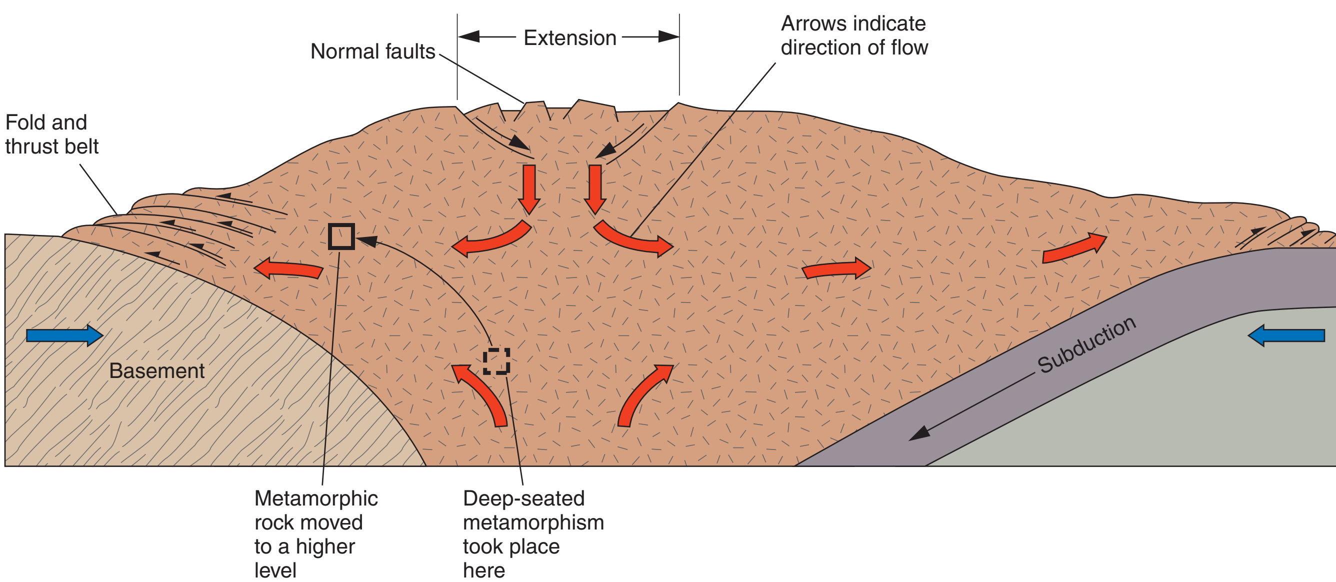


FIGURE 20.10

Schematic cross section of a mountain belt in which gravitational collapse and spreading are taking place during plate convergence. Red arrows indicate flowage of rock. Faulting occurs in brittle rock near the surface. Rock that was metamorphosed at depth flows to a higher level in the mountain belt. Not drawn to scale.

Normal faulting may also take place in the high, central part of a mountain belt during an orogeny while folding and thrust faulting are taking place at the outer parts of the belt (see figure 20.10). As the mountain belt is being compressed and shortening takes place, the central portion is pushed upward. Extension, along with normal faulting, takes place as rock at high levels flows outward over the rock being compressed at the lower level.

Thickness and Density of Rocks

Geophysical investigations yield additional information about mountains and the continental crust. As discussed in chapter 17 about Earth's interior, gravity measurements indicate that the rocks of the continental crust (including mountain belts) are lighter (less dense) than those of the oceanic crust. Seismic velocities indicate a composition approximating that of granite for continental crust. Furthermore, evidence from seismic studies supports the view that this lighter crust is much thicker beneath mountain belts than under the craton and that the crust is thicker under younger mountain belts than under older ones.

Features of Active Mountain Ranges

Frequent earthquakes are characteristic of portions of mountain belts that are geologically young and considered still active. Also, deep-ocean trenches are found parallel to many young mountain belts (the Andes, for example). Trenches lie off the coasts of island arcs, which can be regarded as very young mountain ranges. Isolated active volcanoes perched on top of older rock in a mountain range suggest that melting is still taking place at depth.

IN GREATER DEPTH 20.2

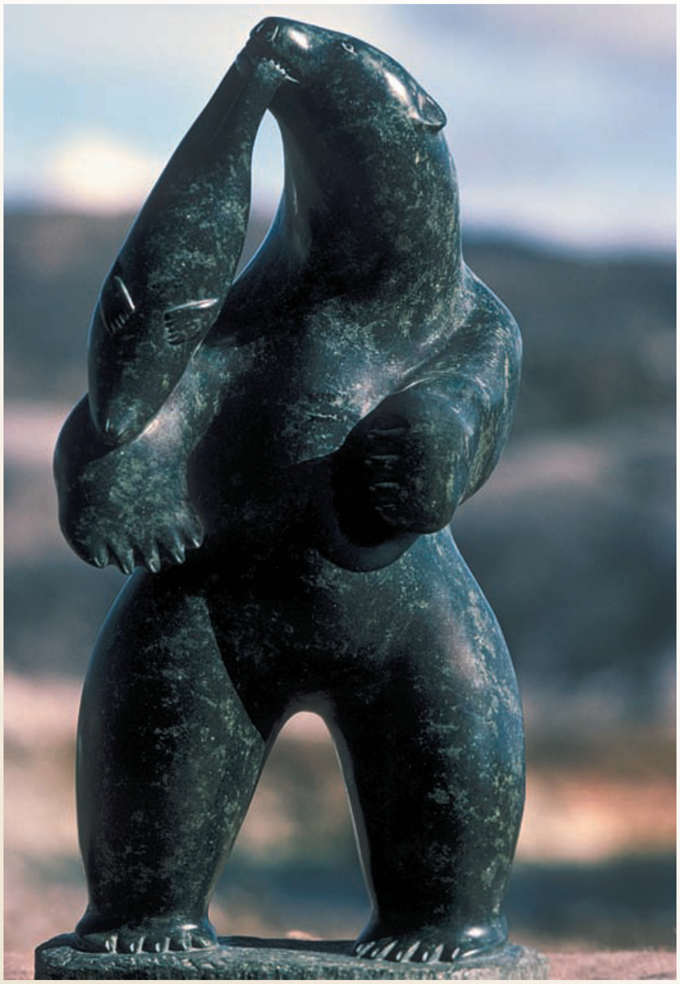
Ultramafic Rocks in Mountain Belts—From the Mantle to Talcum Powder

Ultramafic rocks (described in chapter 3 on intrusive rocks) occur commonly in the portions of mountain belts occupied by metamorphic and plutonic rocks. Ultramafic rocks tend to crop out in long, narrow zones that parallel the trend of a mountain belt. Geologists regard most bodies of ultramafic rocks as being former mantle material that was faulted into the crust during the mountain-building process. Some of the ultramafic bodies are found associated with marine-deposited volcanic and sedimentary rocks in an *ophiolite sequence* (described in chapter 18 about the sea floor). An ophiolite is regarded as a segment of a former oceanic crust together with its underlying mantle.

Ultramafic rocks in mountain belts commonly show the effect of the metamorphism that has altered adjacent rock units. Two of the foliated metamorphic products of ultramafic rocks are of special interest. One is *serpentinite,* a rock composed of the mineral serpentine. Another is a rock composed mostly of the mineral talc, commonly known as *soapstone.* Serpentine and talc are both hydrated magnesium silicates. They are products of metamorphic recrystallization of ultramafic rock when water is present. Metamorphism takes place in the crust under cooler and lower pressure conditions than those under which the original ultramafic rock formed in the mantle.

Serpentinite is a shiny, mottled, dark green and black rock that looks rather like a snake's skin. It splits apart easily along irregular, slippery, foliation surfaces. Hillsides or slopes with serpentinite as bedrock are sparsely vegetated because constant sliding prevents soil and vegetation from building up. Houses built on serpentinite hillsides (by people without a knowledge of geology) also slide downslope. Serpentinite is the official state rock of California—a state in which a large number of homes have been destroyed because they were built on sliding hillsides. (Serpentinite, however, is seldom to blame.)

Soapstone, which is less common than serpentinite, is valuable mainly because of talc's softness (number 1 on Mohs scale). Many sculptures (most notably, Inuit carvings; box figure 1) are made from soapstone because of the ease with which it can be cut. The best-known product of talc, however, is talcum powder.



BOX 20.2 ■ FIGURE 1
Soapstone (talc) sculpture, polar bear and killed seal, by Inuit artist Nalinek Temela, Baffin Island, Canada. *Photo © Fred Bruemmer/Peter Arnold/Getty Images*

EVOLUTION OF MOUNTAIN BELTS

Orogenies and Plate Convergence

As described earlier, an orogeny is an episode of intense deformation of the rocks in a region; the deformation is usually accompanied by metamorphism and igneous activity. Layered rocks are compressed into folds. Reverse faulting (especially thrust faulting) is widespread during an orogeny. Normal faulting may also occur but is not as widespread.

The more deeply buried rocks are subjected to regional metamorphism and are converted to schists and gneisses (see chapter 7). Magma generated in the deep crust or the upper mantle works its way upward to erupt in volcanoes or form batholiths (see chapter 3).

One important aspect of an orogeny is that the continental crust becomes thicker. This is achieved by the intense compression that results in tight folds and reverse faults. The addition of batholiths in the crust also helps thicken the crust and make it more buoyant. The thicker crust will isostatically "float" higher on the underlying mantle, resulting in higher mountains.

Each mountain belt has its own characteristics and history. However, by understanding which one of three kinds of plate convergence took place (described in chapter 19), we can better understand the mountain-building processes that a mountain belt underwent during an orogeny. The three types of convergence are discussed next.

Orogenies and Ocean-Continent Convergence

Figure 20.6 shows a hypothetical mountain belt that has ongoing ocean-continent convergence. The Andes, in which the South American plate is overriding the Nazca plate, is an example, and this type of mountain belt is often referred to as *Andean-type.*

Figures 3.28 and 7.21 show igneous and metamorphic processes during oceanic-continental convergence. Plate convergence also accounts for the folded and reverse-faulted layered rocks found in mountain belts. An *accretionary wedge* develops where newly formed layers of marine sediment are folded and faulted as they are scraped off the subducting oceanic plate (see figure 19.27 and explanation in chapter 19).

Rock caught in and pulled down the subduction zone is subjected to intense shearing. If rock is carried farther down the subduction zone, it becomes metamorphosed (as described in chapter 7).

Fold and thrust belts may develop on the craton (backarc) side of the mountain belt (figures 20.6 and 20.10). Thrusting is away from the magmatic arc toward the craton. The magmatic arc is at a high elevation because the crust is thicker and composed largely of hot igneous and metamorphic rocks. The large thrust sheets move toward and sometimes over the craton. (In the Rocky Mountains, thrust faulting of the craton itself has taken place.) The thrusting probably is largely due to the crustal shortening caused by convergence. There is, however, some controversy among geologists over additional processes that may take place. Some geologists regard gravity flow (from the high and mobile magmatic arc outward over the low and rigid craton) as contributing significantly to the process. Others think that the expanding magmatic arc pushes the sedimentary (and sometimes metamorphic and igneous) rocks outward to become the fold and thrust belt. (The magmatic arc is likened to a bulldozer pushing a wedge of loose material outward.)

In the late 1980s and early 1990s, geologists developed a model that explains (1) fold and thrust belts, (2) simultaneous normal faulting, and (3) how once deep-seated metamorphic rocks rise to an upper level in a mountain belt. What is believed to occur is that the thick and high part of the mountain belt becomes too high and gravitationally unstable, resulting in **gravitational collapse and spreading.** The mobile portion becomes increasingly elevated during plate convergence. This is due to compression of sedimentary and metamorphic rocks, as well as to volcanic eruptions and emplacement of plutons. After some time, the welt in the mountain belt becomes too high to be supported by the underlying rocks, and collapse begins. (Geologist John Dewey, then at Oxford University, suggested that collapse begins when the welt exceeds 3 kilometers above sea level.) As shown in figure 20.10, the gravitational collapse forces rock outward as well as downward. At deeper levels in the mountain belt, the rock is *ductile* (or *plastic*) and flows; nearer the surface, rock fractures, so movement is through faulting. The rock is pushed outward and helps create, along with crustal shortening, the fold and thrust belt.

In the high part, the outward flowing rock results in extension (figure 20.10). Therefore, the brittle, near-surface rocks fracture, and normal faulting takes place.

The flowage pattern (as shown in figure 20.10) can also explain how once deep-seated metamorphic rocks (migmatites, for example) are found in upper levels of a mountain belt. Lower crustal rocks are squeezed, forcing them to flow upward and outward, bringing them closer to the surface.

Arc-Continent Convergence

Sometimes an island arc collides with a continent (figure 20.11). As the arc and continent converge, the intervening ocean floor is destroyed by subduction. When collision occurs, the arc, like a continent, is too buoyant to be subducted. Continued convergence of the two plates may cause the remaining sea floor to break away from the arc and create a new site of subduction and a new trench seaward of the arc (figure 20.11*C*). Note that

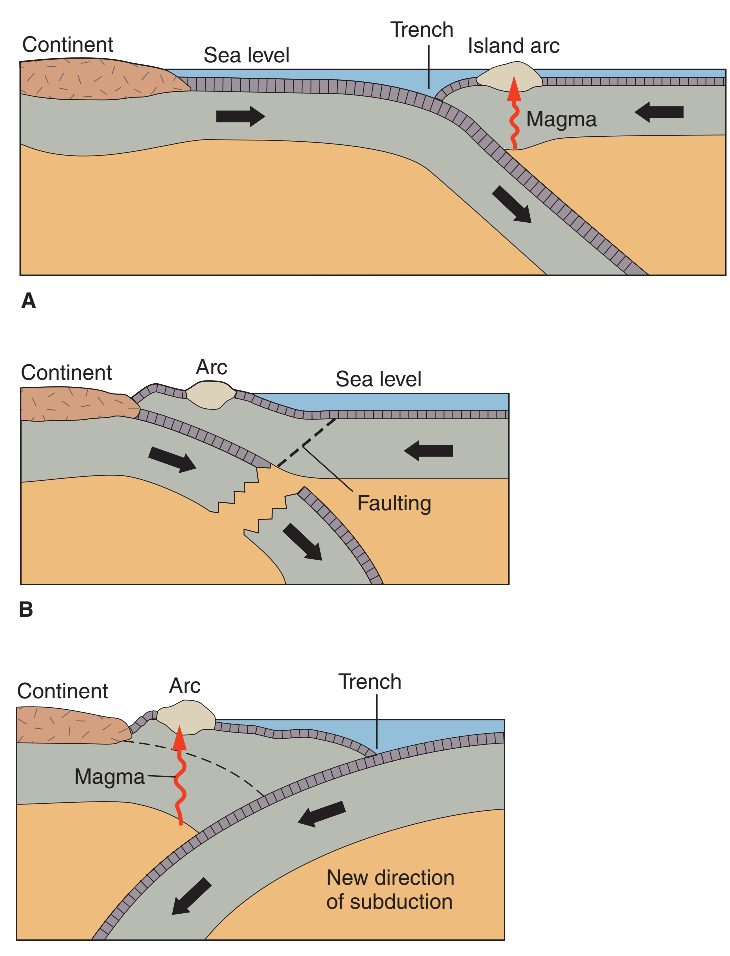


FIGURE 20.11

Arc-continent convergence can weld an island arc onto a continent. The direction of subduction can change after impact.

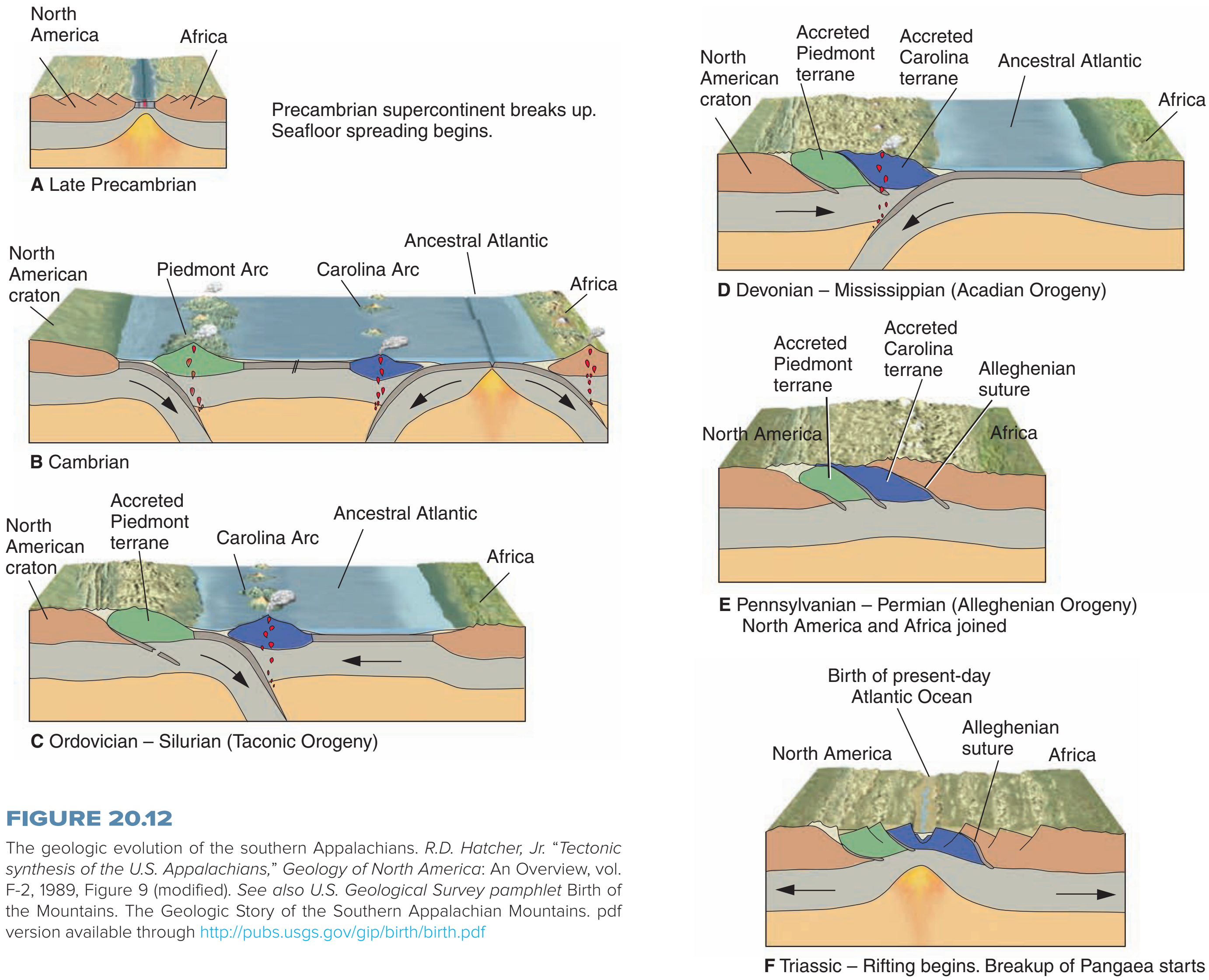


FIGURE 20.12

The geologic evolution of the southern Appalachians. *R.D. Hatcher, Jr. "Tectonic synthesis of the U.S. Appalachians," Geology of North America*: An Overview, vol. F-2, 1989, Figure 9 (modified). *See also U.S. Geological Survey pamphlet* Birth of the Mountains. The Geologic Story of the Southern Appalachian Mountains. pdf version available through http://pubs.usgs.gov/gip/birth/birth.pdf

the direction of the new subduction is opposite the direction of the original subduction (this is sometimes called a *flipping subduction zone*), but it still may supply the arc with magma. The arc has now become welded to the continent, increasing the size of the continent.

This type of collision apparently occurred during recent geologic time in northern New Guinea (north of Australia). A similar collision may have added an island arc to the Sierra Nevada complex in California during Mesozoic time, when a subduction zone may have existed in what now is central California. Many geologists think that much of westernmost North America has formed from a series of arcs colliding with North America (discussed later in this chapter in the "Displaced Terranes" section). During the Paleozoic, arc-continent collision played a significant role in the building of the Appalachians (figure 20.12).

Orogenies and Continent-Continent Convergence

As described in chapter 19 (see figure 19.28), some mountain belts form when an ocean basin closes and continents collide along a suture zone. Mountain belts that we find within continents (with cratons on either side) are believed to be products of continent-continent convergence. The Ural Mountains resulted from the collision of Asia and Europe. Convergence of the African and European plates created the Alps (figure 20.13). Our highest mountains are in the Himalayan belt. The Himalayan orogeny started around 45 million years ago as India began colliding with Asia (India was originally in the Southern Hemisphere). The thick sequences of sedimentary rocks that had built up on both continental margins were intensely faulted and folded. Fold and thrust belts developed and were carved by erosion into the mountain ranges that make up the Himalaya. The mountains are still rising, and frequent earthquakes indicate continuing tectonic activity. North of the Himalaya, Tibet rose to become what is now the highest plateau in the world. Normal faults in the Tibetan Plateau tell us that gravitational collapse is taking place.

The rate and type of erosion that takes place during an orogeny influences the height as well as the shape of mountains. The influence of climate during *isostatic uplift* of the Himalaya and Tibetan Plateau is described in box 20.1. Intense erosion also

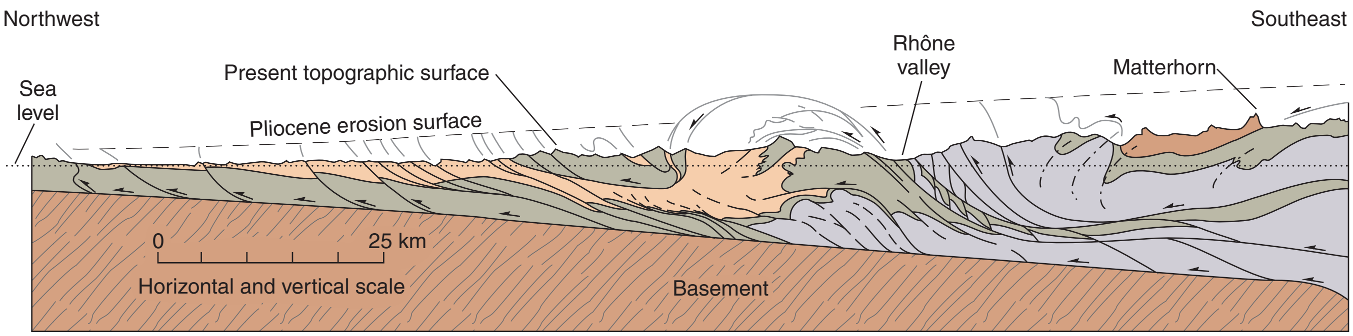


FIGURE 20.13

Cross section through part of the Alps. Thicker lines are thrust faults. Lesser folds are not shown. Movement is from the right to the left of the diagram (southeast to northwest). Only a few arrows are shown to indicate movement of the overriding thrust block. *From S. E. Boyer and D. Elliot, 1982.* AAPG Bulletin. *Reprinted by permission of American Association of Petroleum Geologists*

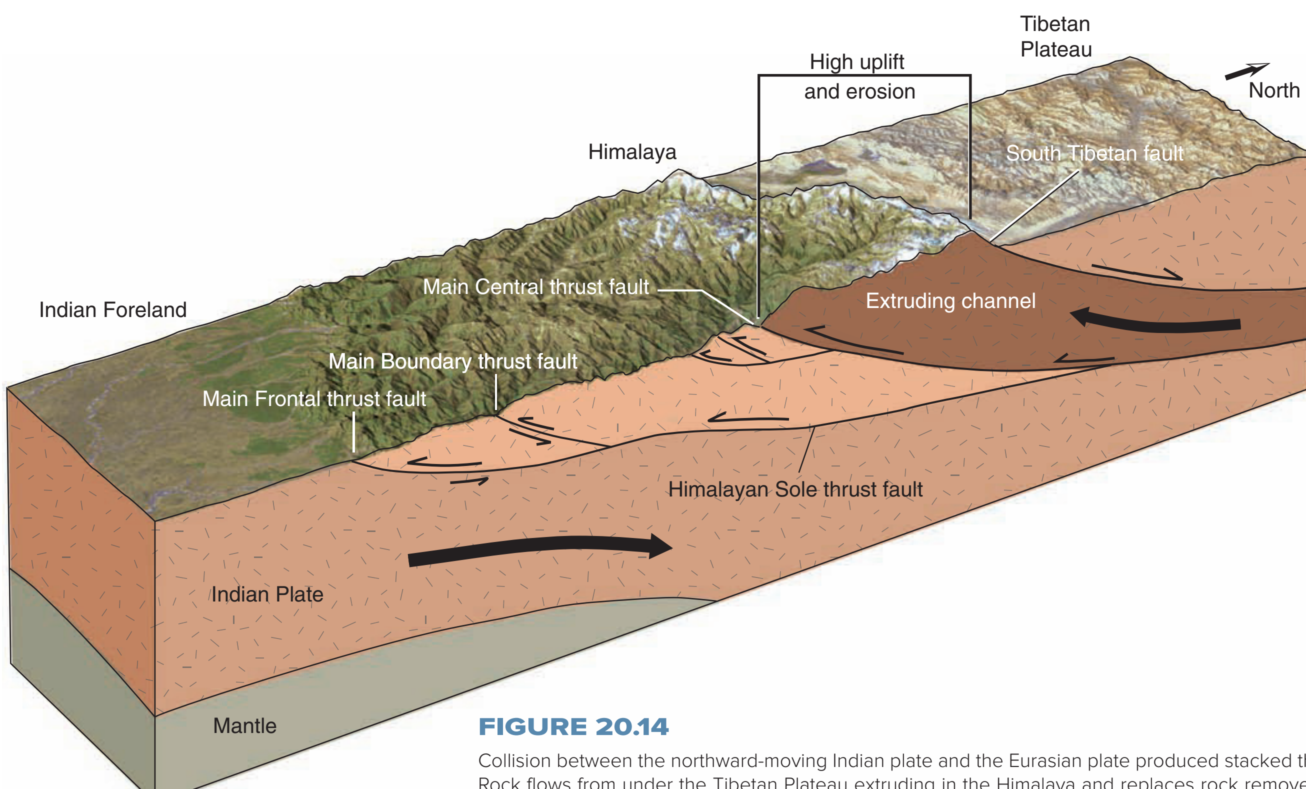


FIGURE 20.14

Collision between the northward-moving Indian plate and the Eurasian plate produced stacked thrust faults. Rock flows from under the Tibetan Plateau extruding in the Himalaya and replaces rock removed due to a high rate of erosion. *From* Scientific American, *August 2006. Reprinted by permission of Jen Christiansen*

interacts with *tectonic forces* to expedite the growth of the high Himalaya, according to a study published in 2006. Figure 20.14 shows thrust faults stacked one upon another. These were produced by the collision of India with Asia. The overall motion of the Himalaya at present is northward, as shown in figure 20.15. However, in the high Himalaya, rock is flowing underground and replacing rock eroded away at the surface. This is the block between the South Tibetan fault and the Main Central thrust fault shown in figure 20.14. According to the hypothesis, the rock here is being extruded from deep under the Tibetan Plateau due to the ongoing collapse of the Tibetan Plateau. Rock that is ductile (or plastic) at depth is squeezed and extruded toward a zone of least resistance. The zone of least resistance is where erosion is taking place at an exceptionally high rate because of the high precipitation of rain and snow during monsoons on the steep slopes of the high Himalaya.[1]

The collision of India and Asia has affected parts of Asia well beyond the Himalaya and Tibet. Figure 20.15 shows present-day crustal motion in and around the Himalaya and Tibet. As India continues to push northward, some of the motion is deflected from Tibet eastward into China. Box 19.1, figure 1 in the plate tectonics chapter shows major fault systems

[1]For more, including supporting evidence, read Kip Hodges, Climate and the evolution of mountains. *Scientific American* (August 2006): 72–79.

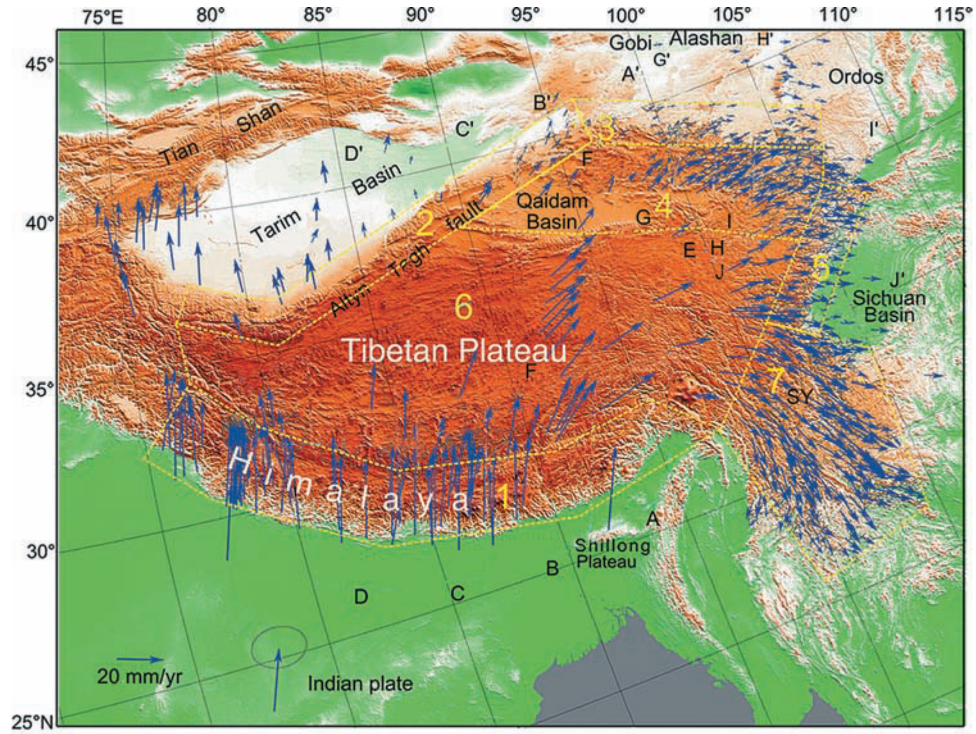


FIGURE 20.15

Motion in and around Tibetan plateau as determined through Global Positioning System (GPS) measurements. Blue arrows point in the direction of motion and their lengths indicate velocities (millimeters/year). The scale in the lower left corner indicates the length of an arrow for 20 millimeters/year. Dashed yellow polygons show regions—for instance, 1 is the Himalaya, 6 the Tibet Plateau. *Pei-Zhen Zhang, et al. "Continuous deformation of the Tibetan Plateau from global positioning system data," Geology, vol. 32, no. 9, p. 810, Figure 1.* Copyright © by the Geological Society of America. All rights reserved. Used with permission.

extending through China and neighboring countries and their relationships to the ongoing plate collision. China's disastrous 2008 earthquake was caused by fault motion along the Sichuan Basin (right side of figure 20.15) and was indirectly caused by the collision of India and Asia.

The Appalachian Mountains are an example of continent-continent convergence but with a more complicated history. Arc-continent convergence and oceanic-continental convergence were also involved, and the mountain belt was later split apart by plate divergence.

A condensed version of orogeny in the Appalachians is as follows (figure 20.12): During late Precambrian and earliest Paleozoic time, the ancestral Atlantic Ocean developed as seafloor spreading forced the passive margins of North America, Europe, and Africa away from one another. During the Paleozoic, plate motion shifted, subduction began, and the ocean basin began closing. Island arcs developed between the continents. These became plastered onto the North American craton as the ancestral Atlantic basin closed. A couple hundred million years after subduction began, the ocean basin closed completely, first with Europe and later with Africa crashing into North America. By the end of the Paleozoic, the three continents were sutured together. The Appalachians and what is now the Caledonide mountain belt of Great Britain and Norway and the Atlas Mountains of North Africa were part of a single mountain belt within the supercontinent *Pangaea.* The mountain belt was comparable to the present-day Himalaya.

Early in the Mesozoic Era, the supercontinent split, roughly parallel to the old suture zone. The present continents moved (and continue to move) farther and farther away from their present divergent boundary, the mid-Atlantic ridge.

What happened to the Appalachians seems implausible. Yet, if one accepts the principles of plate-tectonic theory and examines the rocks and structures in the Appalachians (and their counterparts in Europe and Africa), the argument for this sequence of events is not only plausible but convincing.

The cycle of splitting of a supercontinent, opening of an ocean basin, followed by closing of the basin and collision of continents is known as the *Wilson Cycle.* Canadian geologist J. Tuzo Wilson proposed the cycle in the 1960s for the tectonic history of the Appalachians.

The Wilson Cycle apparently has occurred before. A question raised is why would a continent split apart more or less along a suture zone where one would expect the crust to be thickest? One recently proposed hypothesis is that this zone is weakened and thinned somewhat by outward flow of rock during gravitational collapse and spreading. (Another hypothesis involves *delamination,* detachment and sinking downward of the underlying lithospheric mantle, as described on p. 502.)

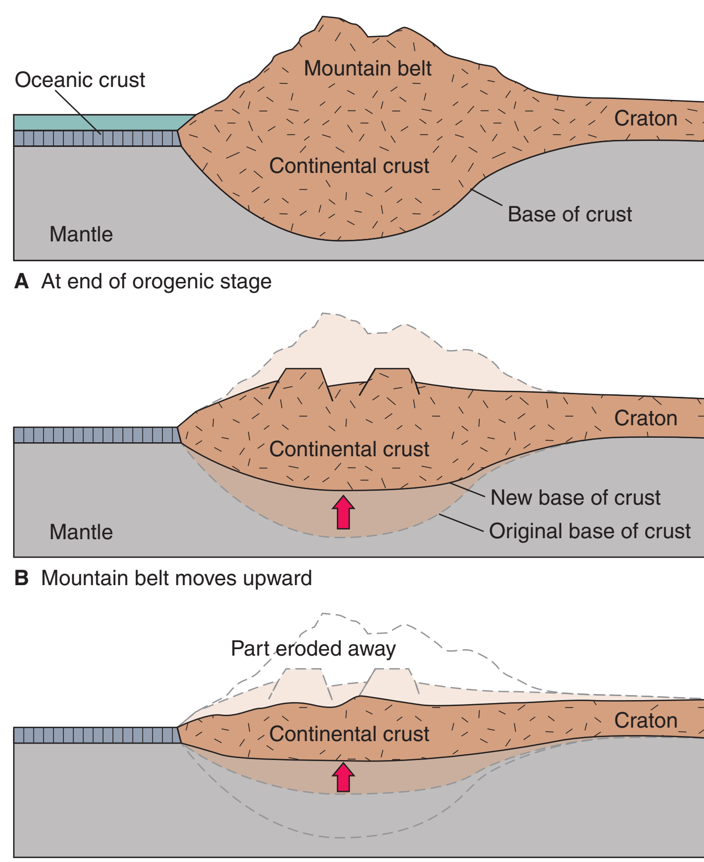
Post-Orogenic Uplift and Block-Faulting

After an orogeny ceases to affect part or all of a mountain belt and the prevailing compressive force is relaxed, there is a long period of uplift accompanied by erosion. Isostatic adjustment takes place during orogeny, but it is typically overshadowed by the compressive horizontal forces of plate convergence. When horizontal forces become insignificant at the end of an orogeny, isostatic adjustment takes over as the dominant process. For many millions of years, large regions in the mountain belt move vertically upward. Erosion may keep pace with uplift, and the area remains low. Alternatively, uplift may temporarily outpace erosion, resulting in plateaus or mountain ranges. The present Appalachian Mountains are the result of uplift and erosion that have taken place long after the last orogeny ended more than 250 million years ago. It is likely that the Appalachian Mountains eroded down to a plain after the last Paleozoic orogeny. The coastal plain east of the Appalachians is made of young sedimentary rock unconformably overlying metamorphic and igneous rocks that were part of the original mountain belt. This region has remained a plain. The present Appalachians represent rejuvenation following relatively recent uplift in late Tertiary time. The uplift may have been due to reactivation of ancient thrust faults caused by compressive stress within the westward-moving North American plate. The coastal plains have not moved upward, probably due to a lack of thrust faults. So the topography of the Appalachians is geologically quite young, while the original structures due to orogenic deformation are quite old. The Adirondack Mountains of northern New York also participated in the uplift and rejuvenation, but the orogeny that they went through is Precambrian—much older than the Appalachian orogenies. Eventually, the entire Appalachian mountain belt will be eroded to a plain and become part of the North American craton.

Isostasy

According to the concept of isostasy, lighter, less-dense continental crust "floats" higher on the mantle than the denser oceanic crust. A craton has achieved an equilibrium and is floating at the proper level for its thickness. Mountains, being thicker continental crust, "float" higher than the stable craton. As material is removed from mountains by erosion, the range floats upward to regain its isostatic balance (figure 20.16). This process can be thought of as "the pull of erosion." Isostatic adjustment does not take place instantaneously. Usually, there will be a considerable time lag between erosion and isostatic adjustment. As the mountains wear down to a low plain, erosion becomes virtually ineffective and the now thin crust achieves isostatic balance; the former mountain belt becomes part of the craton. The reason a craton consists of plutonic and metamorphic rock is that these were the rocks that formed the deep roots of the former mountain belt.

At most places on continents, the altitude above sea level is related to local crustal thickness. Beneath the 5-kilometer-high Tibetan Plateau, the crust is 75 kilometers thick. Under Kansas, the crust is 44 kilometers thick, and beneath Denver, the "mile-high city," the crust is 50 kilometers thick. (If the United States ever joins the rest of the world and goes metric, Denver will be known as the "1.6 kilometer-high city.") Just west of Denver, the altitude of the Rocky Mountains jumps to 2 kilometers higher than that at Denver. Scientists expected to find a corresponding thickening of the crust beneath these mountains. They were surprised by 1995 seismic studies that indicated that the crust is no thicker beneath the Rockies than at Denver. (Similar discrepancies between crustal thickness and mountain elevations have been reported for the southern Sierra Nevada.) Geologists explain the higher elevations by regarding the mantle as hotter and therefore less dense beneath that part of the Rockies. The crust plus less-dense mantle are floating on deeper, denser mantle. Seismic wave studies verify that the mantle here is hot and appears to be asthenosphere that is at a shallower level in Earth than usual.



A At end of orogenic stage

B Mountain belt moves upward

C Erosion and renewed uplift continue until crust beneath mountain belt is the same thickness as that of the craton

FIGURE 20.16

Isostasy in a mountain belt. The thickness of the continental crust is exaggerated.

Normal Faulting

Normal faults develop after orogenies in several settings. One is when a continent is split and a divergent boundary forms (see chapter 19). An example is the breakup of Pangaea in the early Mesozoic, after the final orogeny in the Appalachians (figure 20.12*F*) and counterpart mountains in Africa and Europe. A normal fault will also develop if part of the crust moves upward isostatically more than does adjoining crust.

In parts of some mountain belts, the crust breaks into fault-bounded blocks. If an upthrown block is large enough, it becomes a **fault-block mountain range.** The normal faulting implies a *horizontal extension strain,* the regional pulling apart of the crust. Isostatic vertical adjustment of a fault block probably occurs at the same time.

Fault-block mountain ranges are bounded by normal faults on either side of the range, or, more commonly, are tilted fault blocks in which the uplift has been great along one side of the range, while the other side of the range has pivoted as if hinged (figure 20.17). The Sierra Nevada (California) and Teton (Wyoming) Range are tilted fault-block mountains (figure 20.18).

Isolated volcanic activity may be associated with some faults. Eruptions occur along faults extending deep into the crust or the upper mantle.

Uplift is neither rapid nor continuous. Part of a mountain range may suddenly move upward a few centimeters (or, more rarely, a few meters) and then not move again for hundreds of years. Erosion works relentlessly on newly uplifted mountains, carving the block into peaks during the long, spasmodic rise. Over the long time period, the later episodes of renewed faulting and uplift involve successively less and less vertical movement.

Block-faulting is taking place in much of the western United States—the Basin and Range province (also called the Great Basin) of Nevada and parts of Utah, Arizona, New Mexico, Idaho, and California (figure 20.19). Hundreds of small, block-faulted mountain ranges are in evidence. They are separated by valleys that are filling with debris eroded from the mountains. Extension in the Basin and Range is probably due to hotter mantle beneath the crust as shown in figure 20.20.

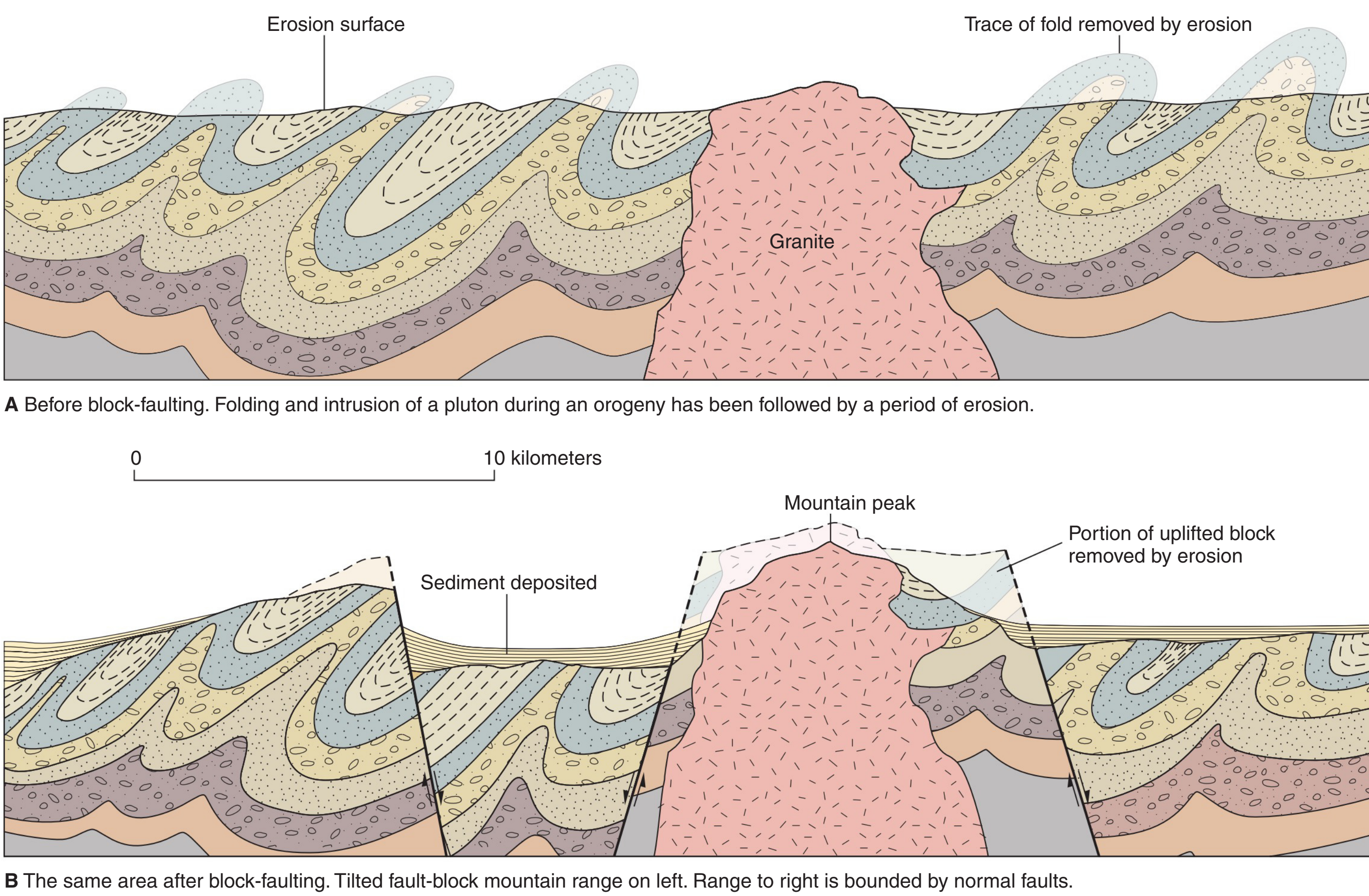


FIGURE 20.17

Development of fault-block mountain ranges.

FIGURE 20.18

The Teton Range, Wyoming, a tilted fault-block range. The rocks exposed are Precambrian metamorphic and igneous rocks that were faulted upward. Extensive past glaciation is largely responsible for their rugged nature. For more information, go to www.winona.edu/geology/travels/tetons/travel.html. *Photo by C. C. Plummer*

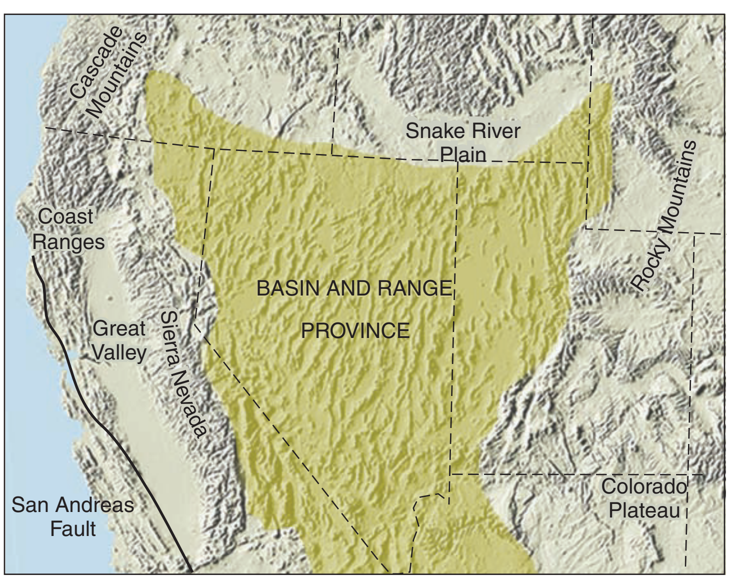


FIGURE 20.19

The Basin and Range and adjoining geological provinces.

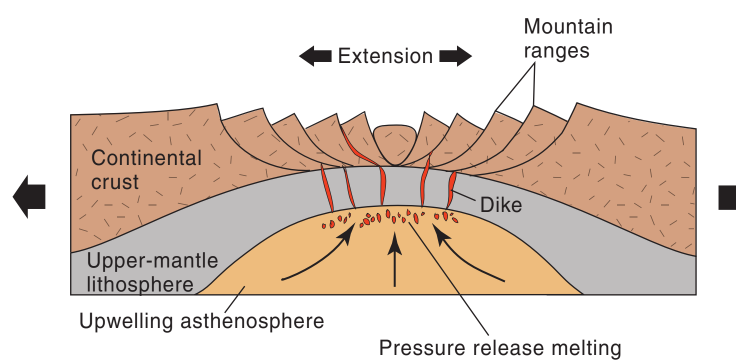


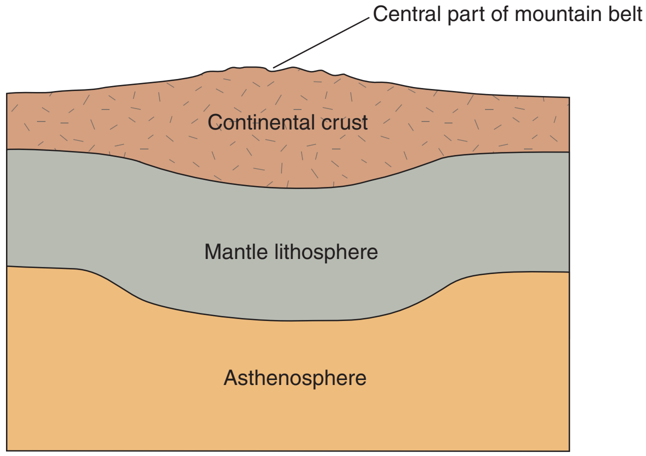
FIGURE 20.20

Upwelling, hot, buoyant mantle (asthenosphere) causes extension, thinning, and block-faulting of the overlying crust.

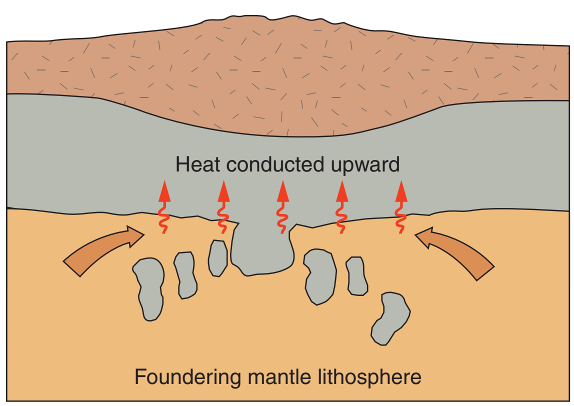
Delamination

The hypothesis of lithospheric delamination is used to explain the block-faulting, thin crust, and geologically young volcanic activity of the Basin and Range. **Lithospheric delamination** (or simply **delamination**) is the detachment of part of the mantle portion of the lithosphere beneath a mountain belt (figure 20.21). As you know, the lithosphere consists of the crust and the underlying, rigid mantle. Beneath the lithosphere is the hotter, ductile mantle of the asthenosphere. During an orogeny, the crust as well as the underlying lithospheric mantle thickens. The lithospheric mantle is cooler and denser than the asthenospheric mantle. As indicated in figure 20.21, the thickened portion of the lithospheric mantle is gravitationally unstable, so after it is softened from convecting asthenosphere, it breaks off and sinks through the asthenosphere to a lower level in the mantle. Hot asthenospheric mantle flows in to replace the foundered, colder mantle. Heating of the crust follows, allowing the lower crust to flow. The once-thick crust becomes thinner than that of adjoining regions of the mountain belt. Extension results in block-faulting in the upper part of the crust (as in figures 20.20 and 20.21*C*).

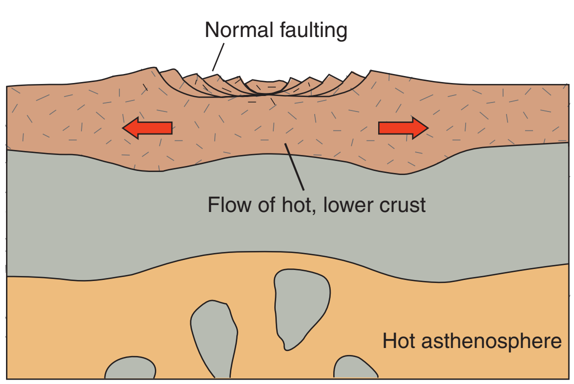
Delamination beneath the Basin and Range helps explain the extensive rhyolitic and basaltic eruptions that occurred tens



A Thick continental crust of a mountain belt produced during orogeny.



B Delamination of gravitationally unstable mantle lithosphere. Hot asthenosphere flows and replaces foundering lithosphere, heating overlying lithosphere.



C Extension with hot, lower crust flows outward.

FIGURE 20.21

Delamination and thinning of continental crust following orogeny. (Not drawn to scale.)

of millions of years after the end of the last orogeny. Heating in the lower part of the crust to 700°C would have generated silicic magma that erupted as rhyolite. Basaltic magma would have formed from partial melting of the asthenosphere when it moved upward (replacing the foundered lithospheric mantle) and pressure was reduced (as explained in chapter 3). That the crust was once thicker in the Basin and Range is supported by recent studies of fossil plants indicating that the Basin and Range was 3 kilometers higher than at present.

Delamination is also being invoked to help explain why, when Pangaea broke up, North America split from Europe and Africa more or less along the old suture zone. *Gravitational collapse* could have contributed to the weakening and thinning of this once-thick part of the mountain belt during its last orogeny. The breakup of the supercontinent began around 30 million years after the late Paleozoic orogeny ended. Delamination of the underlying lithospheric mantle would have resulted in heating and thinning of the overlying, remaining lithosphere. Rifting of the supercontinent began with normal faulting (see chapter 19 and figure 19.20) and was accompanied by basaltic eruptions and intrusions. The Appalachians split from the European Caledonides. Europe, Africa, and North America went their separate ways as the Atlantic opened and widened.

Recently, delamination has been used to explain part of what takes place during an orogeny (see box 20.3).

Delamination (like gravity collapse) is an example of a hypothesis that builds on plate-tectonic theory. It was proposed because it explains data better than other concepts do. It still needs further testing to become widely accepted as a theory.

THE GROWTH OF CONTINENTS

Continents grow bigger as mountain belts evolve along their margins. Accumulation of sediment and igneous activity add new continental crust beyond former coastlines. In the Paleozoic Era, the Appalachians were added to eastern North America, and during the Mesozoic and Cenozoic Eras, the continent grew westward because of accumulation and orogenic processes in many parts of what is now the Cordillera. Therefore, if we isotopically dated rocks that had been through an orogeny, starting in the Canadian Shield and working toward the east and west coasts, we should find the rocks to be progressively younger. In a very general way, this seems to be the case; however, there are some rather glaring exceptions.

Displaced Terranes

In some regions of mountain belts, the age and characteristics of the bedrock appear unrelated to that of adjacent regions. To better understand the geology of mountain belts, geologists have in recent decades begun dividing major mountain belts into **tectonostratigraphic terranes** (or, more simply, **terranes**), regions within which there is geologic continuity. The geology in one terrane is markedly different from that of a neighboring terrane. Terrane boundaries are usually faults.

IN GREATER DEPTH 20.3

Rise of the Andes during Plate Convergence

The Andes is Earth's second-highest mountain belt. It is the product of oceanic-continental convergence between the western-moving South American plate and subduction of the Nazca oceanic plate. The resulting orogeny has been ongoing for the last 50 million years. A group of scientists, using a multidisciplinary approach, determined the rate of increase in elevation for the Central Andes through time. In 2008, Carmata Garzione and coauthors described their research and conclusions:

During the first 40 million years of the orogeny, crustal shortening and thickening of the lithosphere took place, resulting in a slow but steady rise in surface elevation. But, until approximately 10 million years ago (Ma), the surface elevations were anomalously low. The rate of vertical growth increased beginning around 10 Ma. The high rate of uplift continued until 6 Ma when the Andes approached their present heights.

The authors attribute the slow rising prior to 10 Ma to dense rock in the lower crust and lithospheric mantle. These denser rocks kept the thickening upper crust from reaching the isostatic level expected from less-dense crust. Between 10 and 6 Ma, the denser rock was removed from the overlying, less-dense crust, likely through lithospheric delamination. The less-dense crust, now overlying hotter and less-dense mantle, rose isostatically at a more rapid rate. Mountain topography became considerably more elevated as it approached heights of the present Andes.

Reference:

C.N. Garzione, G.D. Hoke, J.C. Libarkin, S. Withers, B. MacFadden, J. Eiler, P. Ghosh, A. Mulch. Rise of the Andes. 2008. *Science,* vol. 320, pp. 1304–1307.

Typically, a terrane covers thousands of square kilometers, but some terranes are considerably smaller. Alaska and western Canada have been subdivided by some geologists into over fifty terranes (figure 20.22). Terranes are named after major geographic features; for instance, Wrangellia, parts of which are now in Alaska and Canada (with fragments in Washington and Idaho, according to some geologists) was named after the Wrangell Mountains of Alaska.

Many terranes appear to have formed essentially in place as a result of accumulation and orogeny along the continent's margin. Other terranes have rock types and ages that do not seem related to the rest of the geology of the mountain belt and have been called **suspect terranes,** that is, terranes that may not have formed at their present site. If evidence indicates that a terrane did not form at its present site on a continent, it is regarded as an **accreted terrane.** Accreted terranes that can be shown to have traveled great distances are known as *exotic terranes.*

A suspect terrane will have rock types and ages different from adjoining terranes, but to prove that it came from elsewhere in the world (and therefore is an accreted terrane), geologists may compare fossil assemblages or determine the paleomagnetic poles (see chapter 19) of the terrane's rocks. If the terrane is exotic, its fossil assemblage should indicate a very different climatic or environmental setting compared to that of the adjoining terrane. (For example, the Cache Creek terrane in western Canada contains fossils from the Permian period that indicate a marine equatorial environment.) For an exotic terrane, the paleomagnetic poles for the rocks in the terrane will plot at some part of the world very distant from poles of adjoining terranes that formed in place. This indicates that a particular terrane formed in a different part of Earth and drifted into the continent of which it is now a part. Some

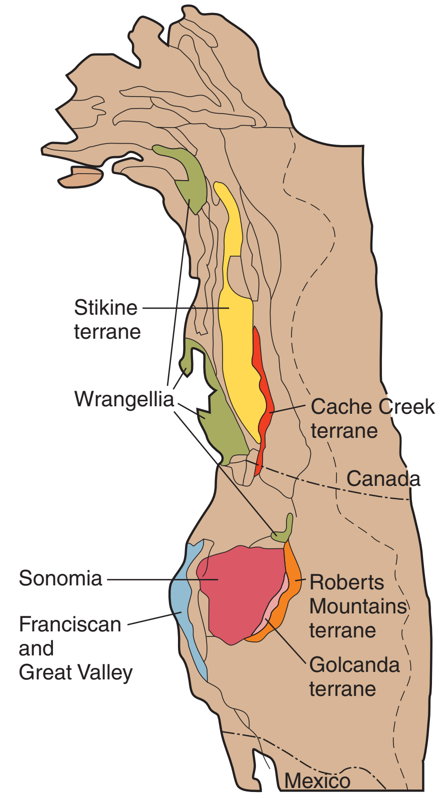


FIGURE 20.22

Some terranes in western North America. Note: Wrangellia is in Alaska, British Columbia, and Idaho. *After U.S. Geological Survey Open File Map 83–716* accreted terranes were island arcs, and some might have been *microcontinents* (such as present-day New Zealand) that moved considerable distances before crashing into other landmasses. Others may have been fragments of distant continents that split off and moved a long distance because of transform faulting. Imagine what might happen if the San Andreas fault remains active for another 100 million years or so. Not only would Los Angeles continue northward toward San Francisco and bypass it in about 25 million years (see box 15.2), but the block of coastal California west of the fault would continue moving out to sea, becoming a large island with continental crust that drifts northward across the Pacific. Ultimately, it would crash into and suture onto Alaska.

The Appalachians as well as mountain belts in other continents have also been divided into terranes. Even the Canadian Shield has been subdivided into terranes. Some geologists think they can determine, despite the great age and complexity of the shield's rocks, the extent to which some terranes traveled before crashing together.

We should caution the reader that geologists do not always agree on the nature and boundaries of terranes. While most would probably agree that some terranes are exotic, many geologists think the subdividing of Alaska and western Canada into fifty terranes is overdoing it and not supported by sufficient evidence. Only time and more painstaking gathering of evidence will allow geologists to determine the history of each alleged terrane.

Concluding Comment

Only a few decades ago, many geologists thought that through the application of plate-tectonic theory, we could easily determine the processes at work in each mountain belt and work back in time to understand the history of each of the continents. Some suggested that there would hardly be any major problems for Earth scientists to solve in the future. Plate tectonics was a breakthrough, and a great many problems were solved; but with this great leap forward in the science we have identified new problems. New generations of geologists will have no shortage of challenges and no less excitement from solving newly discovered problems than did their predecessors who saw the dawn of the plate-tectonics breakthrough. Science present builds on science past.

Summary

Major mountain belts are made up of a number of *mountain ranges.* Mountain belts are generally several thousand kilometers long but only a few hundred kilometers wide.

The major factors that control the growth and development of mountain ranges are *intense deformation* (during an *orogeny*), *isostasy,* and *weathering and erosion.* An orogeny involves folding and faulting of sedimentary and volcanic rock, regional metamorphism, and igneous activity. Orogenies are associated with plate convergence. After an orogeny, there is a long period of uplift, often with block-faulting, and erosion. Eventually, the mountain belt is eroded down to a plain and incorporated into the *craton,* or stable interior of the continent.

According to plate-tectonic theory, mountains on the edges of continents are formed by continent-oceanic convergence, and mountains in the interior of continents are formed by continent-continent collisions.

The uplift of a region following termination of an orogeny is generally attributed to isostatic adjustment of continental crust.

Continents grow larger when new mountain belts evolve along continental margins. They may also grow by the addition of terranes that may have traveled great distances before colliding with a continent.

Terms to Remember

accreted terrane 504
craton 490
fault-block mountain range 501
fold and thrust belts 491
gravitational collapse and spreading 496
lithospheric delamination (or delamination) 502
major mountain belt 486
mountain range 486
orogeny 489
Precambrian shield 490
suspect terrane 504
terrane (tectonostratigraphic terrane) 503

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. What does a fold and thrust belt tell us about what occurred during an orogeny?
2. What differences would you expect to find between a young, active mountain belt and an older mountain belt that is no longer undergoing uplift?
3. Explain how erosion and isostasy eventually produce stable, relatively thin continental crust.
4. In what ways do the rocks and topography of cratons differ from those of mountain belts?
5. How is it possible to form mountain belts in a region undergoing extensional forces? What is the name for this type of mountain belt? Give an example of a mountain belt formed under extension.
6. Using the Appalachian Mountains as an example, describe the Wilson Cycle.
7. The mountain belt that forms the eastern part of North America is called the
   a. Appalachians. b. North American Cordillera.
   c. Himalaya. d. Andes.
   e. Rockies.
8. The portion of a continent that has been structurally stable for a prolonged period of time is called a(n)
   a. orogeny. b. basin.
   c. mountain belt. d. craton.

9. Folds and reverse faults in a mountain belt suggest
   a. crustal shortening.
   b. tensional stress.
   c. deep-water deposition of the sediment.
   d. all of the preceding.
10. What type of plate boundary is most commonly associated with mountain building?
    a. divergent b. convergent
    c. transform
11. The likely reason that the Himalaya is much higher than the adjoining Tibetan Plateau is:
    a. Heavy precipitation results in rapid erosion in the Himalaya.
    b. The crust of the Himalaya is less dense than that of the Tibetan Plateau.
    c. The Tibetan Plateau is being subducted.
    d. The mantle beneath the Himalaya is hotter than that beneath the Tibetan Plateau.
12. To explain fold and thrust belts, simultaneous normal faulting, and how once deep-seated metamorphic rocks rise to an upper level in a mountain belt, geologists use a model called
    a. tectonism. b. gravitational collapse and spreading.
    c. orogeny. d. faulting.
13. Which of the following is *not* characteristic of a mountain belt that formed through ocean-continent convergence?
    a. fold and thrust belts
    b. thick accumulations of marine sediment
    c. prevalence of normal faults over reverse faults
    d. metamorphism
14. Regional metamorphic rocks and plutonic rocks are most commonly associated with
    a. the outer edge of the fold and thrust belt.
    b. the most intensely deformed portions of major mountain belts.
    c. fault-block mountain ranges.
    d. the forearc basin of a convergent plate boundary.
15. Which of the following is *not* an example of a mountain belt formed by continent-continent convergence?
    a. Urals b. Himalaya
    c. Rockies d. Alps
16. The concept of isostacy suggests that higher-elevation mountain ranges are underlain by
    a. a thick root of continental crust.
    b. dense oceanic crust.
    c. a shallow root of continental crust.
    d. a complex of normal faults.
17. The Wilson Cycle describes
    a. the cycle of uplift and erosion of mountains.
    b. the movement of asthenosphere.
    c. the block-faulting that occurs at mountains.
    d. the cycle of splitting of a supercontinent, opening of an ocean basin, followed by closing of the basin and collision of continents.
18. The detachment of part of the mantle portion of the lithosphere beneath a mountain belt is called
    a. gravitational collapse.
    b. rifting.
    c. lithospheric delamination.
    d. none of the preceding.
19. Which is *not* a type of terrane?
    a. accumulated b. exotic
    c. suspect d. accreted
20. Which is a source for terranes?
    a. microcontinents
    b. fragments of distant continents
    c. island arcs
    d. all of the preceding

Expanding Your Knowledge

1. How are unconformities used to determine when orogenies occurred?
2. How has seismic tomography contributed to our understanding of mountain belts?
3. How do basalt and ultramafic rocks from the oceanic lithosphere become part of mountain belts?
4. Why is a craton locally warped into basins and domes?
5. How could fossils in a terrane's rocks be used to indicate that it is an exotic terrane?

Exploring Web Resources

http://pubs.usgs.gov/gip/birth/birth.pdf

Birth of the Mountains. The Geologic Story of the Southern Appalachian Mountains. This is the pdf version of a publication by the U.S. Geologic Survey.

http://info.hartwick.edu/geology/vft/VFT-so-far/VFT.html

Hartwick College Virtual Field Trip. A field trip through part of the Appalachians in central New York. The site includes a geologic history for this part of the Appalachians.

www.winona.edu/geology/travels/tetons/travel.html

Geology of Grand Teton National Park, Wyoming. A photo, map, and text description of the spectacular Grand Teton Range and its geologic history.

http://www.see.leeds.ac.uk/structure/virtualfield/npfront.htm

Nanga Parbat—Mountain Uplift and Tectonics. A virtual field trip to the Nanga Parbat area in the western part of the Himalaya.