Chapter 5

Volcanoes and Volcanism

G. Brad Lewis/Getty Images

Kilauea Volcano, Hawaii
Radiant rivulets of lava delicately drip into the ocean like beams of amber and carnelian light.
When lava streams into the ocean, the sea steams and boils. Brilliant bursts of molten lava and rock spray outward like explosions of fireworks. Kilauea is a dynamic volcano. If you visit, depending on the current volcanic activity you may see an active lava flow. To check Kilauea's activity go to http://hvo.wr.usgs.gov/.

—A. W.

ESSENTIAL QUESTIONS TO ASK

5.1 Introduction
- *How can volcanism be both constructive and destructive?*

5.2 Volcanism and Volcanoes
- *What gases do volcanoes commonly emit?*
- *How and why do aa and pahoehoe lava flows differ?*
- *What are pyroclastic materials, and how are they dangerous to air traffic?*

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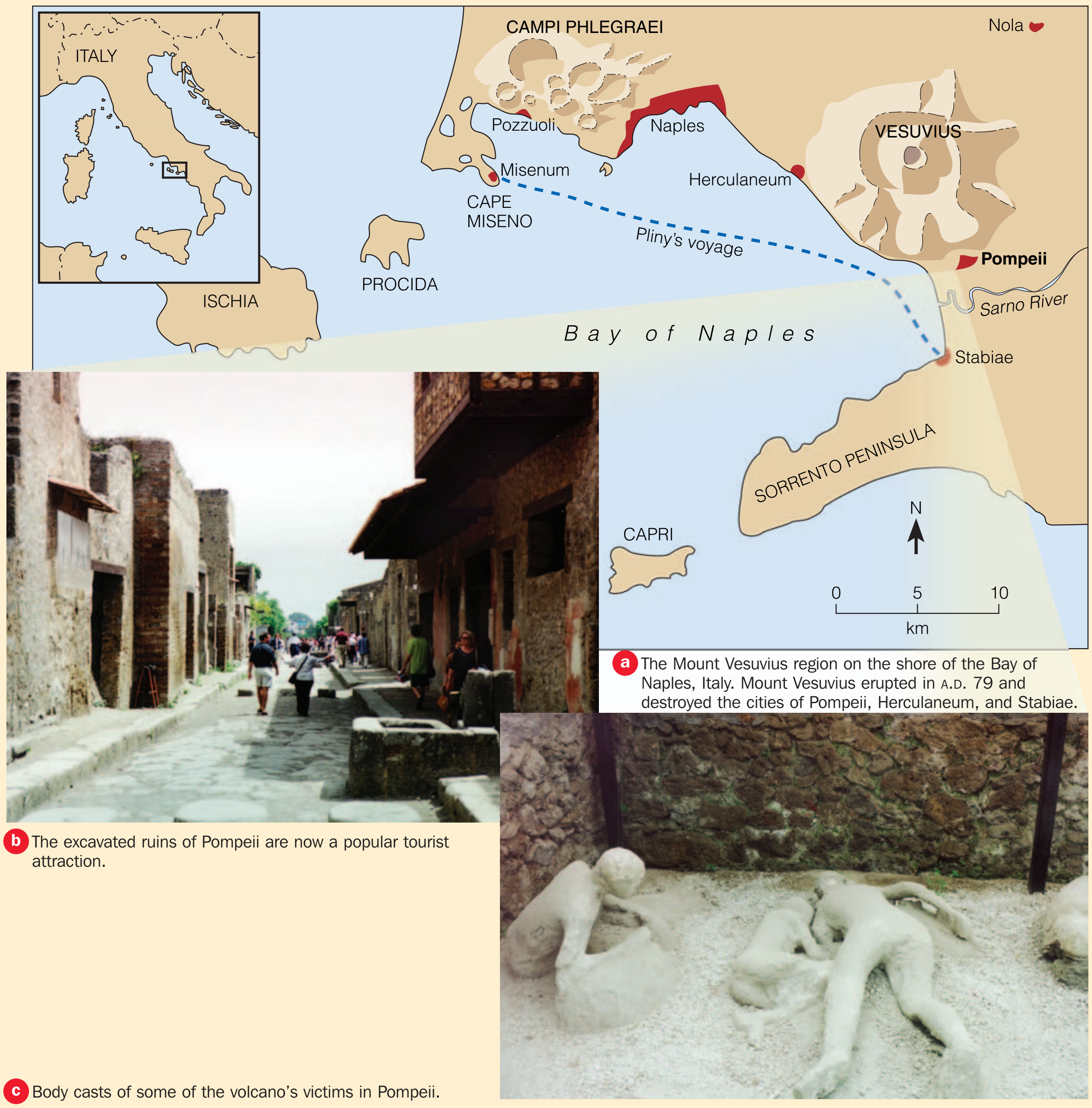
5.1 Introduction

No other geologic phenomenon has captured the public imagination more than erupting volcanoes, especially lava issuing forth in fiery streams or blasted into the atmosphere in sensational pyrotechnic displays. What better subject for a disaster movie? Several such movies of varying quality and scientific accuracy have appeared in recent years. One of the best was *Dante's Peak* in 1997. Certainly the writers and director exaggerated some aspects of volcanism, but the movie depicted rather accurately the phenomenal power of an explosive eruption. Incidentally, the volcano called Dante's Peak was a 10-m-high model built of wood and steel.

▶ Figure 5.1 The Eruption of Mt. Vesuvius



a The Mount Vesuvius region on the shore of the Bay of Naples, Italy. Mount Vesuvius erupted in A.D. 79 and destroyed the cities of Pompeii, Herculaneum, and Stabiae.

Sue Monroe

b The excavated ruins of Pompeii are now a popular tourist attraction.

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c Body casts of some of the volcano's victims in Pompeii.

Incandescent streams of molten rock are commonly portrayed in movies as posing a great danger to humans, and, in fact, on a few occasions lava flows have caused fatalities. Of course, lava flows may destroy homes, roadways, and croplands, but they are the least dangerous manifestation of volcanism. Explosive eruptions accompanied by little or no lava flow activity are quite dangerous, especially if they occur near populated areas. In this respect, *Dante's Peak* was accurate, although it would be most unusual for a volcano to both erupt explosively and produce fluid lava flows at the same time as depicted in the movie.

One of the best-known catastrophic eruptions was the A.D. 79 outburst of Mount Vesuvius, which destroyed the thriving Roman cities of Pompeii, Herculaneum, and Stabiae in what is now Italy (▶ Figure 5.1). Fortunately for us, Pliny the Younger recorded the event in great detail; his uncle, Pliny the Elder, died while trying to investigate the eruption. Pompeii, a city of about 20,000 people and only 9 km from Mount Vesuvius, was buried in nearly 3 m of pyroclastic materials that covered all but the tallest buildings. At least 2000 victims have been found in the city, but certainly far more were killed. Pyroclastic materials covered Pompeii rather gradually, but surges of incandescent volcanic materials in glowing avalanches swept though Herculaneum, quickly covering the city to a depth of 20 m. Since A.D. 79, Mount Vesuvius has erupted 80 times, most violently in 1631 and 1906; it last erupted in 1944. Volcanic eruptions and earthquakes in this area pose a continuing threat to the many cities and towns along the shores of the Bay of Naples (▶ Figure 5.1).

■ *How can volcanism be both constructive and destructive?*

The fact that lava flows and explosive eruptions cause property damage, injuries, and fatalities (Table 5.1) and at least short-term climate changes indicates that eruptions are destructive events, at least from the human perspective. Ironically, though, volcanism is actually a constructive process in the context of Earth history. Earth's atmosphere and surface waters most likely resulted from the emission of volcanic gases during the early history of the planet, and oceanic crust is continuously produced by volcanism at spreading ridges. Many oceanic islands such as Iceland, the Hawaiian Islands, the Azores, and the Galápagos Islands owe their existence to volcanic eruptions. In tropical areas, weathering converts lava, pyroclastic materials, and volcanic mudflows into fertile soils.

One reason to study volcanic activity is that volcanoes provide us with an excellent opportunity to see how Earth's systems interact. The emission of gases and pyroclastic materials has an immediate and profound impact on the atmosphere, hydrosphere, and biosphere, at least in the vicinity of an eruption. And in some cases, the effects are worldwide, as they were following the eruptions of Tambora in 1815, Krakatau in 1883, and Mount Pinatubo in 1991.

Section 5.1 Summary

- Interactions among systems are demonstrated by large volcanic eruptions because they have an impact on the hydrosphere, atmosphere, and biosphere.

TABLE 5.1

Some Notable Volcanic Eruptions

Date	Volcano	Deaths
Apr. 10, 1815	Tambora, Indonesia	92,000; includes deaths from eruption and famine and disease
Oct. 8, 1822	Galunggung, Java	Pyroclastic flows and mudflows killed 4011
Mar. 2, 1856	Awu, Indonesia	2806 died in pyroclastic flows
Aug. 27, 1883	Krakatau, Indonesia	More than 36,000 died; most killed by tsunami
June 7, 1892	Awu, Indonesia	1532 died in pyroclastic flows
May 8, 1902	Mount Pelée, Martinique	Nuée ardente engulfed St. Pierre and killed 28,000
Oct. 24, 1902	Santa Maria, Guatemala	5000 died during eruption
May 19, 1919	Kelut, Java	Mudflows devastated 104 villages and killed 5110
Jan. 21, 1951	Lamington, New Guinea	Pyroclastic flows killed 2942
Mar. 17, 1963	Agung, Indonesia	1148 perished during eruption
May 18, 1980	Mount St. Helens, Washington	63 killed; 600 km^2 of forest devastated
Mar. 28, 1982	El Chichón, Mexico	Pyroclastic flows killed 1877
Nov. 13, 1985	Nevado del Ruiz, Colombia	Minor eruption triggered mudflows that killed 23,000
Aug. 21, 1986	Oku volcanic field, Cameroon	Cloud of CO_2 released from Lake Nyos killed 1746
June 15, 1991	Mount Pinatubo, Philippines	~ 281 killed during eruption; 83 died in later mudflows; 358 died of illness
July 1999	Soufrière Hills, Montserrat	19 killed; 12,000 evacuated
Jan. 17, 2002	Nyiragongo, Zaire	Lava flow killed 147 in Goma

5.2 Volcanism and Volcanoes

What do we mean by the terms *volcanism* and *volcano*? The latter is a landform—that is, a feature on Earth's surface—whereas **volcanism** is the process in which magma rises through Earth's crust and issues forth at the surface as lava flows and/or pyroclastic materials and gases. We will discuss the origin and nature of volcanoes and other volcanic landforms in later sections, but here we point out that volcanism is also responsible for the origin of all extrusive igneous (volcanic) rocks, such as basalt, tuff, and obsidian (see Chapter 4).

Volcanism is a common phenomenon. About 550 volcanoes are *active;* that is, they are erupting or have erupted during historic time. Only about a dozen are erupting at any one time. Most of this activity is minor and goes unreported in the popular press unless an eruption, even a small one, takes place near a populated area or has tragic consequences. However, large eruptions that cause extensive property damage, injuries, and fatalities are not uncommon (Table 5.1). Indeed, a great amount of effort is devoted to better understanding and more effectively anticipating large eruptions.

In addition to active volcanoes, Earth has numerous *dormant* volcanoes that could erupt in the future. The distinction between *active* and *dormant* is not precise. Prior to its eruption in A.D. 79, Mount Vesuvius had not been active in human memory. The largest volcanic outburst since 1912 took place in 1991, when Mount Pinatubo in the Philippines erupted after lying dormant for 600 years. Some volcanoes have not erupted during historic time and show no evidence of erupting again; thousands of these *extinct* or *inactive* volcanoes are known.

All terrestrial planets and Earth's moon were volcanically active during their early histories, but now only Earth and a few other bodies in the solar system have active volcanoes. At least one active volcano is likely present on Venus, and Triton, a moon of Neptune, and Titan, a moon of Saturn, probably have active volcanoes. But Jupiter's moon Io is by far the most volcanically active body in the solar system. Many of its more than 100 volcanoes are erupting at any given time.

▶ **Figure 5.2 Fumeroles** Gases emitted from vents (fumeroles) at the Sulfur Works in Lassen Volcanic National Park in California. Hot, acidic gases and fluids have altered the original igneous rocks to clay. Several other vents are also present in this area, but the two shown here opened up only a few years ago.

Sue Monroe

Volcanic Gases

■ *What gases do volcanoes commonly emit?*

Samples from present-day volcanoes indicate that 50–80% of all volcanic gases are water vapor. Volcanoes also emit carbon dioxide, nitrogen, sulfur dioxide, hydrogen sulfide, and very small amounts of carbon monoxide, hydrogen, and chlorine. In many areas of recent and ongoing volcanism, such as Lassen Volcanic National Park in California, one cannot help but notice the rotten-egg odor of hydrogen sulfide gas (▶ Figure 5.2). In fact, this *hydrothermal (hot water) activity* is one potential source of energy (see Chapter 16).

Most volcanic gases quickly dissipate in the atmosphere and pose little danger to humans, but on occasion they have caused fatalities. In 1783 toxic gases, probably sulfur dioxide, from Laki fissure in Iceland had tragic effects. About 75% of the nation's livestock died, and the haze from the gases caused lower temperatures and crop failures. About 24% of Iceland's population died from what was called the Blue Haze Famine. The eruption also produced a "dry fog" in the upper atmosphere that was likely responsible for dimming the intensity of sunlight and the severe winter of 1783–1784 in Europe and North America.

The 1815 eruption of Tambora in Indonesia, the largest and deadliest historic eruption, was probably responsible for the particularly cold spring and summer of 1816. The eruption of Mayon volcano in the Philippines during the previous year may have contributed to freezing temperatures, frost, and crop failures during the spring and summer in North America, or what residents at the time called the "year without a summer" or "1816 and froze to death."

In 1986, in the African nation of Cameroon, 1746 people died when a cloud of carbon dioxide engulfed them. The gas accumulated in the waters of Lake Nyos, which lies in a volcanic depression. Scientists are not sure why the gas burst forth suddenly, but once it did, it flowed downhill along the surface because it was denser than air. As it moved, it flattened trees and killed thousands of animals and many people, some as far as 23 km from the lake.

Residents of the island of Hawaii have coined the term *vog* for volcanic smog. Kilauea volcano has been erupting continuously since 1983, releasing small amounts of lava and copious quantities of carbon dioxide and sulfur dioxide every day. Car-

▶ **Figure 5.3 Lava Tubes** Lava tubes consisting of hollow spaces beneath the surfaces of lava flows are common in many areas.

J. B. Judd/USGS

a An active lava tube in Hawaii. Part of the tube's roof has collapsed, forming a skylight.

Hawaii Volcanoes National Park, USGS

b A lava tube in Hawaii after the lava has drained out.

bon dioxide has been no problem, but sulfur dioxide produces a haze and the unpleasant odor of sulfur. Vog probably poses no risk for tourists, but a long-term threat exists for people living on the west side of the island where vog is most common.

Lava Flows

Although lava flows are portrayed in movies and on television as a great danger to humans, they only rarely cause fatalities. The reason is that most lava flows do not move very fast, and because they are fluid, they follow low areas. Thus, once a lava flow erupts from a volcano, determining the path it will take is easy, and anyone in areas likely to be affected can be evacuated.

Even low-viscosity (fluid) lava flows usually do not move rapidly, but they flow much faster when their margins and upper surfaces cool and solidify to form a **lava tube**—that is, a tunnel-like structure insulated on all sides. Thus confined, lava may flow at speeds up to 50 km/hr; if part of a lava tube's roof collapses, forming a *skylight*, the active flow can be observed (▶ Figure 5.3a). When an eruption ceases, the tube drains, leaving an empty tube (▶ Figure 5.3b). In Hawaii, lava moves through lava tubes for many kilometers and some discharges into the sea.

▶ **Figure 5.4 Pahoehoe and aa Lava Flows** Pahoehoe and aa were named for lava flows in Hawaii, but the same kinds of flows are found in many other areas.

J. D. Griggs/USGS

a An excellent example of the taffylike appearance of pahoehoe.

Robert Tilling/USGS

b An aa lava flow advances over an older pahoehoe flow. Notice the rubbly nature of the aa flow.

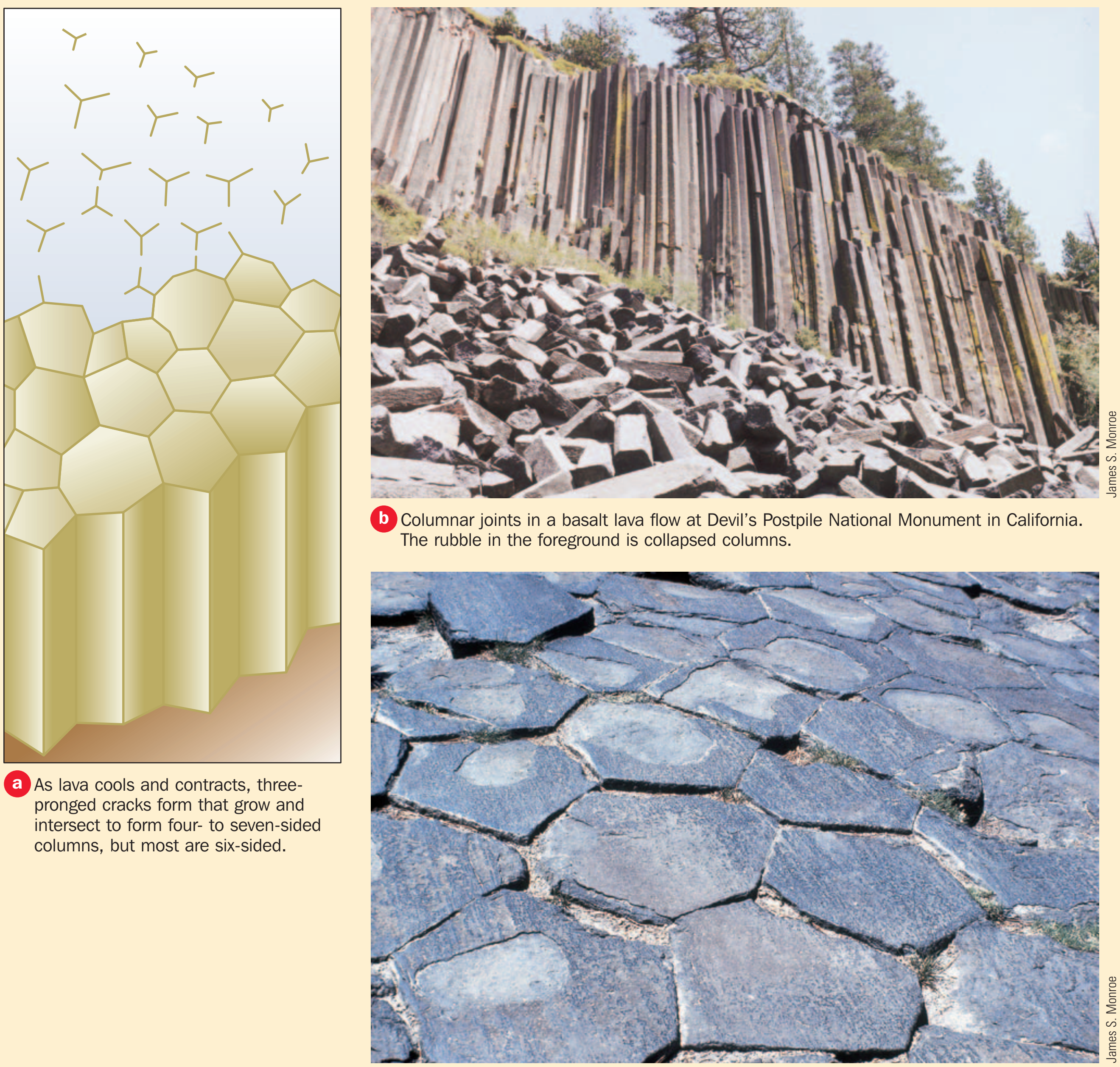
■ *How and why do aa and pahoehoe lava flows differ?*

Geologists define two types of lava flows, both named for lava flows in Hawaii. The type of flow called **pahoehoe** (pronounced *pah-hoy-hoy*) has a smooth, ropy surface much like taffy (▶ Figure 5.4a). An **aa** (pronounced *ah-ah*) flow, in contrast, is made up of jagged, angular blocks and fragments (▶ Figure 5.4b). Pahoehoe flows are less viscous than aa flows; indeed, aa flows are viscous enough to break up into blocks and move forward as a wall of rubble. A pahoehoe flow may change to aa along its length, but aa flows do not change to pahoehoe.

Many lava flows have a distinctive pattern of columns bounded by fractures, or what geologists call **columnar joints** (▶ Figure 5.5). Once a lava flow ceases moving, it contracts as it cools, thus producing forces that cause fractures called *joints* to open. On the surface of a lava flow, these joints intersect and outline polygons, which are commonly six-sided (▶ Figure 5.5b). The joints (fractures) extend down into the flow, thereby forming parallel columns with their long axes perpendicular to the principal cooling surface. Although found mostly in mafic lava flows, columnar joints are also present in some intrusive bodies.

We know that lava flows follow low areas such as stream valleys, and yet we see lava flows in many areas perched on the tops of ridges or hills. So why do they now stand high above the surrounding countryside? When a lava flow cools, it forms rock that is commonly harder and more resistant to erosion than rocks adjacent to it. Accordingly, as erosion proceeds, the rocks along a lava flow's margins erode more

▶ **Figure 5.5 Columnar Jointing** Columnar jointing is seen mostly in mafic lava flows and related intrusive rocks.



a As lava cools and contracts, three-pronged cracks form that grow and intersect to form four- to seven-sided columns, but most are six-sided.

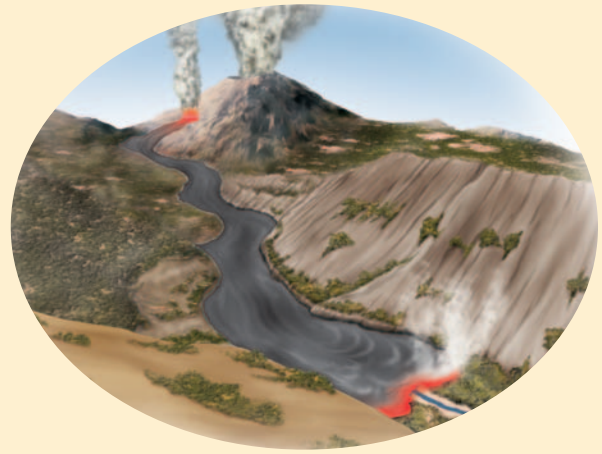
b Columnar joints in a basalt lava flow at Devil's Postpile National Monument in California. The rubble in the foreground is collapsed columns.

c Surface view of the columns from (b). The straight lines and polish resulted from abrasion by a glacier that moved over this surface.

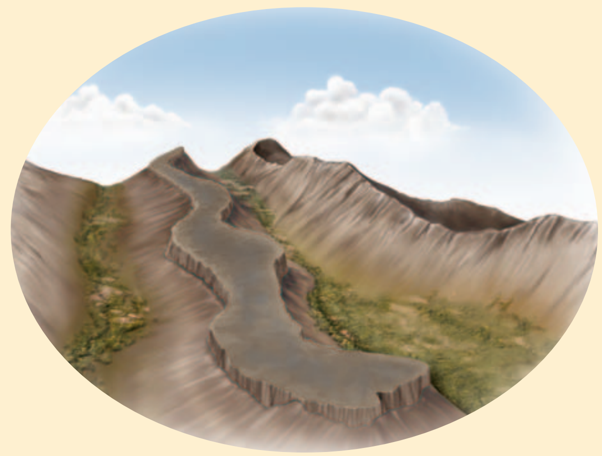
rapidly and what was a valley becomes a ridge or hilltop (▶ Figure 5.6). In short, what was a low area becomes a high area in what geologists call an inversion of topography.

Much of the upper oceanic crust is made up of bulbous masses of basalt that resemble pillows—hence the name **pillow lava** (▶ Figure 5.7). Geologists knew long ago that pillow lava forms when lava is rapidly chilled underwater, but its formation was not observed until 1971. Divers near Hawaii saw pillows form when a blob of lava broke through the crust of an underwater lava flow and cooled quickly, forming a pillow-shaped mass with a glassy exterior. Fluid lava then broke through the crust of the pillow just formed and formed another pillow, repeating the process and resulting in an interconnected accumulation of pillows (▶ Figure 5.7).

▶ **Figure 5.6 Inversion of Topography** In some places we see lava flows on ridges or hilltops, yet when the flow occurred it must have followed a valley.



a Lava flows into a valley, where it cools and crystallizes, forming volcanic rock.



b The areas adjacent to the flow erode more easily than the flow, producing an inversion of topography.

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c The basalt that caps this small hill near Orland, California, was originally a lava flow that followed a valley from its source far to the east.

Pyroclastic Materials

As magma rises toward the surface, pressure decreases and the contained gases begin to expand. In highly viscous felsic magma, expansion is inhibited; gas pressure increases and may eventually cause an explosion and produce particulate matter known as **pyroclastic materials.** In contrast, low-viscosity mafic magma allows gases to expand and escape easily. Accordingly, mafic magma usually erupts rather quietly as fluid lava flows.

Ash is the name for pyroclastic materials that measure less than 2.0 mm (▶ Figure 5.8). In some eruptions, ash is ejected into the atmosphere and settles as an *ash fall.* In 1947 ash erupted from Mount Hekla in Iceland fell 3800 km away on Helsinki, Finland. In contrast to an ash fall, an *ash flow* is a cloud of ash and gas that flows along or close to the surface. Some ash flows move faster than 100 km/hr, and they may cover vast areas.

■ *What are pyroclastic materials, and how are they dangerous to air traffic?*

In populated areas adjacent to volcanoes, ash falls and ash flows pose serious problems, and volcanic ash in the atmosphere is a hazard to aviation. Since 1980, about 80 aircraft have been damaged when they encountered clouds of volcanic ash, some so diffuse that pilots cannot see them. The most serious incident took place in 1989, when ash from Redoubt Volcano in Alaska caused all four jet engines to fail on KLM Flight 867. The plane carrying 231 passengers nearly crashed when it fell more than 3 km before the crew could restart the engines. The plane landed safely in Anchorage, Alaska, but it required $80 million in repairs.

In addition to ash, volcanoes erupt *lapilli*, consisting of pyroclastic materials that measure 2–64 mm, and *blocks* and *bombs*, both of which are larger than 64 mm (▶ Figure 5.8). Bombs have a twisted, streamlined shape, indicating they were erupted as globs of magma that cooled and solidified during their flight through the air. Blocks are angular pieces of rock ripped from a volcanic conduit or pieces of a solidified crust of a lava flow. Because of their size, lapilli, bombs, and blocks are confined to the immediate area of an eruption.

Section 5.2 Summary

- A volcano is a landform, whereas volcanism is the process whereby magma and its contained gases rise to the surface.
- Water vapor is the most common volcanic gas, but several others, including carbon dioxide and sulfur gases, are also emitted.
- Aa lava flows are made up of jagged, angular blocks, whereas pahoehoe flows have a taffy-like texture. Lava tubes, pillow lava, and columnar joints are found in some lava flows.
- Pyroclastic materials are particulate matter ejected from volcanoes during explosive eruptions.

▶ **Figure 5.7 Pillow Lava** Much of the upper part of the oceanic crust is made up of pillow lava that formed when lava erupted underwater.

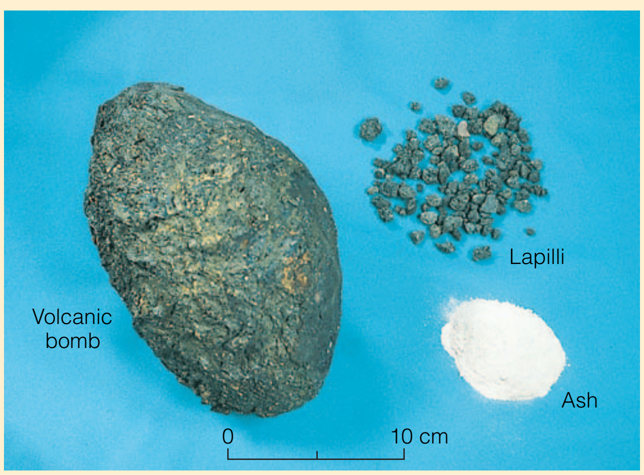
NOAA

a Pillow lava on the seafloor in the Pacific Ocean about 150 miles west of Oregon that formed about 5 years before the photo was taken.

James S. Monroe

b Ancient pillow lava now on land in Marin County, California. The largest pillow measures about 0.6 m across.

▶ **Figure 5.8 Pyroclastic Materials** Pyroclastic materials are all particles ejected from volcanoes, especially during explosive eruptions.



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a The volcanic bomb is elongate because it was molten when it descended through the air. The lapilli was collected at a small volcano in Oregon, whereas the ash came from the 1980 eruption of Mount St. Helens in Washington.

C. Heliker/USGS

b This volcanic block in Hawaii formed when partially solidified lava collapsed into the sea, resulting in a steam explosion.

5.3 Types of Volcanoes

Simply put, a **volcano** is a hill or mountain that forms around a vent where lava, pyroclastic materials, and gases erupt. Although volcanoes vary in size and shape, all have a conduit or conduits leading to a magma chamber beneath the surface. Vulcan, the Roman deity of fire, was the inspiration for calling these mountains *volcanoes*, and because of their danger and obvious connection to Earth's interior, they have been held in awe by many cultures.

In Hawaiian legends, the volcano goddess Pele resides in the crater of Kilauea on Hawaii. During one of her frequent rages, Pele causes earthquakes and lava flows, and she may hurl flaming boulders at those who offend her. Native Americans in the Pacific Northwest tell of a titanic battle between the volcano gods Skel and Llao to account for huge eruptions that took place about 7700 years ago in Oregon and California. Pliny the Elder (A.D. 23–79), mentioned in Section 5.1, believed that before eruptions "the air is extremely calm and the sea quiet, because the winds have already plunged into the earth and are preparing to reemerge."*

■ *What are calderas and how do they form?*

Most volcanoes have a circular depression known as a **crater** at their summit, or on their flanks, that forms by explosions or collapse. Most craters are less than 1 km across, whereas much larger rimmed depressions are called **calderas.** In fact, some volcanoes have a summit crater within a caldera. Calderas are huge structures that form following voluminous eruptions during which part of a magma chamber drains and the mountain's summit collapses into the vacated space below. An excellent example is misnamed Crater Lake in Oregon (▶ Figure 5.9). Crater Lake is actually a steep-rimmed caldera that formed 7700 years ago in the manner just described; it is more than 1200 m deep and measures 9.7 km long and 6.5 km wide. As impressive as Crater Lake is, it is not nearly as large as some other calderas, such as the Toba caldera in Sumatra, which is 100 km long and 30 km wide.

Geologists recognize several types of volcanoes, but one must realize that each volcano is unique in its history of eruptions and development. For instance, the frequency of eruptions varies considerably; the Hawaiian volcanoes and Mount Etna on Sicily have erupted repeatedly, whereas Pinatubo in the Philippines erupted in 1991 for the first time in 600 years. And some volcanoes are complex mountains that have characteristics of more than one type of volcano. Nevertheless, most volcanoes are conveniently classified as *shield volcanoes*, *cinder cones*, *composite volcanoes*, or *lava domes*.

*Quoted from M. Krafft, *Volcanoes: Fire from the Earth* (New York: Harry N. Abrams, 1993), p. 40.

Shield Volcanoes

A **shield volcano** looks like the outer surface of a shield lying on the ground with its convex side up (▶ Figure 5.10). Low-viscosity basalt lava flows issue from a shield volcano's crater or caldera and spread out as thin layers, forming gentle slopes that range from 2 to 10 degrees. Eruptions from shield volcanoes, commonly called *Hawaiian-type eruptions*, are nonexplosive because the fluid lava loses its gases easily and consequently poses little danger to humans. Lava fountains as high as 400 m form where gases escape and contribute pyroclastic materials to shield volcanoes, but otherwise shield volcanoes are made up mostly of basalt lava flows. About 99% of the Hawaiian volcanoes above sea level are composed of lava flows.

Although eruptions of shield volcanoes tend to be rather quiet, some of the Hawaiian volcanoes have, on occasion, produced sizable explosions when magma comes in contact with groundwater, causing it to vaporize instantly. In 1790 Chief Keoua led 250 warriors across the summit of Kilauea volcano to engage a rival chief in battle. About 80 of Keoua's warriors were killed by a cloud of hot volcanic gases.

The current activity of Kilauea is impressive because it has been erupting continuously since January 3, 1983, making it the longest recorded eruption. During these 22 years, more than 2.3 km^3 of molten rock has flowed out at the surface, much of it reaching the sea and forming 2.2 km^2 of new property on the island of Hawaii. Unfortunately, lava flows from Kilauea have also destroyed about 200 homes and caused some $61 million in damages.

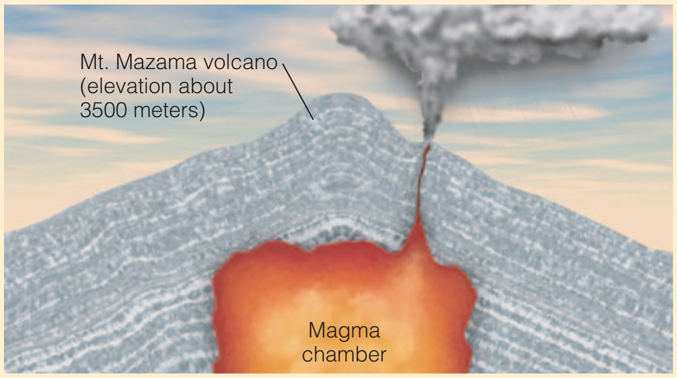
Shield volcanoes are most common in the ocean basins, such as the Hawaiian Islands and Iceland, but some are also present on the continents—for example, in East Africa. The island of Hawaii consists of five huge shield volcanoes; two of them, Kilauea and Mauna Loa, are active much of the time. Mauna Loa, at nearly 100 km across its base and more than 9.5 km above the surrounding seafloor, is the largest vigorously active volcano in the world (▶ Figure 5.10). Its volume is estimated at about 50,000 km^3.

Cinder Cones

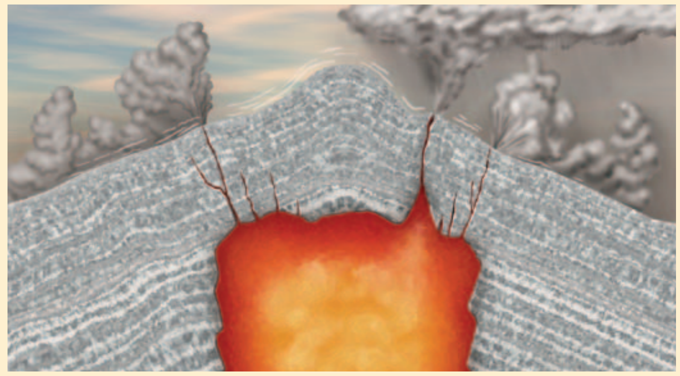
■ *What are cinder cones and what are they composed of?*

Small, steep-sided volcanoes made up of pyroclastic materials that resemble cinders are known as **cinder cones** (▶ Figure 5.11). Cinder cones are only rarely higher than 400 m, with slope angles up to 33 degrees, because they are made up of irregularly shaped particles. Many of these small volcanoes have large, bowl-shaped craters, and if they issue any lava flows at all, they usually break through the lower flanks rather than erupt from the crater (▶ Figure 5.12). A cinder cone may be a nearly perfect cone, but when some erupt, the prevailing winds cause the pyroclastic materials to build up

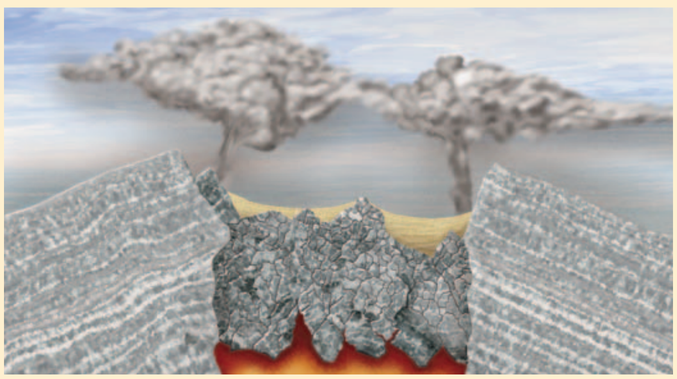
PHYSICAL Geology Now™ ▶ **Geo-focus Figure 5.9 The Origin of Crater Lake, Oregon** Events leading to the origin of Crater Lake, Oregon. Remember, Crater Lake is actually a caldera that formed by partial draining of a magma chamber.



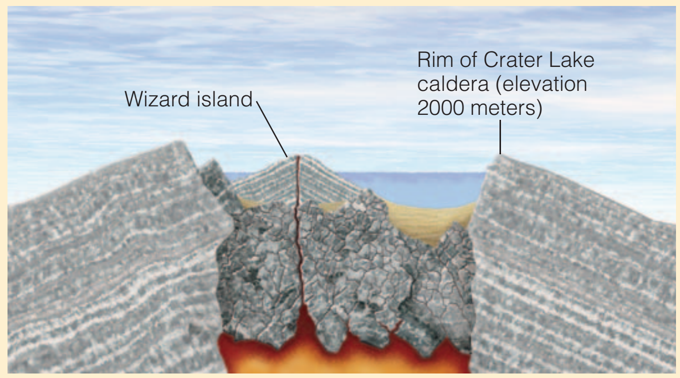
a Eruption begins as huge quantities of ash are ejected from the volcano.



b The eruption continues as more ash and pumice are ejected into the air and pyroclastic flows move down the flanks of the mountain.



c The collapse of the summit into the partially drained magma chamber forms a huge caldera.



d Postcaldera eruptions partly cover the caldera floor, and the small cinder cone called Wizard Island forms.

James S. Monroe

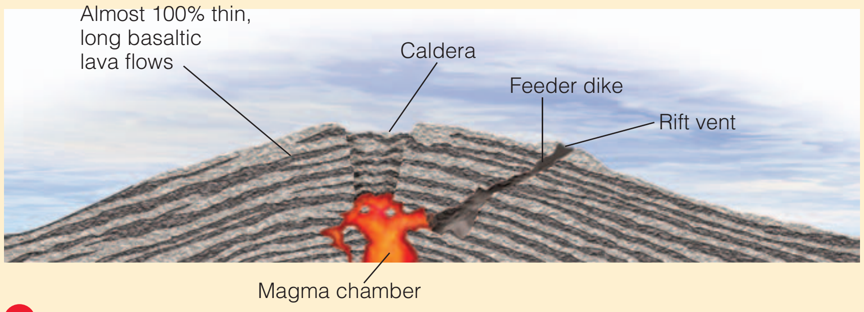
e View from the rim of Crater Lake showing Wizard Island. The lake is 594 m deep, making it the second deepest in North America.

higher on the downwind side of the vent, resulting in a markedly asymmetric shape.

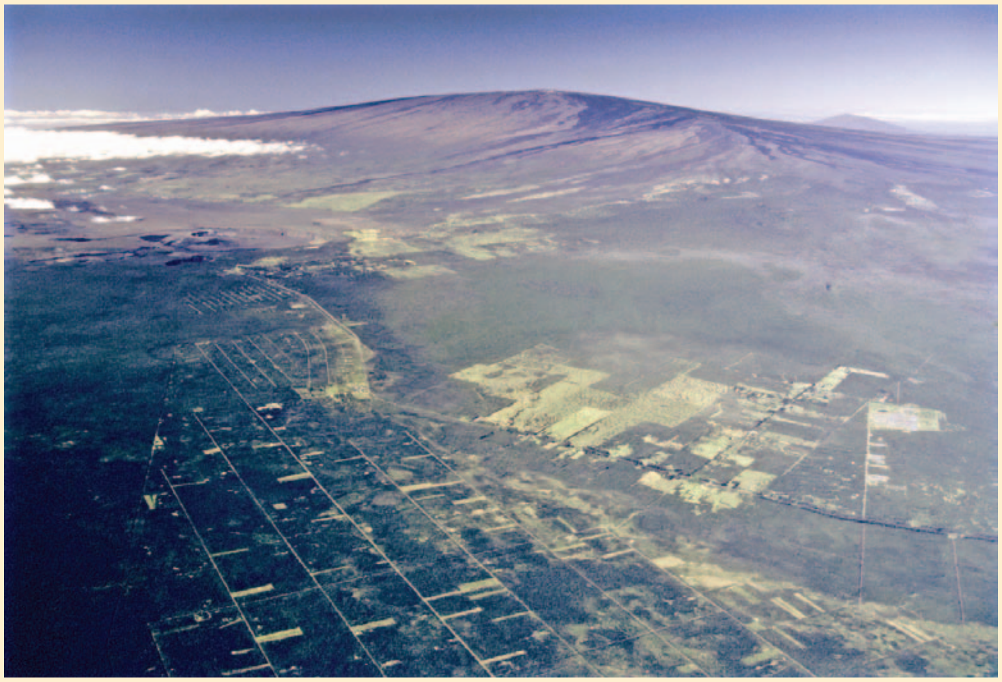
Many cinder cones form on the flanks or within the calderas of larger volcanoes. For instance, Newberry Volcano in Oregon has more than 400 cinder cones on its flanks, and Wizard Island is a small cinder cone that formed following the origin of the caldera we now call Crater Lake in Oregon (▶ Figure 5.9e). Hundreds of cinder cones are present in the southern Rocky Mountain states, particularly in New Mexico and Arizona, and many others are found in California, Oregon, and Washington.

Eruptions at cinder cones are rather short-lived. For instance, on February 20, 1943, a farmer in Mexico noticed fumes emanating from a crack in his cornfield, and a few minutes later ash and cinders were erupted. Within a month, a 300-m-high cinder cone had formed, later named Paríutin, from which lava flowed and covered two nearby towns (▶ Figure 5.11b). Activity ceased in 1952. In Iceland a new cinder cone rose to 100 m above the surrounding area in only two days after it began erupting on January 23, 1973. By February a massive aa lava flow 10–20 m thick at its leading edge was advancing toward the town of Vestmannaeyjar.

Figure 5.10 Shield Volcanoes



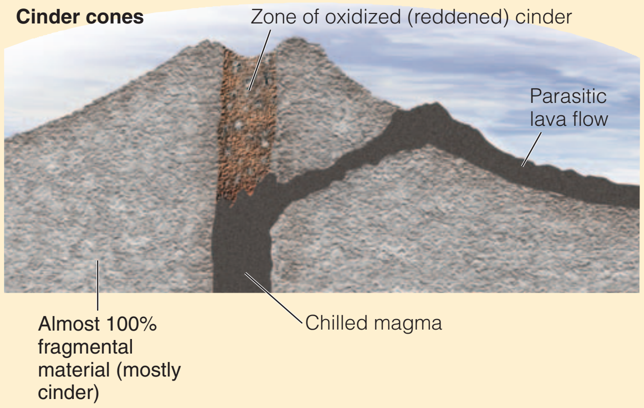
a Diagrammatic view of the internal structure of a shield volcano.



b Mauna Loa on Hawaii is an active shield volcano that has erupted 33 times since 1843; it erupted last in 1983. Its summit stands 17 km above its base on the seafloor.

c Crater Mountain in Lassen County, California, an extinct shield volcano, is about 10 km across and 460 m high. The depression at its summit is a 2-km-wide crater.

▶ **Figure 5.11 Cinder Cones** Cinder cones are small, steep-sided volcanoes made up of pyroclastic materials that resemble cinders.



a Cross section of a cinder cone showing its internal structure. Although composed mostly of pyroclastic materials, lava flows may erupt through the base or flanks of cinder cones.

USGS

b This 400-m-high cinder cone named Paricutín formed in a short time in Mexico in 1943 when pyroclastic materials began to erupt in a farmer's field. Lava flows from the volcano covered two nearby villages, but all activity ceased by 1952.

Residents of the community sprayed the front of the flow with seawater in an effort to solidify it and divert the rest of the flow. The flow in fact diverted around most of the town, but how effective the efforts of the townspeople were is not clear—most likely they were simply lucky.

Composite Volcanoes (Stratovolcanoes)

Composite volcanoes, also called *stratovolcanoes*, are made up of pyroclastic layers and lava flows, although some, perhaps many, of the lava flows may actually be sills (▶ Figure 5.13a). Both the pyroclastic materials and lava have an intermediate composition, so the lava typically cools to form andesite. Another component of composite volcanoes is volcanic mudflows, or what geologists call **lahars.** A lahar may form when rain falls on unconsolidated pyroclastic materials and creates a mixture of particles and water that moves downslope (▶ Figure 5.14). A rather minor eruption of Nevado del Ruiz in Colombia on November 13, 1985, melted snow and ice on the mountain, causing lahars that killed about 23,000 people (Table 5.1).

Composite volcanoes differ from shield volcanoes and cinder cones in composition and shape. Remember that shield volcanoes have very low slopes, whereas cinder cones are small, steep-sided, conical mountains. In contrast, composite volcanoes are steep near their summits, with slope angles up to 30 degrees, but the slope decreases toward the base, where it may be no more than 5 degrees. Mayon volcano in the Philippines is one of the most nearly symmetrical composite volcanoes anywhere (▶ Figure 5.13b). It erupted in 1999 for the 13th time during the 1900s.

Composite volcanoes are what most people visualize when they think of volcanoes. And some of these mountains are indeed impressive. Mount Shasta in northern California is made up of an estimated 350 km^3 of material and measures about 20 km across its base (▶ Figure 5.13c). It dominates the skyline when approached from any direction. Other familiar composite volcanoes are several others in the Cascade Range of the Pacific Northwest as well as Fujiyama in Japan and Mount Vesuvius in Italy.

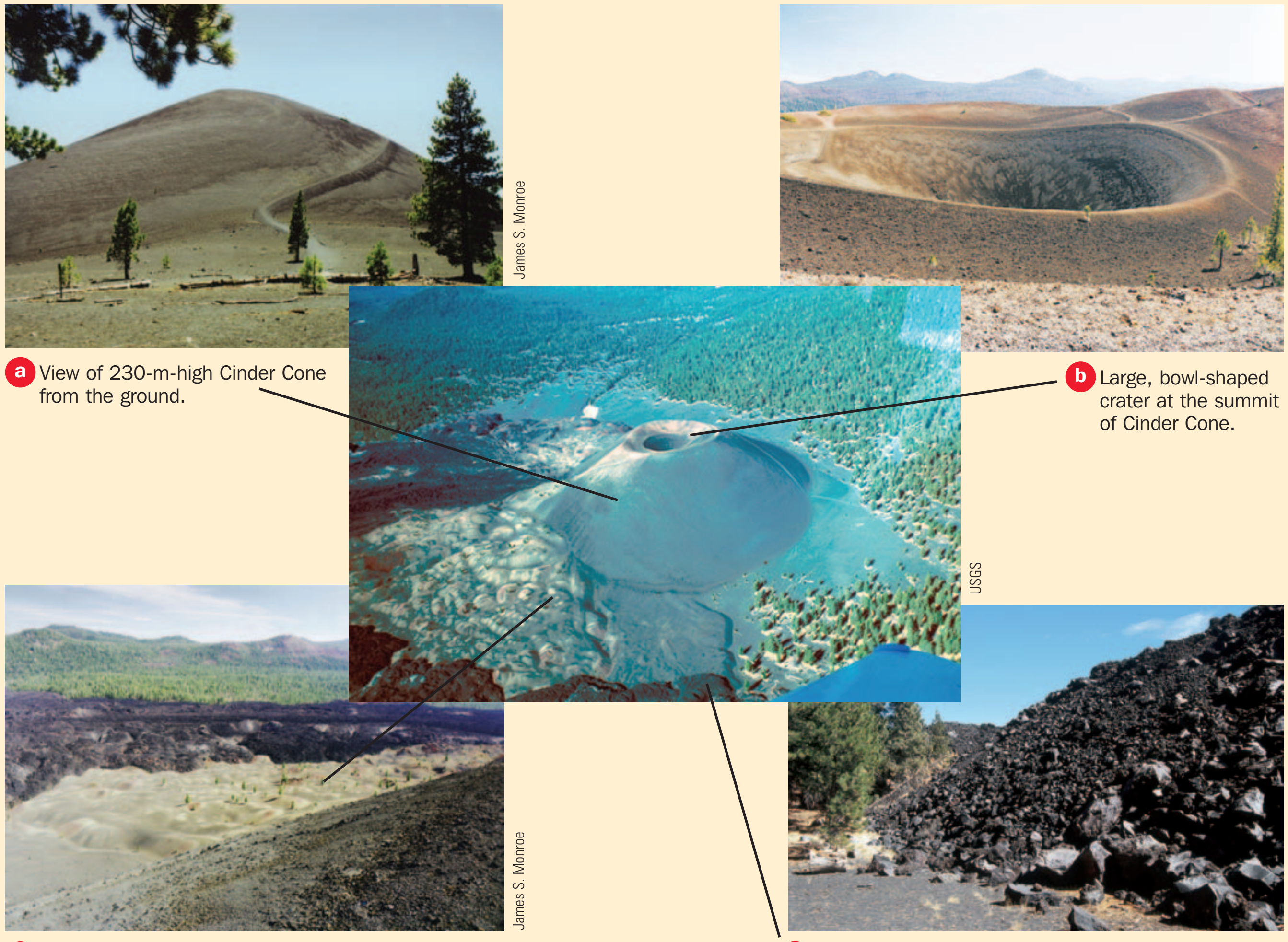
Lava Domes

Volcanoes are complex landforms. Most are shield volcanoes, cinder cones, or composite volcanoes, but some, however, show features of more than one kind of volcano. For example, Mount Etna in Italy is partly a shield volcano and a composite volcano. And, of course, there are a few very unusual volcanoes.

■ *What are lava domes and why are they so dangerous?*

Some volcanic mountains are steep-sided, bulbous masses of viscous magma that geologists call **lava domes** or *volcanic domes*. Most are composed of felsic magma and occasionally intermediate magma that was forced upward under great

▶ **Figure 5.12 Cinder Cone, Lassen Volcanic National Park, California** This aerial view of Cinder Cone in Lassen Volcanic National Park in California shows an area about 6.5 km long, with north toward the right.



a View of 230-m-high Cinder Cone from the ground.

b Large, bowl-shaped crater at the summit of Cinder Cone.

c View from the top of Cinder Cone showing the Painted Dunes, which is volcanic ash that fell on still-hot lava.

d The Fantastic Lava Beds are aa lava flows that broke through the base of Cinder Cone during the 1650s.

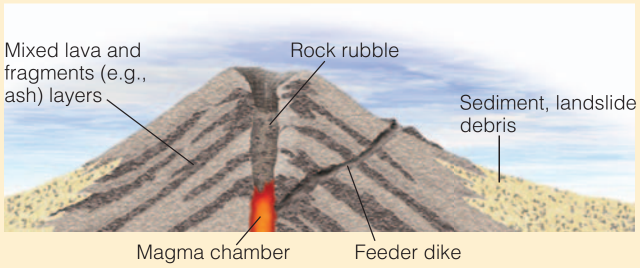
pressure but was too viscous to flow. Lava domes may stand as small, isolated volcanic mountains, or they may rise into the craters of composite volcanoes (▶ Figure 5.15). Unfortunately, lava domes are quite unstable and commonly collapse under their own weight, resulting in huge flows of debris. In June 1991, a lava dome in Japan's Unzen volcano collapsed and the hot debris and ash killed 43 people in a nearby town. During both the 1980 and 2004 eruptions of Mount St. Helens in Washington, lava domes formed and were subsequently destroyed (▶ Figure 5.15a).

Lava domes may be particularly dangerous. In 1902 viscous magma accumulated beneath the summit of Mount Pelée on the island of Martinique in the Caribbean Sea. The gas pressure increased until the side of the mountain blew out in a tremendous explosion, ejecting a mobile, dense cloud of pyroclastic materials and a cloud of gases and ash called a **nuée ardente,** a French term for "glowing cloud." The lower part of this mass, the pyroclastic flow, followed a valley to the sea, but the upper part, the nuée ardente, jumped a ridge and engulfed the city of St. Pierre (▶ Figure 5.16).

A tremendous blast hit St. Pierre and leveled buildings; hurled boulders, trees, and pieces of masonry down the streets; and moved a 3-ton statue 16 m. Accompanying the blast was a swirling cloud of incandescent ash and gases with an internal temperature of 700°C that incinerated everything in its path. The nuée ardente passed through St. Pierre in 2 or 3 minutes, only to be followed by a firestorm as combustible materials burned and casks of rum exploded. But by then most of the 28,000 residents of the city were already dead. In fact, in the area covered by the nuée ardente, only 2 survived!* One survivor was on the outer edge of the nuée ardente, but even there he was terribly burned and his family and neighbors were all killed. The other survivor, a stevedore incarcerated the night before for disorderly conduct, was in a windowless cell partly below ground level. He remained in his cell badly

*Although it is commonly reported that only 2 people survived the eruption, at least 69 and possibly as many as 111 people survived beyond the extreme margins of the nuée ardente and on ships in the harbor. Many, however, were badly injured.

▶ **Figure 5.13 Composite Volcanoes** Composite volcanoes, also known as stratovolcanoes, are the large picturesque volcanoes on the continents.



a Cross section of a composite volcano, which is made up largely of lava flows and pyroclastic materials, although the latter may be reworked as mudflows (lahars).

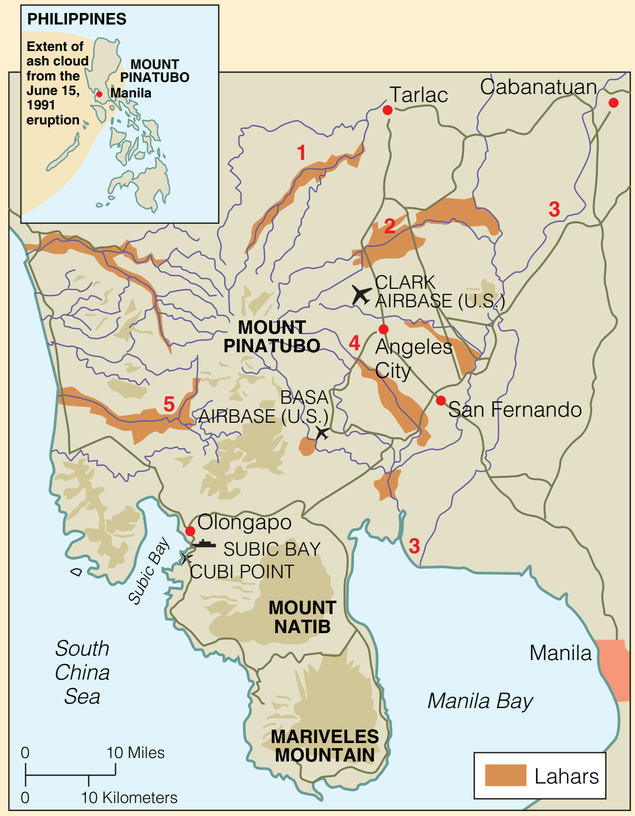
DOI/USGS/David Johnson, Cascades Volcano Observatory, Vancouver, WA

b Mayon volcano in the Philippines is almost perfectly symmetrical. It erupted 13 times during the 1900s, most recently in 1999.

Lyn Topinka/USGS

c View of Mount Shasta in California from the north. The main peak is on the left; the one on the right is Shastina, a smaller cone on the flank of the volcano.

▶ **Figure 5.14 Volcanic Mudflows (Lahars)** Composite volcanoes are made up partly of volcanic mudflows or lahars, mixtures of pyroclastic materials and water that move rapidly downslide.



a Map showing the areas covered by lahars following the 1991 eruption of Mount Pinatubo in the Philippines. By 1993 lahars caused more damage in the lowlands around the volcano than the eruption did.

U.S. Department of the Interior/USGS/David Johnson

b Homes partly buried by a lahar from Mount Pinatubo only hours after the 1991 eruption.

burned for four days after the eruption until rescue workers heard his cries for help. He later became an attraction in the Barnum & Bailey Circus, where he was advertised as "the only living object that survived in the 'Silent City of Death' where 40,000 beings were suffocated, burned or buried by one belching blast of Mont Pelée's terrible volcanic eruption."†

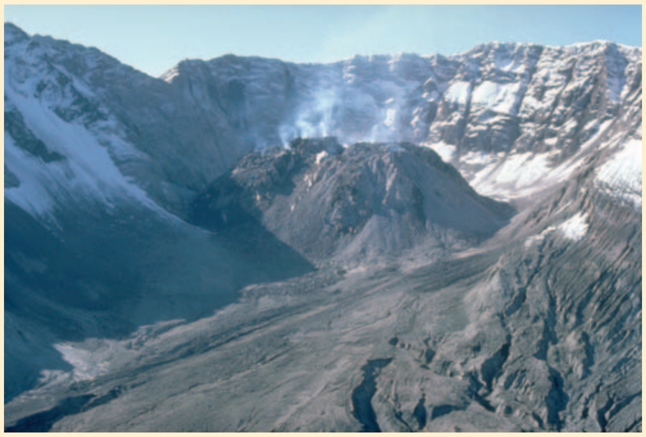
†Quoted from A. Scarth, *Vulcan's Fury: Man Against the Volcano* (New Haven, CT: Yale University Press, 1999), p. 177.

PHYSICAL Geology Now™ Log into GeologyNow and select this chapter to work through a **Geology Interactive** activity on "Volcanic Landforms" (click Volcanism⟶Volcanic Landforms).

Eruptions and the Type of Volcanoes

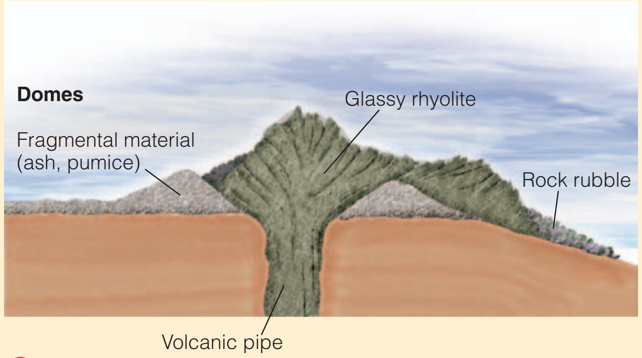
The types of volcanoes we discussed in the preceding sections—shield, cinder cone, composite, and lava dome—differ in size, shape, and composition, largely because of the kinds

Figure 5.15 Lava Domes Lava domes are bulbous masses of magma that are emplaced in craters of composite volcanoes or stand alone as irregularly shaped mountains flanked by debris shed from the dome.



Lyn Topinka/USGS

a This image shows a lava dome in the crater of Mount St. Helens in 1984.



b Diagram of a mass of viscous magma forming a lava dome.

James S. Monroe

c Chaos Crags in the distance are made up of at least four lava domes that formed less than 1200 years ago in Lassen Volcanic National Park in California. The debris in the foreground is Chaos Jumbles, which resulted from the partial collapse of some of the domes.

Figure 5.16 Nuée Ardente

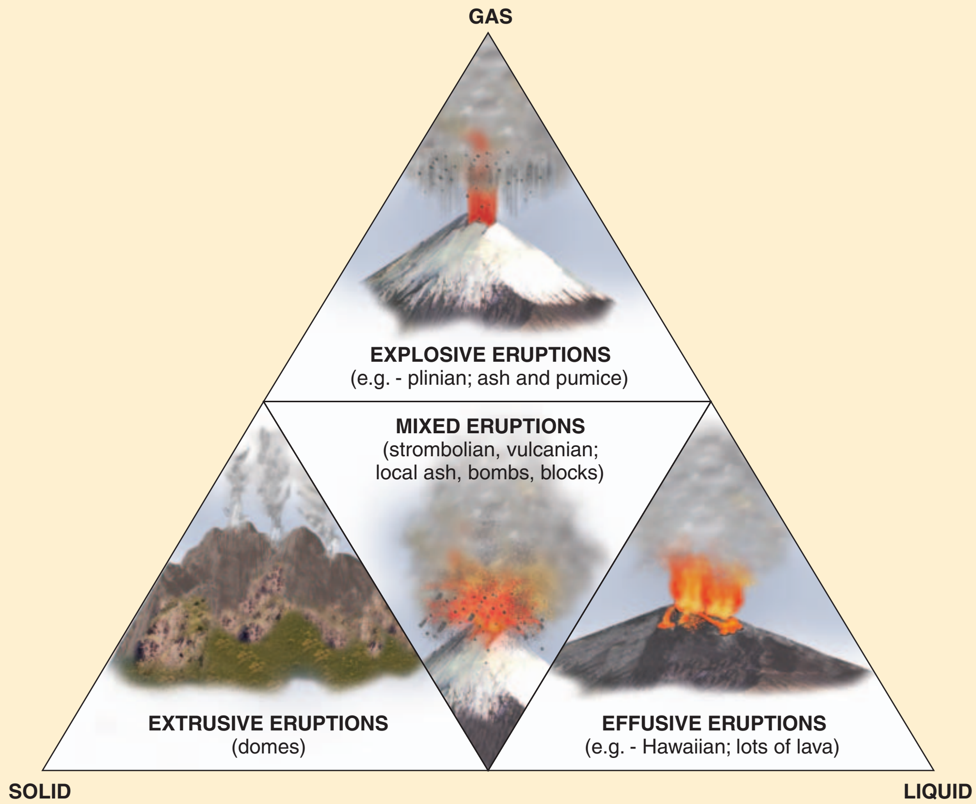
Reuters/Corbis

a St. Pierre, Martinique, after it was destroyed by a nuée ardente from Mount Pelée in 1902. Only 2 of the city's 28,000 inhabitants survived.

USGS

b An April 1986 pyroclastic flow rushing down Augustine volcano in Alaska. This flow is similar to the one that wiped out St. Pierre.

▶ **Figure 5.17 Volcanic Eruptions** The corners of the triangle show the three kinds of materials ejected from volcanic vents. How a volcano erupts and the type of volcano that results depends on the relative mix of these ingredients.



of materials erupted—gases, liquid (lava), and solids (we include very viscous lava here) (▶ Figure 5.17). How a volcano erupts and the type of volcano formed depends on the relative mix of these ingredients. Keep in mind, though, that a volcano's eruptive style may change through time. For example, Mount Etna in Italy is a shield volcano up to an elevation of about 2900 m, but the top 400 m is a composite volcano.

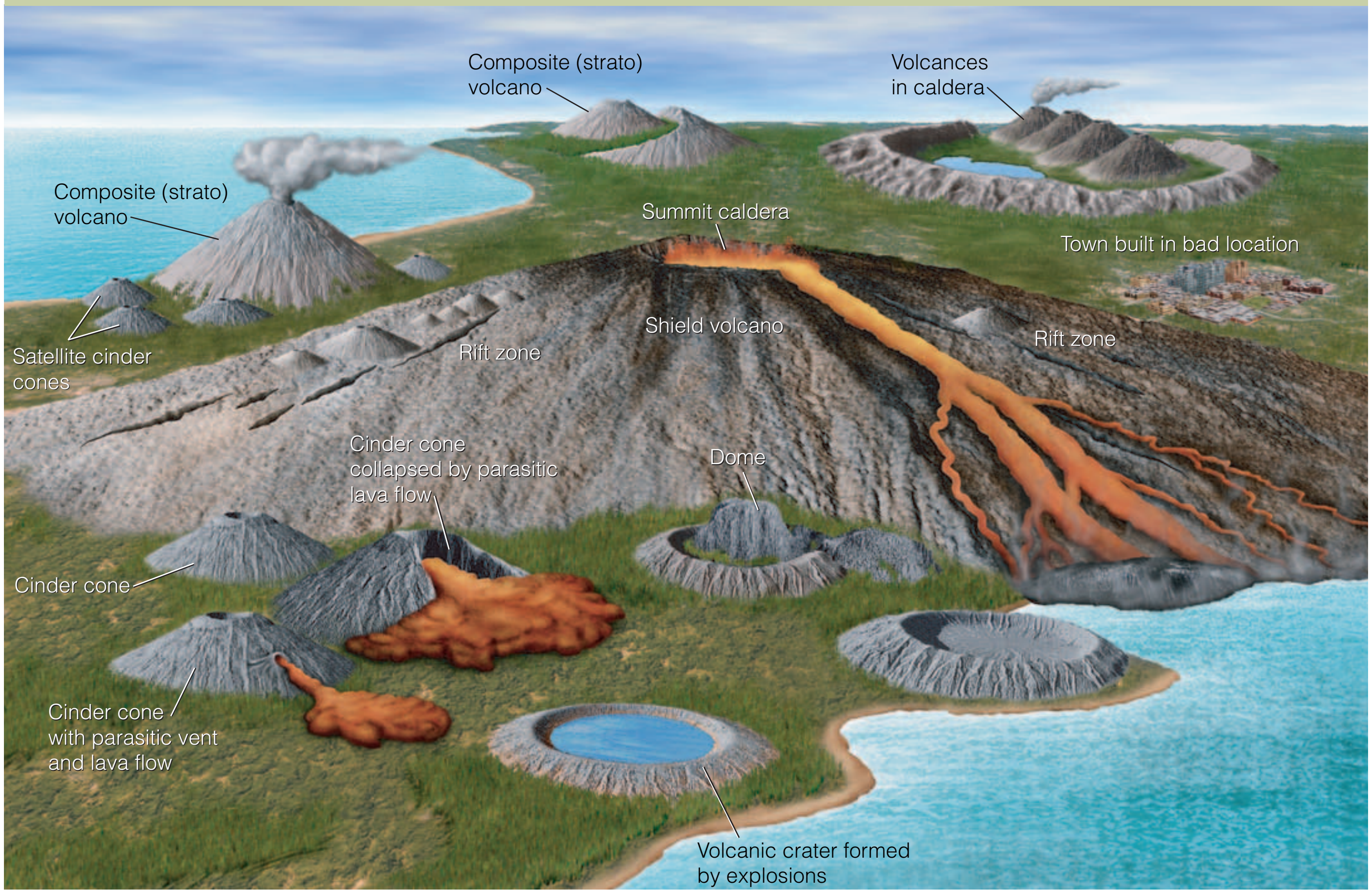
Notice in Figure 5.17 that geologists characterize eruptions as Hawaiian, Strombolian, Vulcanian, and Plinian depending on the mix of solids, liquids, and gases. These are simply names derived from active volcanoes that show the features within the diagram, except for Plinian, which comes from Pliny the Younger, who described the A.D. 79 eruption of Mount Vesuvius (see Section 5.1). For example, Hawaiian type eruptions involve mostly fluid lava, but not much gases or pyroclastic materials, whereas during Plinian eruptions large volumes of gases are discharged along with huge amounts of pumice and ash. We conclude this section with a summary diagram showing the four types of volcanoes we have discussed (▶ Figure 5.18).

You are a natural history enthusiast and would like to share your interests with your family. Accordingly, you plan a vacation that will take you to several of our national parks and monuments in Wyoming, Idaho, Washington, Oregon, and California. What specific areas might you visit, and what kinds of volcanic features would you see in these areas? Are there any other areas in the United States that you might visit in the future to see evidence of past volcanism or ongoing eruptions? If so, where would you go and what would you see?

Section 5.3 Summary

- All volcanoes, regardless of size or shape, form where lava and pyroclastic materials are erupted. Most have one or more craters or a caldera, a large oval to circular structure formed when a volcanic peak collapses into a partially drained magma chamber.
- Shield volcanoes have low, rounded profiles and are made mostly of fluid lava flows; cinder cones are small, steep-sided volcanoes composed of pyroclastic materials; and composite volcanoes consist of lava flows, pyroclastic layers, and lahars.
- Viscous bulbous masses of lava, generally of felsic composition, are lava domes, which are dangerous because they erupt explosively.

PHYSICAL Geology Now™ ▶ **Geo-focus Figure 5.18 Types of Volcanoes** A summary diagram showing the types of volcanoes. Keep in mind, though, that not all of these volcanoes would be found together in one area.



5.4 Other Volcanic Landforms

We mentioned that volcanoes are landforms—that is, features on Earth's surface that result from volcanism. What other kinds of volcanic landforms are there? The most notable are *basalt plateaus*, which form as a result of *fissure eruptions*, and *pyroclastic sheet deposits*, which, as their name implies, have a sheetlike shape.

Fissure Eruptions and Basalt Plateaus

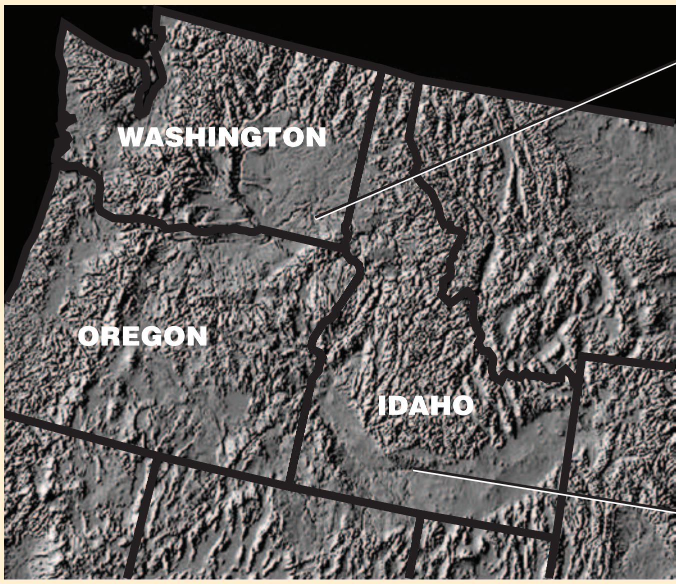
■ *How do basalt plateaus form?*

Rather than erupting from central vents, the lava flows making up **basalt plateaus** issue from long cracks or fissures during **fissure eruptions.** The lava is so fluid (has such low viscosity) that it spreads out and covers vast areas. A good example is the Columbia River basalt in eastern Washington and parts of Oregon, and Idaho. This huge accumulation of 17- to 6-million-year-old overlapping lava flows covers about 164,000 km^2 (▶ Figure 5.19a,b). The Columbia River basalt has an aggregate thickness greater than 1000 m, and some individual flows are enormous; the 30-m-thick Roza flow advanced along a front about 100 km wide and covered 40,000 km^2. Geologists have identified some 300 huge flows here, one of which flowed 600 km from its source.

Similar accumulations of vast, overlapping lava flows are also found in the Snake River Plain in Idaho (▶ Figure 5.19a,c). However, these flows are 1.6 to 5.0 million years old, and they represent a style of eruption between flood basalts and those in Hawaii during which shield volcanoes form. In fact, there are small, low shields as well as fissure flows in the Snake River Plain.

Currently, fissure eruptions occur only in Iceland. Iceland has a number of volcanoes, but the bulk of the island is composed of basalt lava flows that issued from fissures. In fact, about half the lava erupted during historic time in Iceland came from two fissure eruptions, one in A.D. 930 and the other in 1783. The 1783 eruption from Laki fissure, which is more than 30 km long, accounted for lava that covered 560 km^2 and in one place filled a valley to a depth of about 200 m.

▶ **Figure 5.19 Basalt Plateaus** Basalt plateaus are vast areas of overlapping lava flows that issued from long fissures. Fissure eruptions take place today in Iceland, but in the past they formed basalt plateaus in several areas.



USGS/NPS

a Relief map of the northwestern United States showing the locations of the Columbia River basalt and the Snake River Plain.

Frank Kujawa, University of Central Florida/GeoPhoto

b About 20 lava flows of the Columbia River basalt are exposed in the canyon of the Grand Ronde River in Washington.

Sue Monroe

c Basalt lava flows of the Snake River Plain near Twin Falls, Idaho.

Pyroclastic Sheet Deposits

■ *What are pyroclastic sheet deposits?*

Geologists think that vast areas covered by pyroclastic materials a few meters to hundreds of meters thick originated as **pyroclastic sheet deposits.** That is, deposits of pyroclastic materials with a sheetlike geometry. These deposits were known to geologists more than a century ago, and based on observations of present-day pyroclastic flows, such as the one erupted from Mount Pelée in 1902, led them to conclude that they formed in a similar manner. They cover much larger areas than any observed during historic time and evidently erupted from long fissures rather than from central vents. Remember that lithified ash is the volcanic rock known as *tuff* (see Chapter 4), but the ash in many of these flows was so hot that the particles fused to form *welded tuff.*

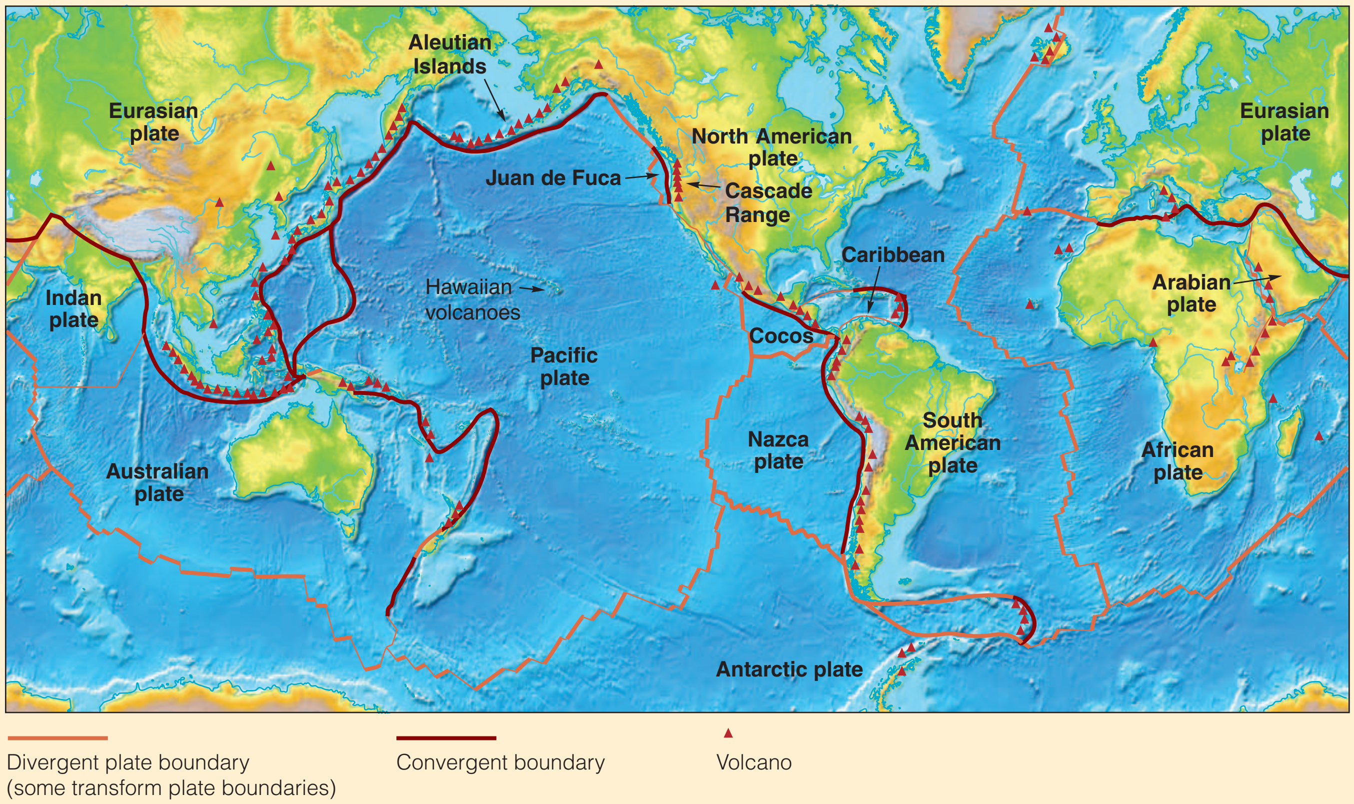
Some of these vast pyroclastic sheet deposits formed during the voluminous eruptions that were followed by the origin of calderas. For instance, pyroclastic flows were erupted during the formation of Crater Lake in Oregon (▶ Figure 5.9). Similarly, the Bishop Tuff of eastern California was erupted shortly before the origin of the Long Valley caldera. It is interesting that earthquakes in the Long Valley caldera and nearby areas beginning in 1978 and the escape of volcanic gases may indicate that magma is moving up beneath part of the caldera.

PHYSICAL Geology Now™ Log into GeologyNow and select this chapter to work through a **Geology Interactive** activity on "Magma Chemistry and Explosivity" (click Volcanism⟶Magma Chemistry and Explosivity) and on "Volcano Watch, USA" (click Volcanism⟶Volcano Watch, USA).

Section 5.4 Summary

- Fluid mafic lava erupted from fissures spreads over large areas to form a basalt plateau.
- Pyroclastic sheet deposits result when huge eruptions of ash and other pyroclastic materials take place, especially when calderas form.

▶ **Figure 5.20 Volcanoes at Convergent and Divergent Plate Boundaries** Most volcanoes are at or near convergent and divergent plate boundaries in two main belts. The circum-Pacific belt has about 60% of all active volcanoes, and about 20% of all active volcanoes are in the Mediterranean belt. Most of the rest are near mid-oceanic ridges (divergent plate boundaries), but not all of them are shown on this map. For example, Axial volcano lies on the Juan de Fuca Ridge west of Oregon.



5.5 The Distribution of Volcanoes

■ *Where are the three zones or belts with most of Earth's volcanoes?*

Rather than being randomly distributed volcanoes are found mostly in three well-defined belts: the circum-Pacific belt, the Mediterranean belt, and along the mid-oceanic ridges. You have probably heard of the *Ring of Fire*, a phrase that alludes to the fact that a nearly continuous belt of volcanoes encircles the Pacific Ocean basin. Geologists refer to this as the **circum-Pacific belt,** where more than 60% of all active volcanoes are found. It includes the volcanoes in South and Central America, those in the Cascade Range of North America, and the volcanoes in Alaska, Japan, the Philippines, Indonesia, and New Zealand (▶ Figure 5.20). Also included in this belt are the southernmost active volcanoes at Mount Erebus in Antarctica, and a large caldera at Deception Island that last erupted in 1970.

The second major area of volcanism is the **Mediterranean belt,** with about 20% of all active volcanoes (▶ Figure 5.20). The famous Italian volcanoes include Mount Etna, which has issued lava flows on more than 200 occasions since 1500 B.C., when activity was first recorded. Mount Vesuvius, also in the Mediterranean belt, erupted violently in A.D. 79 and destroyed Pompeii, Herculaneum, and Stabiae (see Section 5.1). Remember that Mount Vesuvius has erupted 80 times since A.D. 79. Another important volcano in this belt is the Greek island of Santorini.

Most of the remaining 20% of active volcanoes are at or near mid-oceanic ridges or their extensions onto land (▶ Figure 5.20). The volcanoes at or near mid-oceanic ridges include those along the East Pacific Rise, the Mid-Atlantic Ridge, and the Indian Ridge, which account for submarine eruptions as well as the volcanic islands in the Pacific, Atlantic, and Indian Oceans. Iceland in the Atlantic Ocean, for instance, is found on the Mid-Atlantic Ridge. Branches of the Indian Ridge extend into the Red Sea and East Africa, where several volcanoes are found, including Kilamanjaro in Tanzania, Nyiragongo in the Democratic Republic of Congo, and Erta Ale in Ethiopia with its continuously active lava lake.

Anyone with a passing familiarity with volcanoes will have noticed that we have not mentioned the Hawaiian volcanoes. This is not an oversight; they are the notable exceptions to the distribution of active volcanoes in well-defined belts. We discuss their location and significance in Section 5.7, Plate Tectonics, Volcanoes, and Plutons.

PHYSICAL Geology Now™ Log into GeologyNow and select this chapter to work through a **Geology Interactive** activity on "Distribution of Volcanism" (click Volcanism→ Distribution of Volcanism).

Section 5.5 Summary

- About 60% of all active volcanoes are in the circum-Pacific belt, another 20% are in the Mediterranean belt, and the remaining 20% are mostly at or near mid-oceanic ridges or their extensions onto land.

5.6 North America's Active Volcanoes

We mentioned in the previous section that part of the circum-Pacific belt includes volcanoes in the Pacific Northwest as well as those in Alaska. Both of these areas of volcanism are at convergent plate boundaries. Of the 80 or so potentially active volcanoes in Alaska, at least half have erupted since 1760. Indeed, as of this writing, three Alaskan volcanoes were erupting—Mount Spurr, Veniaminof volcano, and Shishaldin volcano.

The other active North American volcanoes are in the Cascade Range in the Pacific Northwest where the Juan de Fuca plate is subducted beneath North America. Many of these volcanoes have been historically active, although during the 1900s only Lassen Peak in California and Mount St. Helens in Washington erupted. And of course Mount St. Helens began erupting again during late September 2004.

Alaska's Volcanoes

Many of the volcanoes in mainland Alaska and in the Aleutian Islands are composite volcanoes, some with huge calderas (▸ Figure 5.20). Mount Spurr has erupted explosively at least 35 times during the last 5000 years, but its eruptions pale by comparison with that of Novarupta in 1912. Novarupta Volcano now lies in Katmai National Park and Preserve, which has a total of 15 active volcanoes. Its defining event was the June 1912 eruption, the largest in the world since the late 1800s. At least 15 km^3 and perhaps as much as 23 km^3 of volcanic materials, mostly pyroclastic materials, erupted during about 60 hours. "The expulsion of such a large volume of magma excavated a funnel-shaped vent 2 kilometers wide and triggered the collapse of Mount Katmai volcano 10 kilometers away."*

When the eruption was over, 120 km^2 of land was buried beneath pyroclastic deposits as deep as 213 m. In fact, the deposits filled the Valley of Ten Thousand Smokes—so named because of the hundreds of fumaroles where gases vented through the hot deposits for as long as 15 years following the eruption. Fortunately, the eruption took place in a remote area so there were no injuries or fatalities, but enough ash, gases, and pumice were ejected that for several days the sky was darkened over much of the Northern Hemisphere.

By the time you read this chapter, several more volcanoes in Alaska will have erupted as the Pacific Plate moves relentlessly northward only to be subducted at the Aleutian Trench. The Alaska Volcanoes Observatory in Anchorage, Alaska, continues to monitor these volcanoes and issue warnings about potential eruptions.

The Cascade Range

- *Where is the Cascade Range and what types of volcanoes are found there?*

The **Cascade Range** stretches from Lassen Peak in northern California north through Oregon and Washington to Meager Mountain in British Columbia, Canada, which erupted 2350 years ago (see "Cascade Range Volcanoes" on pp. 154–155). Most of the large volcanoes in the range are composite volcanoes, such as Mount Shasta in California (▸ Figure 5.13c), Mount Hood in Oregon, and Mount St. Helens in Washington, but Lassen Peak in California is the world's largest lava dome. Actually it is a rather small volcano that developed 27,000 years ago on the flank of a much larger, deeply eroded composite volcano. It erupted from 1914 to 1917 but has since been quiet except for ongoing hydrothermal activity.

Two large shield volcanoes lie just to the east of the main Cascade Range volcanoes—Medicine Lake Volcano in California and Newberry Volcano in Oregon. Distinctive features at Newberry Volcano are a 1600-year-old obsidian flow and casts of trees that formed when lava flowed around them and solidified. Cinder cones are common throughout the range, such as Wizard Island in Crater Lake, Oregon (▸ Figure 5.9e), and Cinder Cone in Lassen Volcanic National Park, California (▸ Figure 5.12).

What was once a nearly symmetrical composite volcano changed markedly on May 6, 1980, when Mount St. Helens in Washington erupted explosively, killing 63 people and thousands of animals and leveling some 600 km^2 of forest (see "Cascade Range Volcanoes" on pp. 154–155). Geologists, citing Mount St. Helens's past explosive eruptions, warned that it was the most likely

*From Brantley, 1994. *Volcanoes in the United States.* USGS General Interest Publication, p. 30.

Cascade Range volcano to erupt violently. In fact, a huge lateral blast caused much of the damage and fatalities, but snow and ice on the volcano melted and pyroclastic materials displaced water in lakes and rivers, causing lahars and extensive flooding.

Mount St. Helens's renewed activity beginning in late September 2004 has resulted in dome growth and small steam and ash explosions. At the time of this writing (February 2005), scientists at the Cascades Volcano Observatory in Vancouver, Washington, have issued a low-level alert for an eruption, but they think that if one takes place it will be much less violent than the one in 1980.

Several of the Cascade Range volcanoes will almost certainly erupt again, but the most dangerous is probably Mount Rainier in Washington. Rather than lava flows or even a colossal explosion, the greatest danger from Mount Rainier is volcanic mudflows or huge debris flows. Of the 60 large flows that have occurred during the last 100,000 years, the largest, consisting of 4 km^3 of debris, covered an area now occupied by more than 120,000 people. Indeed, in August 2001 a sizable debris flow took place on the south side of the mountain, but it caused no injuries or fatalities. No one knows when the next flow will take place, but at least one community has taken the threat seriously enough to formulate an emergency evacuation plan. Unfortunately, the residents would have only 1 or 2 hours to carry out the plan.

Section 5.6 Summary

- Since 1760 more than 40 volcanoes have erupted in Alaska, including the Aleutian Islands, some of them many times. The largest volcanic outburst since the late 1800s took place at Novarupta in Alaska in 1912.
- The Cascade Range includes volcanoes in northern California, Oregon, Washington, and British Columbia, Canada. Only three eruptions have occurred since 1914, one at Lassen Peak in California (1914–1917) and two at Mount St. Helens in Washington (1980 and 2004–2006).
- The large volcanoes in Alaska and the Cascade Range are mostly composite volcanoes, although some shield volcanoes are present and both areas have many cinder cones.

5.7 Plate Tectonics, Volcanoes, and Plutons

In Chapter 2 we noted that plate tectonic theory is a unifying theory in geology that explains many seemingly unrelated geologic phenomena. So how do we relate the eruption of volcanoes and the emplacement of plutons to plate tectonics? You already know from Chapter 4 that (1) mafic magma is generated beneath spreading ridges and (2) intermediate magma and felsic magma form where an oceanic plate is subducted beneath another oceanic plate or where an oceanic plate is subducted beneath a continental plate. Accordingly, most of Earth's volcanism and emplacement of plutons take place at or near divergent and convergent plate boundaries.

Divergent Plate Boundaries and Igneous Activity

- *What kinds of igneous rocks make up the oceanic crust?*

Much of the mafic magma that forms beneath spreading ridges is emplaced at depth as vertical dikes and gabbro plutons. But some rises to the surface, where it forms submarine lava flows and pillow lava (▶ Figure 5.7). Indeed, the oceanic crust is composed largely of gabbro and basalt. Much of this submarine volcanism goes undetected, but researchers in submersible craft have observed the results of these eruptions.

Pyroclastic materials are not common in this environment because mafic lava is very fluid, allowing gases to escape easily, and at great depth, water pressure prevents gases from expanding. Accordingly, the explosive eruptions that yield pyroclastic materials are not common. If an eruptive center along a ridge builds above sea level, however, pyroclastic materials may be erupted at lava fountains, but most of the magma issues forth as fluid lava flows that form shield volcanoes.

Excellent examples of divergent plate boundary volcanism are found along the Mid-Atlantic Ridge, particularly where it is above sea level as in Iceland (▶ Figure 5.20). In November 1963 a new volcanic island, later named Surtsey, rose from the sea just south of Iceland. The East Pacific Rise and the Indian Ridge are areas of similar volcanism. Not all divergent plate boundaries are beneath sea level as in the previous examples. For instance, divergence and igneous activity are taking place in Africa at the East African Rift system (▶ Figure 5.20).

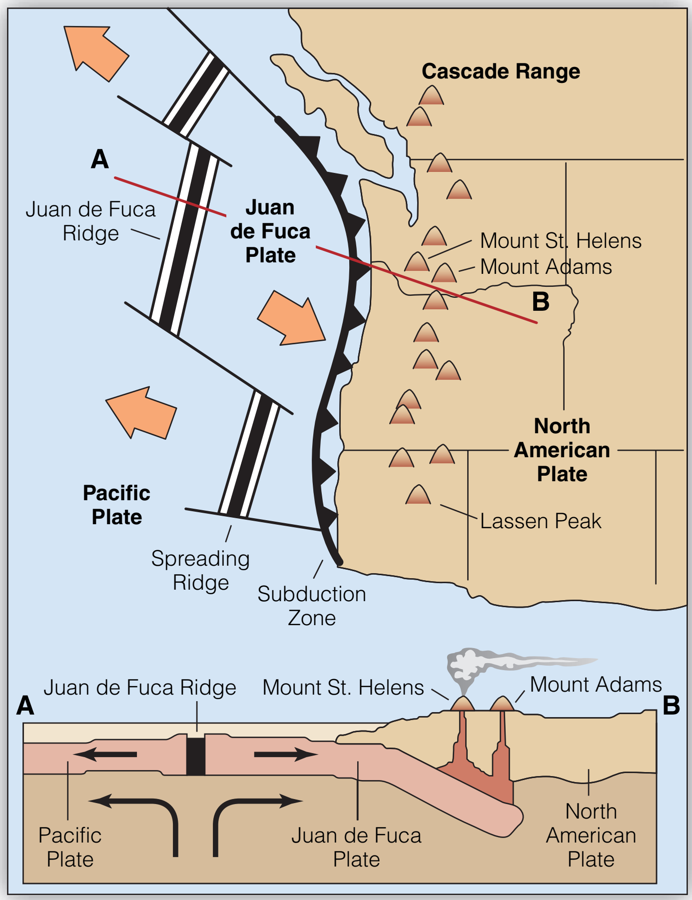
Igneous Activity at Convergent Plate Boundaries

Nearly all of the large active volcanoes in both the circum-Pacific and Mediterranean belts are composite volcanoes near the leading edges of overriding plates at convergent plate boundaries (▶ Figure 5.20). The overriding plate, with its chain of volcanoes, may be oceanic as in the case of the Aleutian Islands, or it may be continental as is, for instance, the South American plate with its chain of volcanoes along its western edge.

As we have noted, these volcanoes at convergent plate boundaries consist largely of lava flows and pyroclastic materials of intermediate to felsic composition. Remember

Cascade Range Volcanoes

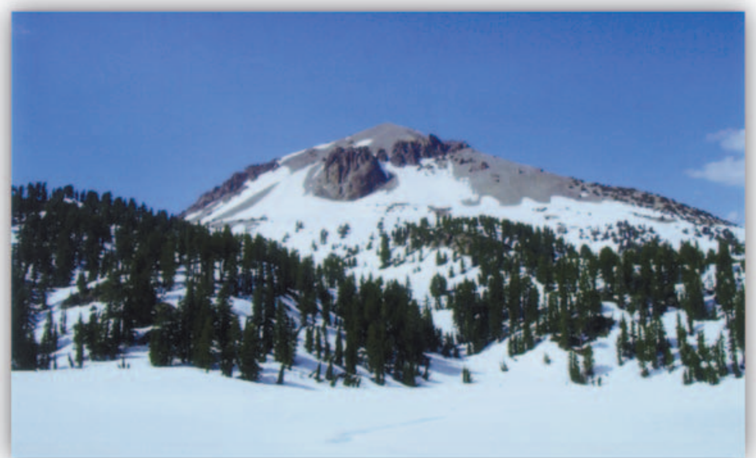
Several large volcanoes and hundreds of smaller volcanic vents are in the Cascade Range, which stretches from northern California into southern British Columbia, Canada. Medicine Lake Volcano and Newberry Volcano are shield volcanoes that lie just east of the main trend of the Cascade Range.



▲ **1.** Plate tectonic setting for the Pacific Northwest. Subduction of the Juan de Fuca plate beneath North America accounts for the continuing volcanism in this region.

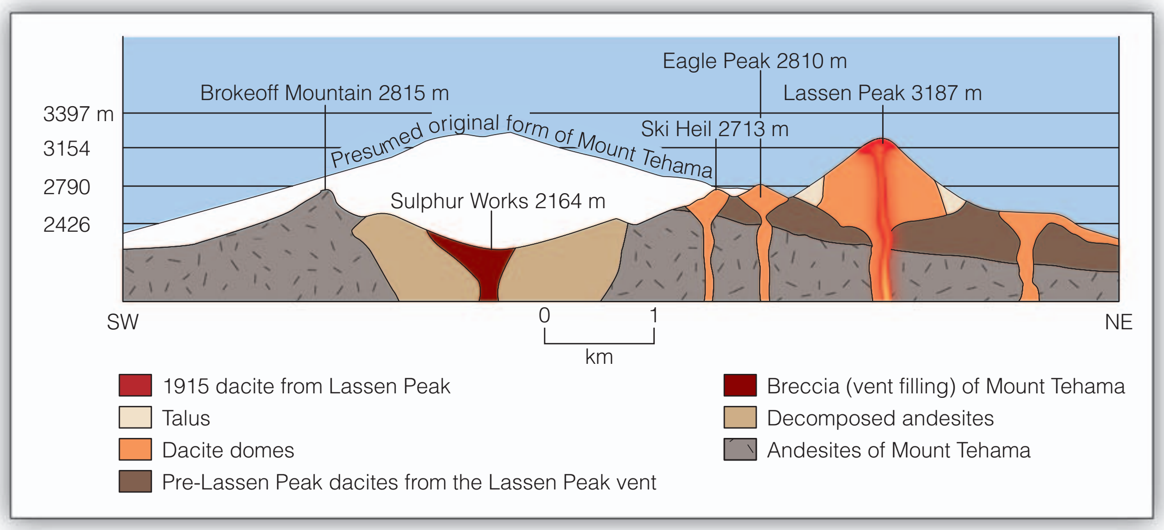
Sue Monroe

▲ **4.** A huge steam explosion called the Great Hot Blast leveled the area in the foreground in 1915. In the 89 years since the eruption, trees are becoming reestablished in this area, known as the Devastated Area.



Sue Monroe

▶ **3.** Lassen Peak today. This most southerly peak in the Cascade Range is made up of 2 km³ of material, including the bulbous masses of rock visible in this image.



USGS

▶ **2.** Lassen Peak is a dacite lava dome that formed 27,000 years ago on the flank of an eroded composite volcano called Mount Tehama. Dacite has a composition between andesite and rhyolite.

5. Lassen Peak erupted numerous times from 1914 to 1917. This eruption took place in 1915.

6. Mount St. Helens, a composite volcano, as it appeared from the east in 1978.

D. R. Crandel/USGS

Courtesy of Keith Ronnholm

7. Mount St. Helens. The lateral blast on May 18, 1980, took place when a bulge on the volcano's north face collapsed, reducing the pressure on gas-charged magma. The lateral blast killed 63 people and leveled 600 km^2 of forest.

PhotoDisc/Getty Images

9. Shortly after the lateral blast, this 19-km-high ash and steam cloud erupted from Mount St. Helens.

8. Mount St. Helens in Washington began erupting during late September 2004. Earthquakes beneath the peak as well as eruptions of gases and ash continue into 2006, but geologists at the Cascade Volcano Observatory in Vancouver, Washington, do not expect an outburst as devastating as the one on May 18, 1980.

Steve Schilling/USGS

that when mafic oceanic crust partially melts, some of the magma generated is emplaced near plate boundaries as plutons and some is erupted to build up composite volcanoes. More viscous magmas, usually of felsic composition, are emplaced as lava domes, thus accounting for the explosive eruptions that typically occur at convergent plate boundaries.

In previous sections, we mentioned several eruptions at convergent plate boundaries. Good examples are the explosive eruptions of Mount Pinatubo and Mayon volcano in the Philippines, both of which are situated near a plate boundary beneath which an oceanic plate is subducted. Mount St. Helens in Washington is similarly situated, but it is on a continental rather than an oceanic plate (see "Cascade Range Volcanoes" on pp. 154–155). Mount Vesuvius in Italy, one of several active volcanoes in that region, lies on a plate that the northern margin of the African plate is subducted beneath.

Intraplate Volcanism

■ *How do plate tectonics and volcanism account for the origin of the Hawaiian Islands?*

Mauna Loa and Kilauea on the island of Hawaii and Loihi just 32 km to the south are within the interior of a rigid plate far from any divergent or convergent plate boundary (▶ Figure 5.20). The magma is derived from the upper mantle, as it is at spreading ridges, and accordingly is mafic so it builds up shield volcanoes. Loihi is particularly interesting because it represents an early stage in the origin of a new Hawaiian island. It is a submarine volcano that rises higher than 3000 m above the seafloor, but its summit is still about 940 m below sea level.

Even though the Hawaiian volcanoes are not at a spreading ridge near a subduction zone, their evolution is related to plate movements. Notice in Figure 2.22 that the ages of the rocks that make up the various Hawaiian Islands increase toward the northwest; Kauai formed 3.8 to 5.6 million years ago, whereas Hawaii began forming less than 1 million years ago, and Loihi began to form even more recently. Continuous movement of the Pacific plate over the hot spot, now beneath Hawaii and Loihi, has formed the islands in succession.

Section 5.7 Summary

- Most of the magma that is emplaced as plutons or that rises to the surface as lava at divergent plate boundaries is mafic, even where divergence takes place on land, as in East Africa.
- Igneous activity at convergent plate boundaries involves mostly intermediate and felsic magma and lava. Huge plutons such as batholiths as well as composite volcanoes are common in this geologic setting.

5.8 Volcanic Hazards, Volcano Monitoring, and Forecasting Eruptions

You no doubt suspect that living near an active volcano poses some risk, and of course this is a correct assessment. But what exactly are volcanic hazards, is there any way to anticipate eruptions, and what can we do to minimize the dangers from eruptions? We already mentioned that lava flows pose little danger to humans, but there are exceptions. In 1977 a lava lake in the crater of Nyiragongo volcano in the Democratic Republic of Congo (formerly Zaire) suddenly drained through a fracture and killed 70 people (300 in some reports) and a herd of elephants. More recently, on January 17, 2002, a lava flow from Nyiragongo sliced through the city of Goma, 19 km south, destroying everything in a 60-m-wide path (▶ Figure 5.21a). The lava ignited fires and huge explosions where it came into contact with gasoline storage tanks, killing 147 people. Nevertheless, lava flows are low on the list of direct dangers to humans, although they may destroy croplands, houses, roadways, and other structures.

■ *What are the most dangerous manifestations of volcanoes?*

Of much greater concern than lava flows are nuée ardentes, volcanic gases, lahars, and landslides (▶ Figure 5.21). Indeed, the latter two phenomena may take place even when no eruption has occurred for a long time. And remember that volcanic gases caused many fatalities in Cameroon and Iceland.

The areas most vulnerable to volcanic hazards in the United States are Alaska, Hawaii, California, Oregon, and Washington, but some other parts of the western states might also experience renewed volcanism. Canada's most recent eruption took place in northern British Columbia about 150 years ago, but there is the potential for future eruptions from volcanoes in the northern Cascade Range. The greatest threat may be from Mount Baker in Washington, which lies about 24 km south of the U.S.–Canadian border. It last erupted in 1870.

The Size and Duration of Eruptions

The most widely used indication of the size of a volcanic eruption is the **volcanic explosivity index (VEI)** (▶ Figure 5.22). The VEI has numerical values corresponding to eruptions characterized as gentle, explosive, and cataclysmic. It is based on several aspects of an eruption, particularly the volume of material explosively ejected and the height of the eruption cloud; the volume of lava, fatalities, and property damage are not considered. The 1985 eruption of Nevado del Ruiz in Colombia killed 23,000 people yet had a VEI value of only 3, whereas the huge eruption (VEI = 6) of Novarupta in Alaska in 1912 caused no fatalities or injuries. Since A.D. 1500, only the 1815 eruption of Tambora in Indonesia has had a VEI

▶ **Figure 5.21 Volcanic Hazards** A volcanic hazard is any manifestation of volcanism that poses a threat, including lava flows and, more importantly, volcanic gas, ash, and lahars.

AFP/Getty Images

a This 2002 lava flow in Goma, Democratic Republic of Congo, killed 147 people, mostly by causing gasoline storage tanks to explode.

Sue Monroe

b This sign at Mammoth Mountain volcano in California warns of the potential danger of CO_2 gas, which has killed 170 acres of trees.

Reuters/Corbis

c When Mount Pinatubo in the Philippines erupted on June 15, 1991, this huge cloud of ash and steam formed over the volcano.

value of 7; it was both large and deadly (Table 5.1). Geologists have assigned VEI values to nearly 5700 eruptions that took place during the last 10,000 years, but none has exceeded 7 and most (62%) have a value of 2.

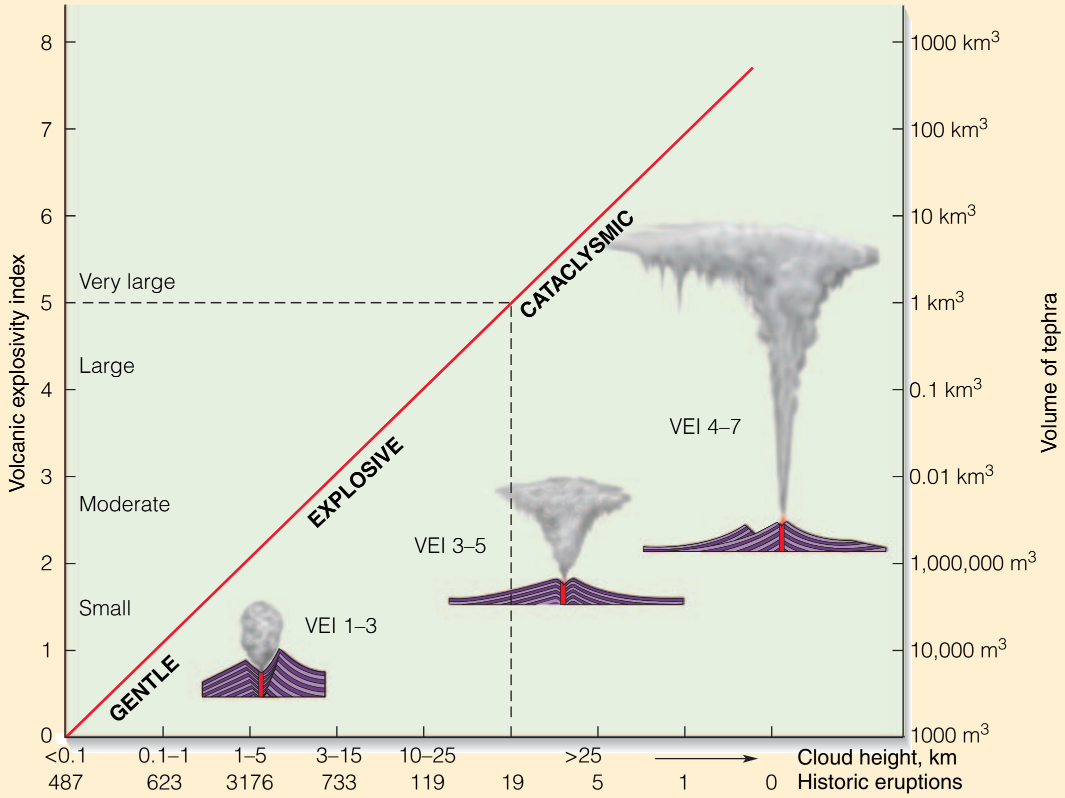
The duration of eruptions varies considerably. Fully 42% of about 3300 historic eruptions lasted less than one month. About 33% erupted for one to six months, but some 16 volcanoes have been active more or less continuously for longer than 20 years. Stromboli and Mount Etna in Italy and Erta Ale in Ethiopia are good examples. In some explosive volcanoes, the time from the onset of their eruptions to the climactic event is weeks or months. A case in point is the explosive eruption of Mount St. Helens on May 18, 1980, which occurred two months after eruptive activity began. Unfortunately, many volcanoes give little or no warning of large-scale eruptions; of 252 explosive eruptions, 42% erupted most violently during their first day of activity. As one might imagine, predicting eruptions is complicated by those volcanoes that give so little warning of impending activity.

Forecasting Eruptions

Only a few of Earth's potentially dangerous volcanoes are monitored, including some in Japan, Italy, Russia, New Zealand, and the United States. Many of the methods now used to monitor volcanoes were developed at the Hawaiian Volcano Observatory.

Volcano monitoring involves recording and analyzing physical and chemical changes at volcanoes. Geologists may use various instruments to detect ground deformation—that is, changes in a volcano's slopes as it inflates when magma rises beneath it. Using some instruments requires that geologists actually visit a potentially dangerous volcano, but now

▶ **Figure 5.22 The Volcanic Explosivity Index** The volcanic explosivity index (VEI). In this example, an eruption with a VEI value of 5 has an eruption cloud up to 25 km high and ejects about 1 km³ of tephra, a collective term for all pyroclastic materials.



global positioning system (GPS) technology allows them to monitor a volcano from a safe distance (▶ Figure 5.23). During the renewed activity at Mount St. Helens beginning in September 2004, helicopters placed GPS instruments on the lava dome in the volcano's crater. Geologists also monitor gas emissions, changes in groundwater level and temperature, hot springs activity, and changes in local magnetic and electrical fields. Even the accumulating snow and ice, if any, are evaluated to anticipate hazards from floods should an eruption take place.

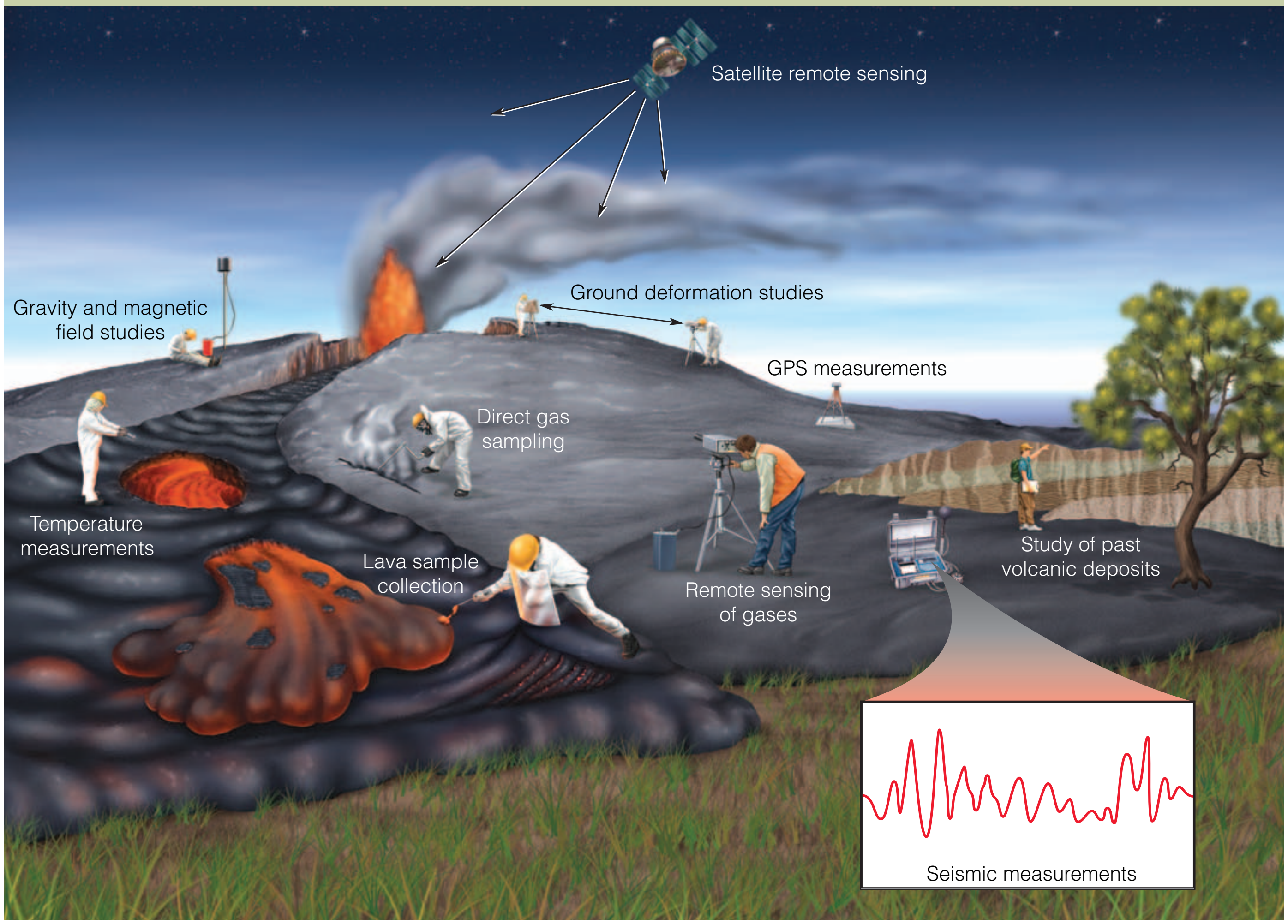
Of critical importance in volcano monitoring and warning of an imminent eruption is the detection of **volcanic tremor,** the continuous ground motion lasting for minutes to hours as opposed to the sudden, sharp jolts produced by most earthquakes. Volcanic tremor, also known as *harmonic tremor*, indicates that magma is moving beneath the surface.

Geologists study the record of past eruptions preserved in rocks to better anticipate the future activity of a volcano. Detailed studies before 1980 indicated that Mount St. Helens had erupted explosively 14 or 15 times during the last 4500 years, so geologists concluded that it was one of the most likely Cascade Range volcanoes to erupt again. In fact, the maps they prepared showing areas in which damage from an eruption could be expected were helpful in determining which areas should have restricted access and evacuations once an eruption did take place.

Geologists successfully gave timely warnings of impending eruptions of Mount St. Helens in Washington and Mount Pinatubo in the Philippines, but in both cases the climactic eruptions were preceded by eruptive activity of lesser intensity. In some cases, however, the warning signs are much more subtle and difficult to interpret. Numerous small earthquakes and other warning signs indicated to geologists of the U.S. Geological Survey (USGS) that magma was moving beneath the surface of the Long Valley caldera in eastern California, so in 1987 they issued a low-level warning and then nothing happened.

Volcanic activity in the Long Valley caldera occurred as recently as 250 years ago, and there is every reason to think it will occur again, but when it will take place is an unanswered question. Unfortunately, the local populace was largely unaware of the geologic history of the region, the USGS did a poor job in communicating its concerns, and premature news releases caused more concern than was justified. In any case, local residents where outraged because the warnings caused a decrease in tourism (Mammoth Mountain on the margins of the caldera is the second largest ski area in the country) and property values plummeted. Monitoring continues in the Long Valley caldera, and the signs of renewed volcanism, including earthquake swarms, trees being killed by carbon dioxide gas apparently emanating from magma (▶ Figure 5.21b), and hot spring activity, cannot be ignored.

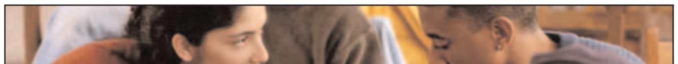
▶ **Figure 5.23 Volcanic Monitoring** Some important techniques used to monitor volcanoes.



For the better-monitored volcanoes, it is now possible to make accurate short-term predictions of eruptions. But for many volcanoes, little or no information is available.

Section 5.8 Summary

- Geologists have devised a volcanic explosivity index (VEI) to indicate the size of an eruption. VEI values depend on the volume of material erupted and the height of an eruption plume; fatalities and property damage are not considered.
- Although lava flows and lava fountains are impressive, the most dangerous manifestations of volcanoes are eruptions of pyroclastic materials, especially nuée ardentes, as well as mudflows and debris flows, which may take place even when a volcano is not erupting.
- Volcano monitoring involves evaluating physical and chemical aspects of volcanoes. Especially important for anticipating eruptions is detecting volcanic tremor and determining the eruptive history of a volcano.



What Would You Do?

No one doubts that some of the Cascade Range volcanoes will erupt again (actually Mount St. Helens in Washington was erupting when this was written in February 2005). But no one knows when future eruptions will take place or how large they will be. A job transfer takes you to a community in Oregon with several nearby volcanoes, and you have some concerns about future eruptions. What kinds of information about specific threats would you seek out before buying a home in this area? Also, as a concerned citizen, could you make any suggestions about what members of your community should do in case of an eruption?

Review Workbook

ESSENTIAL QUESTIONS SUMMARY

5.1 Introduction

■ *How can volcanism be both constructive and destructive?*
Volcanism may destroy houses and farmland and cause injuries and fatalities so it is destructive, but it is also constructive because it is responsible for the origin of many oceanic islands as well as the oceanic crust.

5.2 Volcanism and Volcanoes

■ *What gases do volcanoes commonly emit?*
Most volcanic gases are water vapor, with lesser amounts of carbon dioxide, nitrogen, sulfur dioxide, and hydrogen sulfide, and very small amounts of carbon monoxide, hydrogen, and chlorine.

■ *How and why do aa and pahoehoe lava flows differ?*
Aa is made up of angular blocks and fragments, whereas pahoehoe has a smooth surface much like taffy. The flows differ mostly because aa is viscous enough to fragment.

■ *What are pyroclastic materials, and how are they dangerous to air traffic?*
Pyroclastic materials are solids, including ash, lapilli, blocks, and bombs, that are explosively ejected by volcanoes. Ash is dangerous to aircraft because it fouls jet engines.

5.3 Types of Volcanoes

■ *What are calderas and how do they form?*
A caldera is a large oval to circular volcanic depression that forms when the summit of a volcano collapses into its magma chamber following voluminous eruptions.

■ *What are cinder cones and what are they composed of?*
Cinder cones are small, steep-sided volcanoes made up of pyroclastic materials that resemble cinders.

■ *What are lava domes and why are they so dangerous?*
Lava domes are bulbous masses of viscous magma that commonly erupt explosively.

5.4 Other Volcanic Landforms

■ *How do basalt plateaus form?*
Basalt plateaus are made up of numerous overlapping basalt lava flows that erupt from fissures rather than from a central vent.

■ *What are pyroclastic sheet deposits?*
Huge eruptions of pyroclastic materials, especially ash, from fissures that form during the origin of calderas are responsible for pyroclastic sheet deposits.

5.5 The Distribution of Volcanoes

■ *Where are the three zones or belts with most of Earth's volcanoes?*
About 60% of all active volcanoes are in the circum-Pacific belt, another 20% are in the Mediterranean belt, and most of the remaining 20% are at or near mid-oceanic ridges or their extensions onto land.

5.6 North America's Active Volcanoes

■ *Where is the Cascade Range and what types of volcanoes are found there?*
The Cascade Range stretches from Lassen Peak in California north through Oregon and Washington to Meager Mountain in British Columbia, Canada. Most of the large volcanoes in the range are composite volcanoes, but there are also two huge shield volcanoes and numerous cinder cones.

5.7 Plate Tectonics, Volcanoes, and Plutons

■ *What kinds of igneous rocks make up the oceanic crust?*
The oceanic crust is made up of mafic igneous rocks. Gabbro is found in the lower part of the oceanic crust, whereas vertical dikes and pillow lava, both composed of basalt, make up the upper part.

■ *How do plate tectonics and volcanism account for the origin of the Hawaiian Islands?*
As the Pacific plate moved over a hot spot, a chain of volcanoes formed in succession, so the oldest in the chain is far to the northwest and active volcanism now occurs only on the island of Hawaii and at Loihi.

5.8 Volcanic Hazards, Volcano Monitoring, and Forecasting Eruptions

■ *What are the most dangerous manifestations of volcanoes?*
Lava dome eruptions during which huge amounts of pyroclastic materials and gases are ejected are the most dangerous volcanic eruptions. Lahars are also dangerous and they may take place long after an eruption.

ESSENTIAL TERMS TO KNOW

aa (p. 137)
ash (p. 139)
basalt plateau (p. 149)
caldera (p. 141)
Cascade Range (p. 152)
cinder cone (p. 141)
circum-Pacific belt (p. 151)
columnar joint (p. 138)
composite volcano (stratovolcano) (p. 144)
crater (p. 141)
fissure eruption (p. 149)
lahar (p. 144)
lava dome (p. 144)
lava tube (p. 137)
Mediterranean belt (p. 151)
nuée ardente (p. 145)
pahoehoe (p. 137)
pillow lava (p. 139)
pyroclastic materials (p. 139)
pyroclastic sheet deposits (p. 150)
shield volcano (p. 141)
volcanic explosivity index (VEI) (p. 156)
volcanic tremor (p. 158)
volcanism (p. 136)
volcano (p. 141)

REVIEW QUESTIONS

1. Suppose you find rocks on land that consist of layers of pillow lava overlain by deep-sea sedimentary rocks. Where and how did the pillow lava form, and what type of rock would you expect to find beneath the pillow lava?
2. How do columnar joints and lava tubes form? Where are good places to see each?
3. What geologic events would have to take place for a chain of composite volcanoes to form along the east coasts of the United States and Canada?
4. Explain why eruptions of mafic lava are nonexplosive but eruptions of felsic magma are commonly explosive.
5. What does volcanic tremor indicate, and how does it differ from the shaking caused by most earthquakes?
6. Describe a nuée ardente and explain why they are so dangerous.
7. Why do shield volcanoes have such gentle slopes whereas cinder cones have very steep slopes?

APPLY YOUR KNOWLEDGE

1. Considering what you know about the origin of magma and about igneous activity, why is the magma (lava) at divergent plate boundaries mostly mafic, whereas at convergent plate boundaries it is mostly intermediate and felsic?
2. What criteria are used to assign a volcanic explosivity index (VEI) value to an eruption? Why do you think the number of fatalities and property damage are not considered when assigning a value?

FIELD QUESTIONS

1. The Mona Schist at Marquette, Michigan (see the image), is basalt that has been changed slightly by metamorphism. How do you think the elliptical features in this ancient lava formed?

James S. Monroe

PHYSICAL Geology Now™ ▶ **Geo-focus Figure**

2. The accompanying image shows part of the Giant's Causeway in Northern Ireland. How did these vertical columns form?

James S. Monroe

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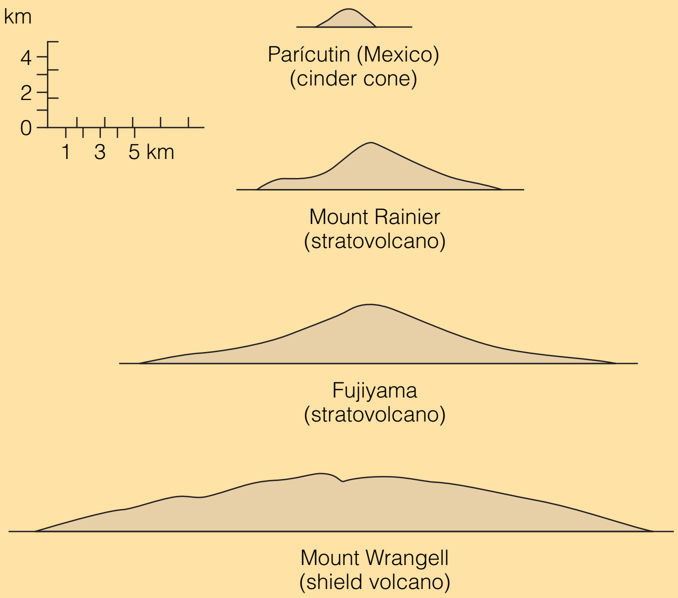
3. Identify the types of volcanoes shown in the diagram. Which of these do you think would erupt mostly violently? Why?



4. The accompanying image shows a basalt lava flow (black) overlying a layer of pyroclastic materials (light colored) in Colorado. Why is the upper part of the pyroclastic layer discolored?

James S. Monroe

PHYSICAL Geology Now™ ▶ **Geo-focus Figure**

GEOLOGY IN FOCUS The Bronze Age Eruption of Santorini

Crater Lake in Oregon, which formed about 7700 years ago, is the best-known caldera in the United States (Figure 5.9), but many others are equally impressive. One that formed recently, geologically speaking, resulted from a Bronze Age eruption of Santorini, an event that figured importantly in Mediterranean history (▶ Figure 1a). Actually, Santorini consists of five islands in that part of the Mediterranean called the Aegean Sea. The islands have a total area of 76 km^2, all of which owe their present configuration to a colossal volcanic eruption that took place about 3600 years ago (estimates range from 1596 BC to 1650 BC). Indeed, the eruption was responsible for the present islands, the origin of the huge caldera, and it probably accounted for or at least contributed to the demise of the Minoan culture on Crete. Furthermore, some authorities think that the disappearance of much of the original island during this eruption was the basis for Plato's story about Atlantis (see Chapter 12).

As you approach Santorini from the sea, the first impression is snow-covered cliffs in the distance. On closer inspection, though, the "snow" is actually closely spaced white buildings that cover much of the higher parts of the largest island (▶ Figure 1b). Perhaps the most impressive features of Santorini are the near vertical cliffs rising as much as 350 m from the sea. Actually, these cliffs are the walls of a caldera that measures about 6 by 12 km and is as much as 400 m deep. The caldera-forming eruption, "known as the 'Minoan eruption,' ejected into the air 30 cubic kilometers of magma in the form of pumice and volcanic ash. This material buried the island [as much as 50 m deep] and its civilization. . . ."[1] The two small islands within the caldera, where volcanic activity continues, appeared above sea level in 197 BC, and since then have grown to their present size. The most recent activity occurred in 1950 on the larger of the two islands (▶ Figure 1a).

Santorini volcano began forming two million years ago, and during the last 400,000 years it has erupted at least 100 times, each eruption adding new layers to the island, making it larger. Today, about 8000 people live on the islands, and we know from archaeological evidence that several tens of thousand of people resided there before the Minoan eruption when Santorini was larger. However, a year or so before the catastrophic eruption, a devastating earthquake occurred and many people left the island then; perhaps there were signs of an impending eruption by this time.

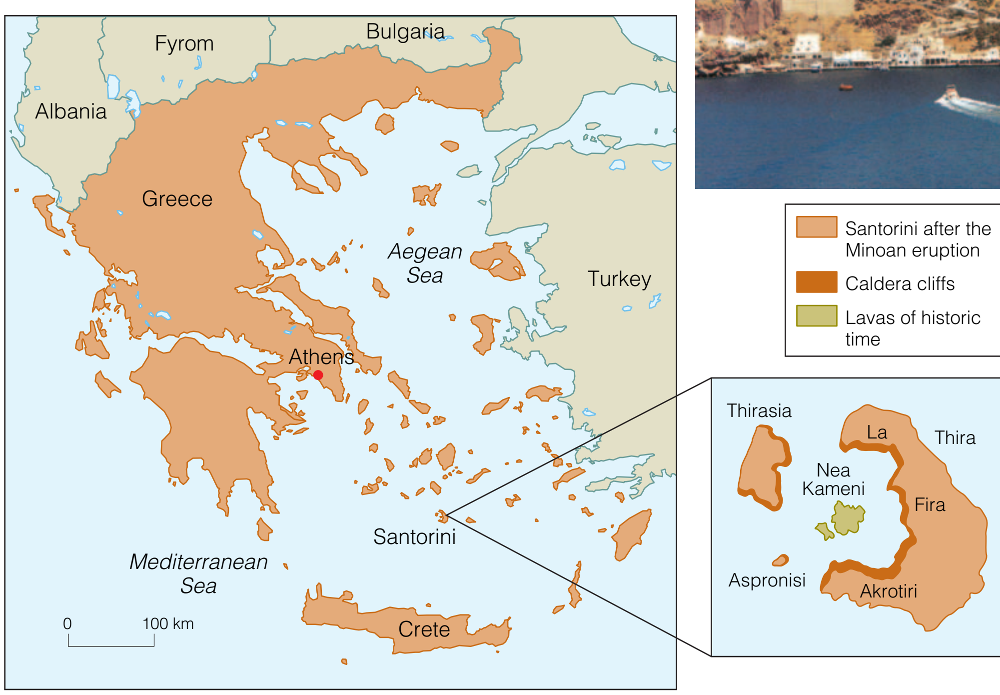
The fact that the island's residents escaped is indicated by the lack of human and animal skeletons in the ruins of the civilization, the only exception being one pig skeleton. In fact, archaeological excavations, many still in progress, show that the people had time to collect their valuables and tools before evacuating the island. Their destination, however, remains a mystery.

[1]Vougioukalakis, G., *Santorini: The Volcano* (Institute for the Study and Monitoring of the Santorini Volcano, 1995), p. 7.

James S. Monroe

(b)

Figure 1
The Minoan eruption of Santorini that took place between 1596 and 1650 B.C. formed a large caldera. It may have contributed to the demise of the Minoan culture on Crete and may be the basis for Plato's account of the sinking of Atlantis. **(a)** Map showing Santorini and nearby areas in the Aegean Sea, which is part of the northwestern Mediterranean Sea. **(b)** These 350-m-high cliffs are part of the caldera wall just west of Fira.



(a)

GEOLOGY IN UNEXPECTED PLACES

Oldoinyo Lengai Volcano

The East African Rift is not an unexpected place for volcanoes, but the one known as Oldoinyo Lengai (or Ol Doinyo Lengai) in Tanzania is certainly among Earth's most peculiar volcanoes. Oldoinyo Lengai, which means "Mountain of God" in the Masai language, is an active composite volcano standing about 2890 m high (▶ Figure 1a). It is one of 20 or so volcanoes in an east-west belt near the southern part of the East African Rift, a divergent plate boundary (see Figure 2.16a). Oldoinyo Lengai is peculiar because it is the world's only volcano that erupts carbonatite lava rather than lava with abundant silica. *Carbonatite* refers to an igneous rock with at least 50% carbonatite minerals, that is, minerals with the $(CO_3)^{-2}$ radical. In fact, carbonatite looks much like the metamorphic rock marble (see Chapter 8).

Why is the carbonatite lava at Oldoinyo Lengai unique? Remember that based on silica content most magma ranges from mafic to felsic, or even ultramafic; only rarely does magma have the elements necessary to form carbonatite-rich rocks. Carbonatite is found at about 330 localities worldwide, but most of it is in small plutons and thus intrusive. So the carbonatite lava that erupts at Oldoinyo Lengai makes it unusual because it is extrusive. Another feature of the Oldoinyo Lengai carbonatite is that it contains significant amounts of sodium and potassium, whereas most carbonatites are made up of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$].

The carbonatite lava at Oldoinyo Lengai has some surprising characteristics. For one thing it is fluid at temperatures of only 540°C and 595°C, and because it has so little silica it has very low viscosity and flows quickly. Indeed, the temperature is so low that the lava is not incandescent, so we do not see the red glow we expect in lava flows. In fact, it looks more like black mud. And because the minerals in carbonatite are unstable, they react with water in the atmosphere and their color quickly changes to pale gray (▶ Figure 1b).

Until the 1960s, there was disagreement among geologists about the origin of carbonatite. Some thought that the carbonatite plutons noted above were made up of marble that was altered from limestone by heat and as a result looked like igneous rock. Observations at Oldoinyo Lengai, however, provided compelling evidence that carbonatite is found in lava flows as well as in plutons.

We now know that carbonatite is found in small plutons and erupts as lava, but geologists continue to debate the origin of carbonatite magma. Some think that it forms by partial melting of carbonatite rocks in Earth's crust, but others think it is not a primary magma at all but rather forms by alteration of sodium-rich carbonatite from which hydrothermal fluids removed the sodium.

Although the rocks at Oldoinyo Lengai have no economic importance, carbonatites elsewhere are mined because they have higher percentages of rare earth elements[1] that any other type of igneous rock. They are also sources of niobium, phosphates, and fluorite.

[1] Rare earth elements are 17 chemical elements that have similar atomic structures, atomic radii, and 3+ or 4+ electrical charges.

Figure 1
Of the hundreds of volcanoes in the world, Oldoinyo Lengai in Tanzania is one of the most unusual because it erupts lava that cools to form igneous rock rich in carbonate minerals. **(a)** Lava spattering from a small cone in the crater of Oldoinyo Lengai in 1990. **(b)** In 1994 this black lava from Oldoinyo Lengai flowed over a lava flow only a few months old that had already turned gray.

Courtesy of Frederick A. Belton

(a)

Celia Nyamweru

(b)

GEOLOGY IN YOUR LIFE

Do Volcanic Gases Cause Ozone Depletion?

Earth supports life because of its distance from the Sun, and the fact that it has abundant liquid water and an oxygen-rich atmosphere. An ozone layer (O_3) in the stratosphere (10 to 48 km above the surface) protects Earth because it blocks out most of the harmful ultraviolet radiation that bombards our planet. During the early 1980s, scientists discovered an *ozone hole* over Antarctica that has continued to grow. In fact, depletion of the ozone layer is now also recognized over the Arctic region and elsewhere. Any depletion in ozone levels is viewed with alarm because it would allow more dangerous radiation to reach the surface, increasing the risk of skin cancer, among other effects.

This discovery unleashed a public debate about the primary cause of ozone depletion, and how best to combat the problem. Scientists proposed that one cause of ozone depletion is chlorofluorocarbons (CFCs), which are used in various consumer products; for instance, in aerosol cans. According to this theory, CFCs rise into the upper atmosphere where reactions with ultraviolet radiation liberate chlorine, which in turn reacts with and depletes ozone (▶ Figure 1). As a result of this view, an international agreement called the Montreal Protocol was reached in 1983, limiting the production of CFCs, along with other ozone-depleting substances.

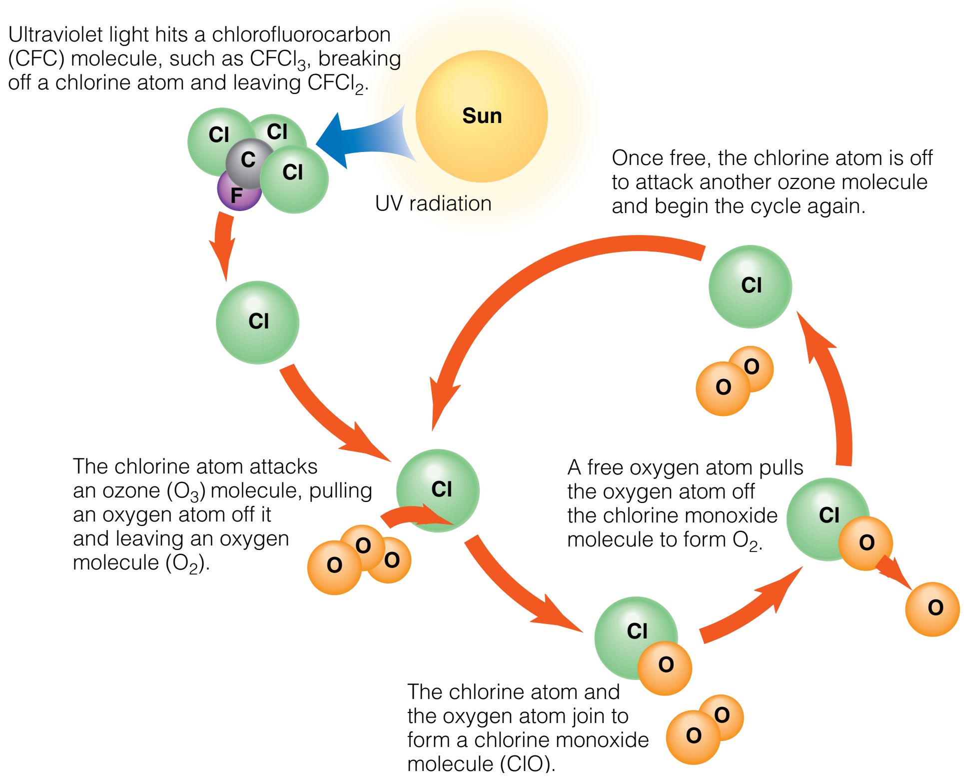
However, during the 1990s this view was challenged by some radio talk show hosts as well as a few government officials. They proposed an alternative idea that ozone depletion was because of natural causes rather than commercial products such as CFCs. They pointed out that volcanoes release copious quantities of hydrogen chloride (HCl) gas that rises into the stratosphere and which could be responsible for ozone depletion. Furthermore, they claimed that because CFCs are heavier than air they would not rise into the stratosphere.

It is true that volcanoes release HCl gas as well as several other gases, some of which are quite dangerous—recall the cloud of CO_2 gas in Cameroon that killed 1746 people and the Blue Haze Famine in Iceland. However, most eruptions are too weak to inject gases of any kind high into the stratosphere. Even when it is released, HCl gas from volcanoes is very soluble and quickly removed from the atmosphere by rain and even by steam (water vapor) from the same eruption that released HCl gas in the first place. Measurements of chlorine concentrations in the stratosphere show that only temporary increases occur following huge eruptions. For example, the largest volcanic outburst since 1912, the eruption of Mount Pinatubo in 1991, caused little increase in upper atmosphere chlorine. The impact of volcanic eruptions is certainly not enough to cause the average rate of ozone depletion taking place each year.

Although it is true that CFCs are heavier than air, this does not mean that they cannot rise into the stratosphere. Earth's surface heats differentially, meaning that more heat may be absorbed in one area than in an adjacent one. The heated air above a warmer area becomes less dense, rises by convection, and carries with it CFCs and other substances that are actually denser than air. Once in the stratosphere, ultraviolet radiation, which is usually absorbed by ozone, breaks up CFC molecules and releases chlorine that reacts with ozone. Indeed, a single chlorine atom can destroy 100,000 ozone molecules (▶ Figure 1). In contrast to the HCl gas produced by volcanoes, CFCs are absolutely insoluble; it is the fact that they are inert that made them so desirable for various uses. Because a CFC molecule can last for decades, any increase in CFCs is a long-term threat to the ozone layer.

Another indication that CFCs are responsible for the Antarctic ozone hole is that the rate of ozone depletion has slowed since the implementation of the Montreal Protocol. A sound understanding of the science behind these atmospheric processes helped world leaders act quickly to address this issue. Now scientists hope that with continued compliance with the Protocol, the ozone layer will recover by the middle of this century.

Figure 1
Ozone is destroyed by chlorofluorocarbons (CFCs). Chlorine atoms are continuously regenerated, so one chlorine atom can destroy many ozone molecules.

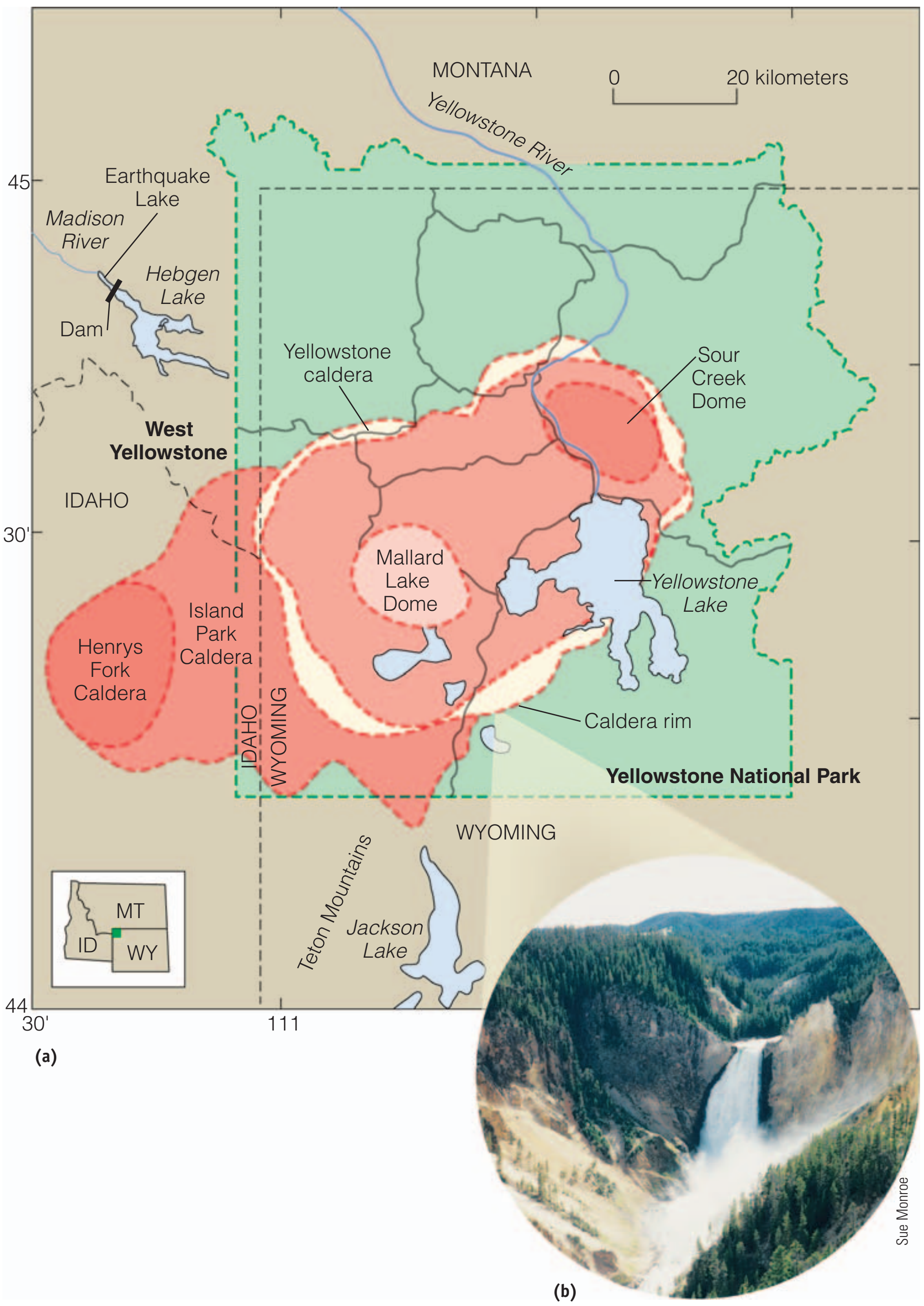


Geology AT WORK

Volcano Observatories and Volcano Monitoring

The United States Geological Survey maintains several volcano observatories around the country, each with the goal of monitoring local volcanic activity to add to our scientific understanding of volcanoes as well as to ensure public safety. Geologists at the Hawaii Volcano Observatory developed many of the methods now used to monitor volcanoes elsewhere, although other observatories have also contributed. The Alaska Volcano Observatory in Fairbanks monitors active volcanoes in that state, and issues warnings of imminent eruptions, particularly to aircraft. The David A. Johnston Cascades Volcano Observatory in Vancouver, Washington, was established following the 1980 eruption of Mount St. Helens and named for a geologist who was killed in the eruption. And the Long Valley Observatory at Menlo Park, California, monitors activity at Long Valley Caldera in eastern California. Personnel at the US Geological Survey operate the Yellowstone Volcano Observatory in cooperation with the University of Utah and the National Park Service. Their function is to monitor and assess possible hazards, and to conduct research at Yellowstone National Park in Wyoming, Montana, and Idaho.

Figure 1
(a) The Yellowstone caldera (shown in yellow) has been partly filled with younger volcanic rocks. **(b)** The walls of the Grand Canyon of the Yellowstone River are made up of the hydrothermally altered Yellowstone Tuff that partly fills the Yellowstone caldera.



(a)

(b)

The Yellowstone region has had a history of huge volcanic eruptions, although the most recent one was about 70,000 years ago. Why monitor an area so closely given that no volcanic outbursts have taken place for thousands of years? Continuing earthquake activity, 80 cm of uplift of the ground surface since 1923, and the hydrothermal activity (see Chapter 16) for which the park is famous, indicate that future eruptions are possible. And judging from the geologic record, renewed eruptions may be catastrophic.

Geologist have no formal definition for *supervolcano,* but we can take it to mean a volcano that erupts explosively, ejecting hundreds of cubic kilometers of pyroclastic materials followed by the origin of a vast caldera. No supervolcano eruption has occurred in recorded history, but geologists know of several that occurred during the past two million years—Long Valley in eastern California, Toba in Indonesia, and Taupo in New Zealand, for example. The origin of the Yellowstone caldera in Yellowstone National Park in Wyoming is a good example of a caldera formed by a supervolcano eruption.

On three separate occasions, supervolcano eruptions followed the accumulation of rhyolitic magma beneath the Yellowstone region, each yielding a widespread blanket of volcanic ash and pumice. In each instance, collapse of the magma chamber led to the formation of a huge caldera (▶ Figure 1a). We can summarize Yellowstone's volcanic history by noting that supervolcano eruptions took place 2 million years ago when 2500 km^3 of pyroclastic materials were ejected, 1.3 million years ago (280 km^3), and 600,000 years ago (1000 km^3). It was during this last eruption that the present-day Yellowstone caldera formed, which is actually part of a larger composite caldera that resulted from the three cataclysmic eruptions. Between 150,000 and 75,000 years ago, an additional 1000 km^3 of pyroclastic materials were erupted within the caldera (▶ Figure 1b).

What caused such voluminous eruptions in the Yellowstone area? Many geologists are convinced that a mantle plume, a cylindrical mass of magma rising from the mantle, underlies the area. As this rising mass of magma nears the surface, it triggers volcanic eruptions, and because the magma is rhyolitic, and thus viscous, the eruptions are particularly explosive. Thanks to the personnel at Yellowstone Volcano Observatory, who continue to collect data and assess the possibility of renewed eruptions, we should have ample warning before another supervolcano eruption.