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Patrick L. Abbott
San Diego State University

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CHAPTER 7

Volcano Case Histories: Killer Events

Past civilizations are buried in the graveyards of their own mistakes.

—Lord Ritchie-Calder,
1970, "Mortgaging the Old Homestead"

LEARNING OUTCOMES

Active volcanoes are natural hazards, but understanding their processes helps us coexist with them. After studying this chapter you should

- recognize that humans can live successfully on oceanic hot-spot and spreading-center volcanoes.
- understand why subduction-zone volcanoes are so deadly.
- be able to explain the sequence of events in a catastrophic volcanic eruption as at Mount Saint Helens in 1980.
- be familiar with the leading causes of death by volcano.
- be able to explain pyroclastic flows and lahars.
- know the signs of impending volcanic eruption.

OUTLINE

View over the harbor city of Catania, Sicily, toward Mount Etna. The city has been buried seven times by lavas from Etna. Each time, the city has been rebuilt on top of its predecessor to await its turn to be buried.

Pat Abbott

Walking on an active volcano can lead to death without warning. Magma does not need to move or be physically involved. Underground water fed by rain or seawater inflow can contact magma or hot rock. Superheated volumes of water can form yet give no clue to their presence; a steam explosion can occur at any time. One minute you are walking and happy, the next minute you are dead.

Mount Ontake, Japan 2014 Mount Ontake is a sacred mountain; it is a popular site for hiking. Saturday, 27 September 2014, was a beautiful autumn day with leaves changing color and welcoming weather that attracted visitors. Several hundred people were on the slopes at 11:52 a.m. when, with no warning, the volcano erupted steam, gas, ash, and rocks that killed 63 hikers. People high up the mountain died from inhaling steam and lung-choking ash, while others were hit by flying rocks. The iPhones of some deceased hikers contained photos of the oncoming ash flows that killed them.

White Island, New Zealand 2019 White Island volcano has erupted during every decade since the year 1900. One wall of the volcano has blown out, leaving a portion of the active crater at low elevation and easily accessible to small boat dockings. On the warm spring day of 9 December 2019, 47 visitors were ashore, many of them wearing only shorts and T-shirts. At 2:11 p.m., with no advance warning, a 2-minute-long series of steam-powered blasts killed 21 people and blistered 26 others with severe to critical injuries—the steam had horrifically burned up to 95% of their bodies. New Zealand doctors immediately ordered 1,200,000 cm^2 (190,000 in^2) of cadaver skin from the United States and Australia to begin plastic surgery on surviving victims. Additionally, these tourists suffered severe burns inside their lungs after breathing in the superhot steam and caustic ash.

These events were *hydrothermal* explosions. It is very difficult to predict when slowly flowing groundwater will meet up with magma, but when it does, explosions will occur. Hikers beware.

Volcanism at Spreading Centers

Most of the volcanism on Earth takes place along the oceanic ridge systems where seafloor spreading occurs. Solid, but hot and ductile mantle rock rises upward into regions of lower pressure, where up to 30–40% of the rock melts and flows as basaltic magma. The worldwide rifting process creates new basaltic oceanic crust each year. Virtually all of this volcanic activity takes place below sea level and is thus difficult to view. We see and are impressed by the tall and beautiful volcanic mountains on the edges of the continents, but the volume of magma they release is small compared to that of spreading centers.

ICELAND

Iceland is a volcanic plateau built of basaltic lava erupted from a hot spot below the mid-Atlantic Ocean spreading center. The country is a little bit bigger than the state of Virginia; about 13% of its surface is covered by glaciers, and one-third consists of active volcanoes. During the nearly 1,000 years of human records, volcanic eruptions have occurred about every five years, on average. Most Icelandic eruptions do not cause deaths, but exceptions do occur (see famine of 1783 later in this chapter).

The most typical Icelandic eruptions are fissure eruptions, where lava pours out of long fractures up to 25 km (16 mi) long. To understand Icelandic eruptions, visualize the linear spreading center (see figure 4.3) that controls the rise of magma as it is fed upward through fractures. An Icelandic eruption can be beautiful to watch as an elongate "curtain of fire" shoots upward with varying intensity and height. Icelandic eruptions of low-viscosity, low-volatile lava flows can be so peaceful that their movement is almost waterlike.

Lava Flows of 1973

The recent story of Iceland shows that humans can make enough adjustments to live profitably and happily next to active basaltic volcanism. The 1973 eruptions on the small island of Heimaey south of the big island of Iceland illustrate the "peaceful" nature of these eruptions. The town of Vestmannaeyjar is built next to the premiere fishing port in Iceland. The safe harbor is itself a gift of volcanism; it was formed between ancient lava flows. On 23 January 1973, a fissure opened up only 1 km (3,300 ft) from the town of 5,300 people (figure 7.1). By early July, the eruption had emitted 230 million m^3 of lava and 26 million m^3 of pyroclastic material. The lava flows increased the size of the island by 20%. Gases vented during the eruptive sequence, other than water vapor, were dominantly CO_2 with lesser amounts of H_2, CO, and CH_4. The only fatality was a person asphyxiated inside a gas-filled building.

The early lava flows on Heimaey began filling in the harbor and destroying about 300 buildings; pyroclastic fallout buried another 70 buildings. But the volume of lava was not overwhelming, so the Icelanders took over. Pyroclastic material was bulldozed to create barriers that diverted and controlled the flow of later lavas and even controlled the flow paths of the dense volcanic gases. To save their harbor and economic livelihood, the Icelanders sprayed seawater on the lava flows, causing rapid cooling and hardening into wall-like features that forced the lava to flow off in another direction (figure 7.2). This action prevented the harbor from being filled and closed. Now, with its new shape and larger size, the harbor is better than before the 1973 eruption (see figure 7.1).

When the eruptions stopped, the people set up a pipe system that poured water into the 100 m (330 ft) thick mass of slowly cooling lava. Return pumps were installed to bring the water, which had been heated to 91°C (196°F), back to

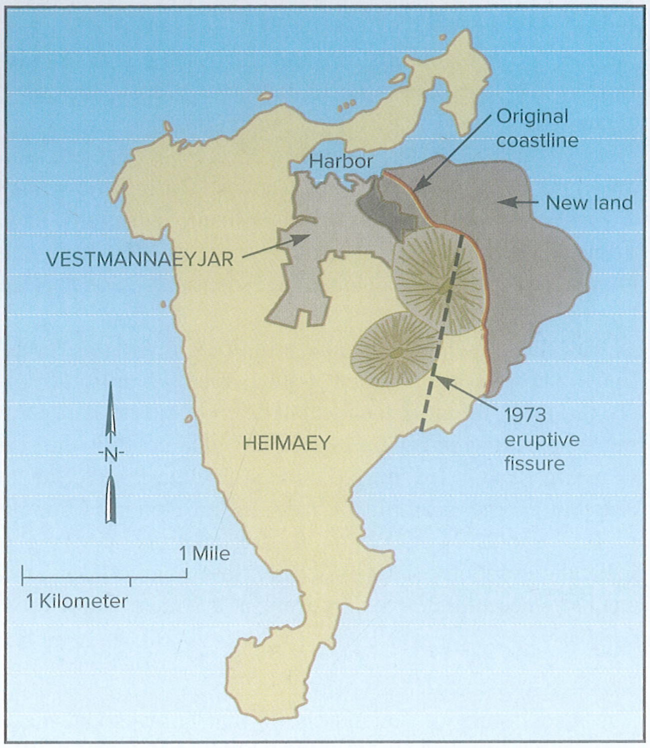


Figure 7.1 The island of Heimaey with the old coastline shown as an orange line. The dark gray area is new land formed by the 1973 lava flow. Note that the new harbor is bigger and better protected.

Source: Williams, R. S., Jr., and Moore, J. G., "Man against Volcano: The Eruption on Heimaey, Vestmannaeyjar, Iceland," US Geological Survey 1983.

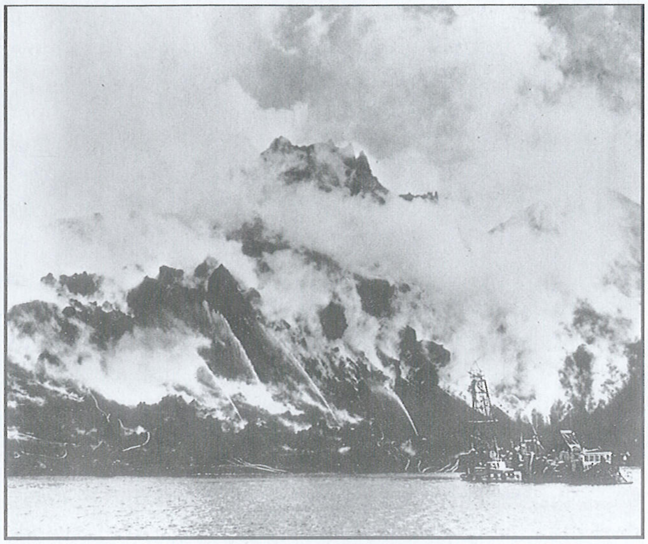


Figure 7.2 Seawater is being sprayed on the lava front to cool, harden, and stop it from closing off Vestmannaeyjar harbor, 4 May 1973.

Source: USGS

the surface and into town, where it was used to heat buildings. Basaltic eruptions do not have to be killers. Humans and volcanoes can coexist in harmony, with luck and with some exceptions.

Pyroclastic Eruptions of 2010

When glacial ice and meltwater encounter magma, violent explosions occur. From 15 to 20 April 2010, air travel to, within, and from Europe was disrupted by a volcanic explosion of this kind.

In southernmost Iceland, the ice cap Eyjafjallajokull covers 100 km^2 (0.39 mi^2), including a 1,666 m (5,464 ft) tall stratovolcano. Strombolian eruptions were occurring for weeks in 2010 but on 14 April, glacial meltwater poured into the magma chamber, triggering a Vulcanian eruption of VEI 4. An eruption cloud of ash, volcanic glass, and small rock fragments blew 9 km (5.6 mi) high directly into the atmospheric jet stream flowing southeast across Europe. Airplane engines cannot handle volcanic ash, so European air travel stopped for six days.

One nearby Icelandic farm was buried with pyroclastic debris and hit with glacial meltwater floods (called **jokulhlaups**). The family rebounded by clearing volcanic debris, adding a small building with a theater showing their home videos of the eruption, and selling souvenirs. Their business is a success. You know the saying: When life hands you lemons, make lemonade.

Volcanism at Subduction Zones

Through newspapers and television, we learn of death-dealing volcanic eruptions at Galeras Volcano in Colombia, Mount Unzen in Japan, Mounts Pinatubo and Mayon in the Philippines, Mount St. Helens in Washington, and Soufriere Hills on Montserrat. They are all subduction-zone volcanoes. These stratovolcanoes have the biggest impact on humans. Many of the regions around subduction-zone volcanoes are heavily populated and feel the wrath of the eruptions. Also, because these volcanoes erupt directly into the atmosphere, they can affect climate worldwide (see chapter 12).

CASCADE RANGE, PACIFIC COAST OF UNITED STATES AND CANADA

Explosive eruptions are frequent at the numerous volcanoes in the Pacific Northwest region of the United States and in British Columbia (figure 7.3). The plate-tectonic process responsible for these volcanoes is identical to the cause of the region's great earthquakes—subduction. In fact, the frequent eruptions from the Cascade Range volcanoes provide clear evidence for active subduction. The melting of part of the mantle (asthenosphere) wedge above the subducting

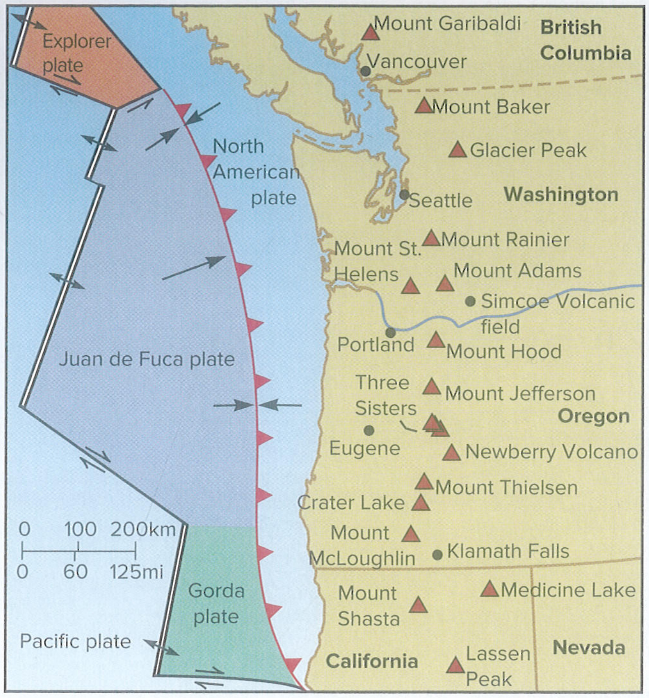


Figure 7.3 Plate-tectonic map of Cascade Range volcanoes. Volcanoes are subparallel to the subduction zone and spaced somewhat regularly.

plate is aided by water released within the subducting basaltic plate and from sediments on top of the subducting plate. The rising basaltic magma increases its content of SiO_2 and water. Much of the magma changes its composition to andesite or rhyolite and increases its viscosity as it rises (figure 7.4). Some collects in great pods and cools underground, forming plutonic rocks, but some erupts explosively at the surface.

How often do major eruptions occur? An example was documented in a 1975 study of Mount St. Helens by Dwight Crandell and colleagues. Their report stated that the latest large, volcanic mountain had formed in the last 2,500 years. Since then, Mount St. Helens has experienced major eruptions every century or two and has never been free from major volcanism for longer than 500 years. Their 1975 report stated, "Although dormant since 1857, St. Helens will erupt again, perhaps before the end of this century." The geologic analysis was prophetic (figure 7.5).

Figure 7.6 shows the age distribution and eruption history along the line of Cascade Range volcanoes. Basically, the volcanoes are all the same age; they sit above subducting plates and are active now. Volcanoes built above hot spots also line up—for example, Hawaii (see figure 2.22) and Yellowstone (see figure 6.39). In contrast to subduction-zone volcanoes, the ages along lines of hot-spot volcanoes range from young to old in orderly progressions.

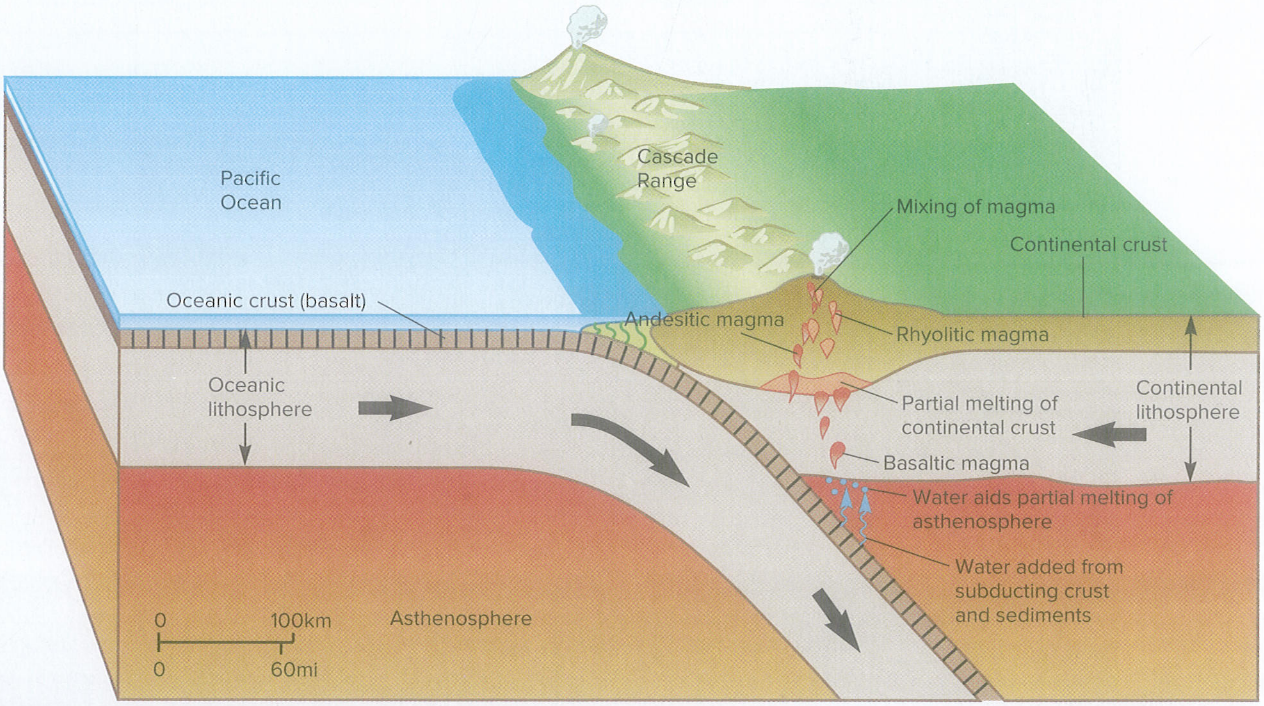
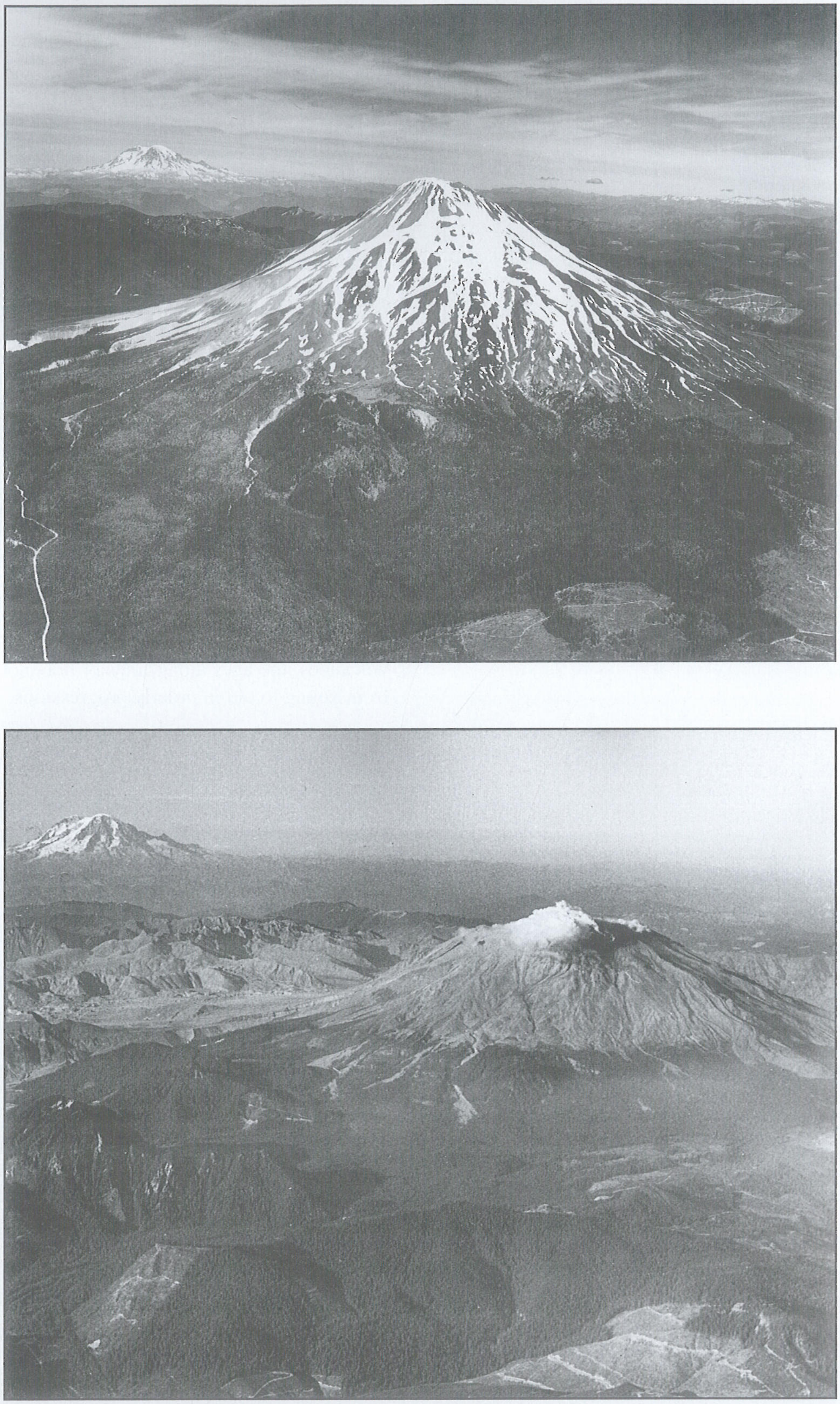


Figure 7.4 Subduction-zone volcano "factory." Basaltic magma forms in the upper asthenosphere where subducted water aids partial melting of oceanic crust and asthenosphere. Rising magma partially melts some continental crust, forming water-rich andesitic to rhyolitic magmas that erupt explosively.



(a)

(b)

Figure 7.5 Mount St. Helens, Washington. (a) *Before:* View to the northeast of the beautiful cone of Mount St. Helens on 25 August 1974. Mount Rainier is in the distance. (b) *After:* Same view on 24 August 1980, after the volcano had blown off its top 400 m (1,313 ft).

(a) University of Washington Libraries, Special Collections, John Shelton Collection, Shelton 6754; (b) ©University of Washington Libraries, Special Collections, John Shelton Collection, Shelton 67-706cr

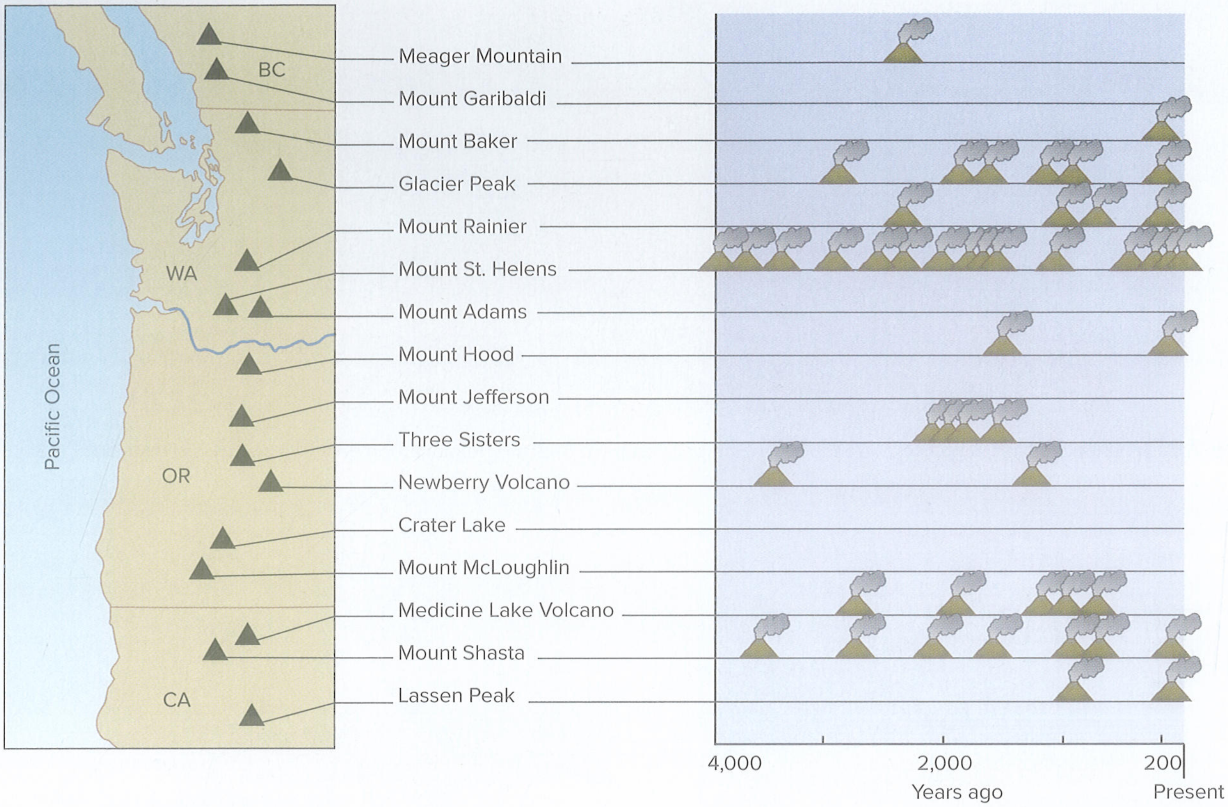


Figure 7.6 Eruption histories of Cascade Range volcanoes during the last 4,000 years.

Figure 7.7 What was once a mature forest is now a field of fallen trees pointing in the direction traveled by the volcanic blast from Mount St. Helens on 18 May 1980.

Source: J. DeVine/USGS

How are prehistoric eruptions documented? The process is the same as that used to work out dates of prehistoric earthquakes. The slopes near a volcano reveal the remains of trees knocked down by volcanic blasts (figure 7.7). These trees may be buried by volcanic ash, incorporated in lahars, or otherwise preserved. Radiocarbon determinations of the dates when trees died also tell the dates of the volcanic eruptions that killed them (figure 7.8).

Mount St. Helens, Washington, 1980

In late March 1980, Mount St. Helens awoke from a 123-year-long slumber. Dozens of magnitude 3 earthquakes occurred each day as magma pushed its way toward the surface. On 27 March, small explosions began as groundwater and magma came in contact. The spectacle of an erupting volcano was a tremendous lure for sightseers. People flocked to Mount St. Helens. The weekend traffic was so jammed that it reminded folks of rush hour in big cities. But this was an explosive giant just warming up its act, and all nearby life was in grave danger. Then, at 8:32 a.m. on 18 May 1980, the volcano blew off the top 400 m (1,313 ft) of its cone during a spectacular blast that generated about 100 times the power of all U.S. electric-power plants combined. Most of the 62 people killed had come to get a closer view of an erupting volcano. A look at the eruptive sequence provides a good example of how an explosive volcano does its thing (figure 7.9).

First, Mount St. Helens achieved its beautiful conical shape during the mid-1800s (figure 7.9a). In 1843, a SiO_2-rich lava dome grew at the volcano peak. In 1857, andesitic lava flows cooled high on the slopes. But these events also set up discontinuities, or weaknesses, within the volcanic cone.

Second, in 1980, rising magma began changing the shape of the volcano (figure 7.9b). Earthquake hypocenters were

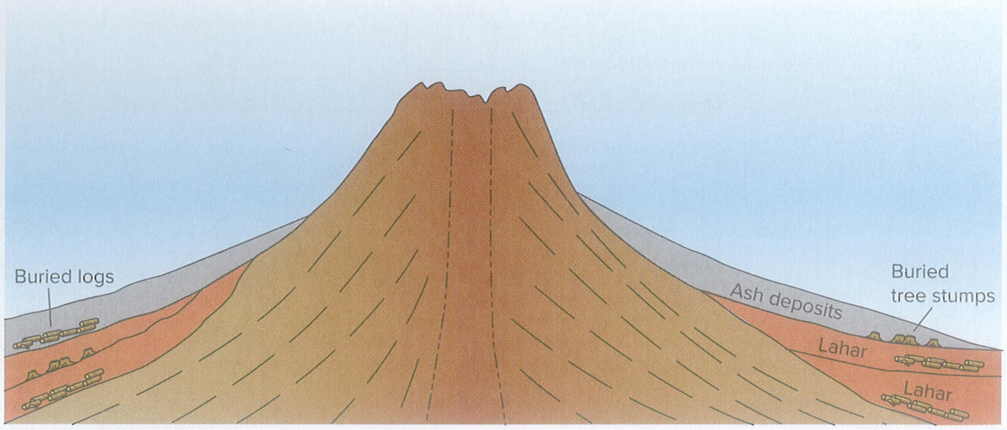


Figure 7.8 Schematic cross-section of a volcano and some of its eruptive deposits. Radiocarbon dates on buried wood tell when trees died—that is, when the volcano erupted.

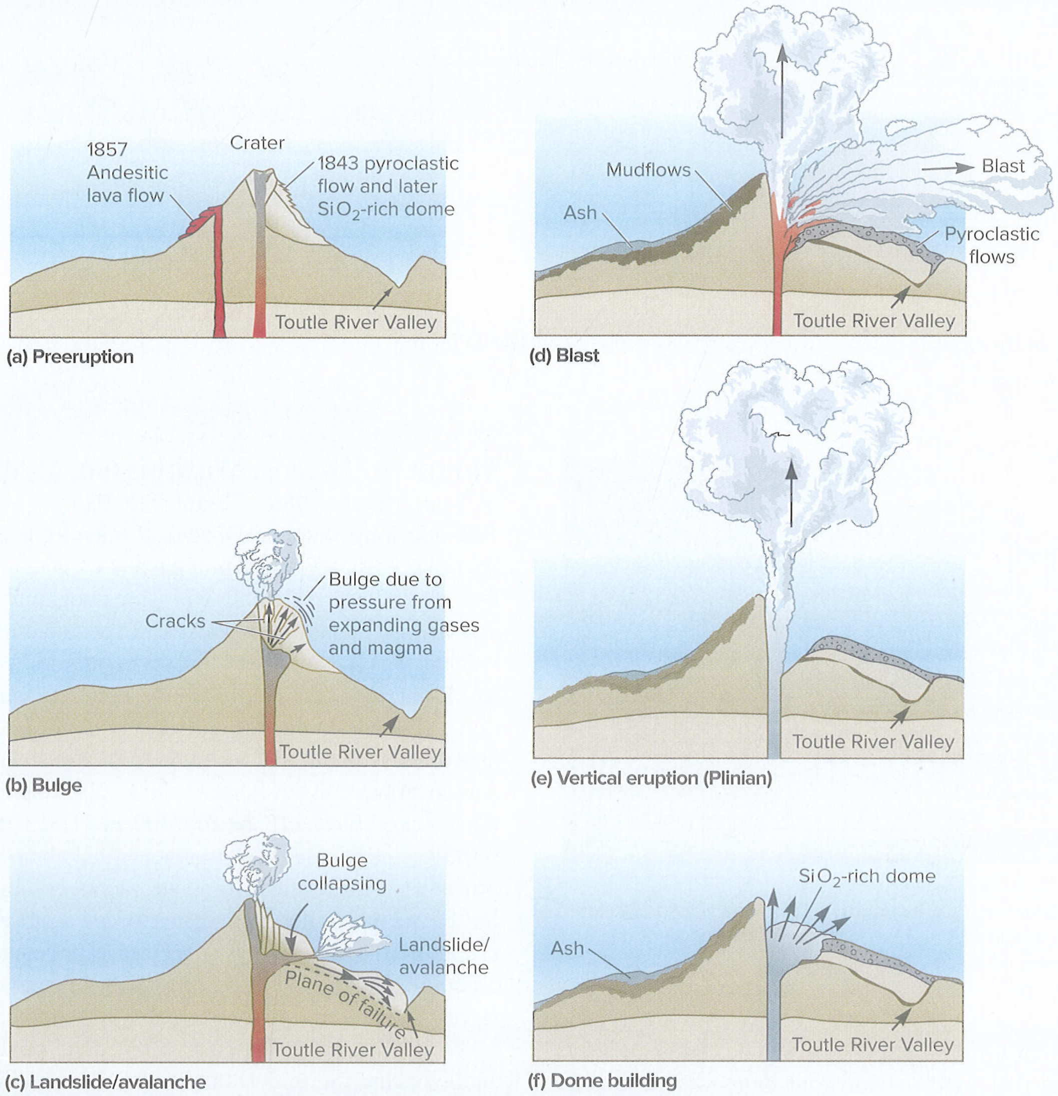


Figure 7.9 Eruptive sequence (VEI = 5) of Mount St. Helens in 1980. (a) The symmetrical volcanic cone was shaped in 1843 and 1857. (b) In late March, rising magma and expanding gases caused a growing bulge on the northern side. (c) At 8:32 a.m. on 18 May 1980, the bulge failed in a massive landslide/debris avalanche recorded as a magnitude 5.1 earthquake. (d) The landslide released pressure on the near-surface body of magma, causing an instantaneous blast of fragmented rock and magma. (e) The "throat" of the volcano was now clear, and the vertical eruption of gases and small blobs of magma shot up to heights of more than 20 km (12 mi) for nine hours. (f) Today, the mountain is slowly rebuilding a volcanic dome of low–water content, SiO_2-rich magma.

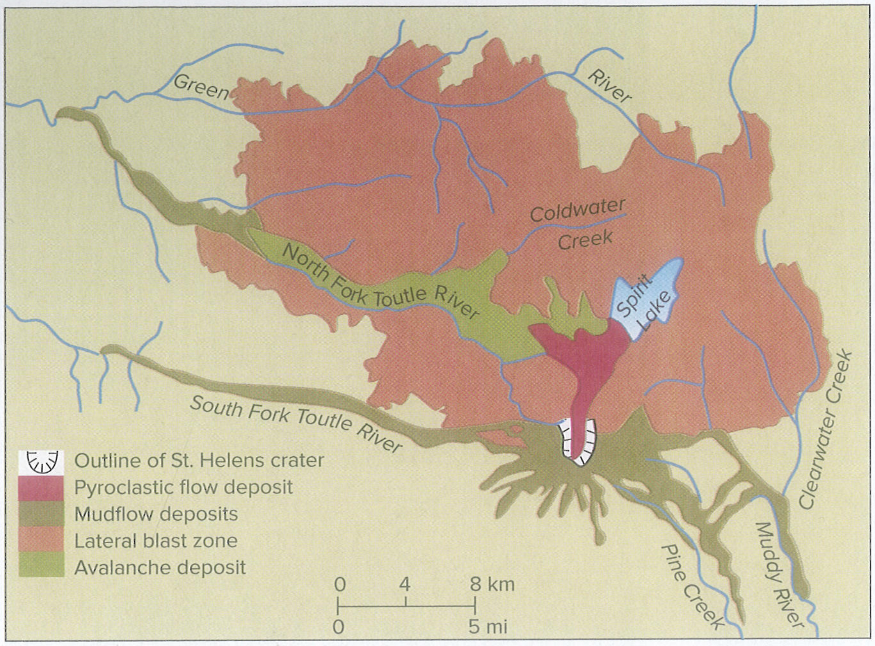


Figure 7.10 Map of materials dumped in the 18 May 1980 eruption of Mount St. Helens. Avalanche deposit was from the initial landslide. A lateral blast followed immediately. Then pyroclastic flows spilled out of the exposed magma body. Through it all, the superheated groundwater, plus melting snow and ice, fluidized sediments on the steep slopes as lahars (mudflows) that ran down the valleys.

Source: R. Tilling, "Eruptions of Mount St. Helens: Past, Present and Future," 1984, US Geological Survey.

abundant at 1 to 3 km (0.6 to 2 mi) depth. The seisms were recording the injection and pooling of magma. With magma forcing its way upward, the northern side of the volcano began rising. The increasing volume of magma also caused the groundwater body to expand its volume. The effect on the volcano was dramatic. By 12 April, a 2 km^2 (1.2 mi^2) area on the north flank had risen upward and outward by 100 m (330 ft). This unstable situation grew worse as the "mega-blister" kept growing about 1.5 m (5 ft) per day.

Third, at 8:32 a.m. on 18 May 1980, the bulge failed. With magma injecting into the bulge from below and gravity pulling from outside, the huge mass of the bulge, with its weak strength, failed and pulled away as an avalanche. The shaking ground was recorded as a magnitude 5.1 earthquake. The avalanche material was 2.5 km^3 of the north side of the mountain; it fell away at speeds up to 250 km/hr (150 mph) (figure 7.9c). The avalanche was a roiling mass of fragmented rock that once was the mountaintop and side, combined with ice blocks, snow, magma, soil, and broken trees; the internal temperature of the mass was about 100°C (212°F). Part of the avalanche slammed into Spirit Lake, causing waves 200 m (650 ft) high. Another part overrode a 360 m (1,180 ft) high ridge that lay 8 km (5 mi) to the north; then it turned and moved 23 km (14 mi) down the north fork of the Toutle River (figure 7.10). The resulting deposit was a chaotic mixture of broken rocks and loose debris that averaged 45 m (150 ft) in thickness and had a hummocky surface relief of 20 m (65 ft). Only a short time earlier, this material had been the top of the mountain. At the same time as the avalanche occurred, lahars were forming and flowing down the river valleys as rock particles mixed with water derived from melting snow and ice, from Spirit Lake, and from within the avalanche. These slurries continued to form and flow for many hours after the eruption began. Lahars moved long distances at speeds up to 40 km/hr (25 mph), carrying huge boulders and flowing with a consistency like wet concrete.

Fourth, as the landslide began to pull away, the dramatic drop in pressure on the gaseous magma and superheated groundwater caused a stupendous blast (see figure 7.9d). The blast and surge roared outward at speeds up to 400 km/hr (250 mph). The blast overtook and passed the fast-moving avalanche, racing over four major ridges and scorching an area of 550 km^2 (210 mi^2) with 0.18 km^3 of volcanic rock fragments and swirling gases at about 300°C (572°F) (figure 7.10). The blast was a pyroclastic flow. It was denser than air, flowing along the ground as a dark cloud, with turbulent volcanic gases keeping solid rock fragments, magma bits, and splintered trees in suspension; it behaved as a very low-viscosity fluid.

Fifth, the big blast opened up the throat of the volcano, exposing an effervescing magma body. Rapidly escaping gases blew upward, carrying small pieces of magma to heights greater than 20 km (12 mi) during the Plinian phase, which lasted about nine hours (figure 7.9e). The boiling gases carried about 1 km^3 (0.24 mi^3) of volcanic ash up and away. About 0.25 km^3 of ash was blown across the United States at different heights by various wind systems. Another 0.25 km^3 formed pyroclastic flows by either spilling out of the volcano or falling down from the eruption cloud (figure 7.11). These pyroclastic flows had temperatures of 300° to 370°C (570° to 700°F) and moved at speeds up to 100 km/hr (more than 60 mph).

Today, the volcano is slowly repairing the damage done to its once-symmetrical cone as it builds an SiO_2-rich lava dome (figures 7.9f and 7.12). The magma building the lava

Figure 7.11 High-temperature pyroclastic flow rolling down the side of Mount St. Helens, 7 August 1980.

Peter W. Lipman/U.S. Geological Survey

Figure 7.12 Lava dome of high-viscosity, low-volatile magma growing in the central magma pipe of Mount St. Helens since its big eruption in 1980.

Source: USGS (USGS)/Photograph by Lyn Topinka

dome has not erupted explosively, probably because it lost most of its volatiles during the big eruption on 18 May 1980.

Mount St. Helens looks very different these days (figure 7.13). Gone are the mountaintop, snowfields, forests, and lakes. The once tree-lined river valleys are clogged with volcanic debris (figure 7.14). But recovery is progressing well. Bacteria have eaten the sludge from dirty lakes, leaving pure water that has been stocked with trout. Plants have sprouted anew in devastated ground, and animals have returned to feed on them and on each other. Life is erasing the effects of the volcanic events.

Future Eruptions In figure 7.6, it is easily seen that Mount St. Helens has been the most active Cascade Range volcano during the past 4,000 years. This suggests that some condition of the magma reservoir maintains a bit of stability over time. Conditions can be evaluated using seismic P-wave velocities; they slow down progressively as rocks become softer or magma percentages increase. P waves slow down inside Mount St. Helens at depths of 3.5 to 14 km (2.2 to 8.7 mi); they define a magma reservoir of complex shape. The P waves indicate that anomalously high melt contents of 10 to 12% occur at 4 to 6 km (2.5 to 3.7 mi) depth. The major eruptions of the past 4,000 years came from this shallow depth range. It appears that the background conditions for another major eruption simply await some additional magma input. A major eruption this century would not be a surprise.

Lassen Peak, California, 1914–1917

Lassen Peak is not the typical volcano; rather, it is an unusually large (about 1 mi^3) lava dome of SiO_2-rich volcanic rock analogous to that growing in Mount St. Helens today (see figure 7.12). Lava domes form when magma is too poor in volatiles and too viscous to flow away, so instead it oozes upward as a conduit-plugging mass (see figure 6.33).

Lassen Peak awakened in May 1914 with numerous eruptions, culminating on 18 July 1914 with a major episode that sent up an ash cloud more than 3,350 m (11,000 ft) high. Small-scale volcanic activity continued, but large events did not resume until May 1915. On 16–18 May 1915, the 300 m (1,000 ft) wide crater overfilled with water-deficient, sticky magma that stood higher than the rim. The magma was too viscous to flow over the lip, so instead, red-hot blocks broke off and rolled downslope. Meanwhile, the melting snow combined with rocky debris to set in motion a massive lahar that flowed outward 50 km (30 mi). On 19 May, on the north slope, the side of

Figure 7.13 View of the devastated northeastern side of Mount St. Helens, 20 August 1980. Mount Hood is in the background.
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Figure 7.14 The Toutle River, choked with eruption debris.
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Figure 7.15 View of the north side of Lassen Peak, devastated by the 19 May 1915 eruption.

Lassen Peak split, and a pyroclastic flow blasted forth as a mixture of superhot gases, fragmental rock debris, trees, and water, devastating a triangular-shaped area 6.5 km (4 mi) long and 1.6 km (1 mi) wide (figure 7.15). Volcanic activity continued with more lahars and pyroclastic flows, and on 22 May, a broad mushroom cloud of ash was blasted 8 km (5 mi) high. Lassen remained relatively peaceful through 1916, but May and June 1917 brought renewed activity.

In three of four years, the month of May saw the start of extensive volcanic activity. Was this a coincidence? Maybe, but it is possible that as water from the melting snow sank and was heated underground, its volume expansion helped fracture Lassen Peak and reduce internal pressure enough to begin the eruptions. In the nonvolcanic year of 1916, Lassen Peak was too hot for snow to accumulate.

In the 20th century, two Cascade Range volcanoes underwent similar eruptions with sideward-directed blasts, pyroclastic flows, far-reaching volcanic mudflows (lahars), and great vertical eruptions of ash (Plinian phase). Luckily, each of these eruption sequences took place in sparsely inhabited areas. What are the prospects for similar eruptions near towns and cities?

Mount Shasta, California

Mount Shasta, at 4,318 m (14,162 ft) elevation, is the second-tallest of the Cascade Range volcanoes (figure 7.16). The third highest is Shastina (3,759 m, or 12,330 ft), perched on its shoulder. The combined mountain mass is particularly impressive, standing over 3,000 m (10,000 ft) higher than its surroundings and visible from more than

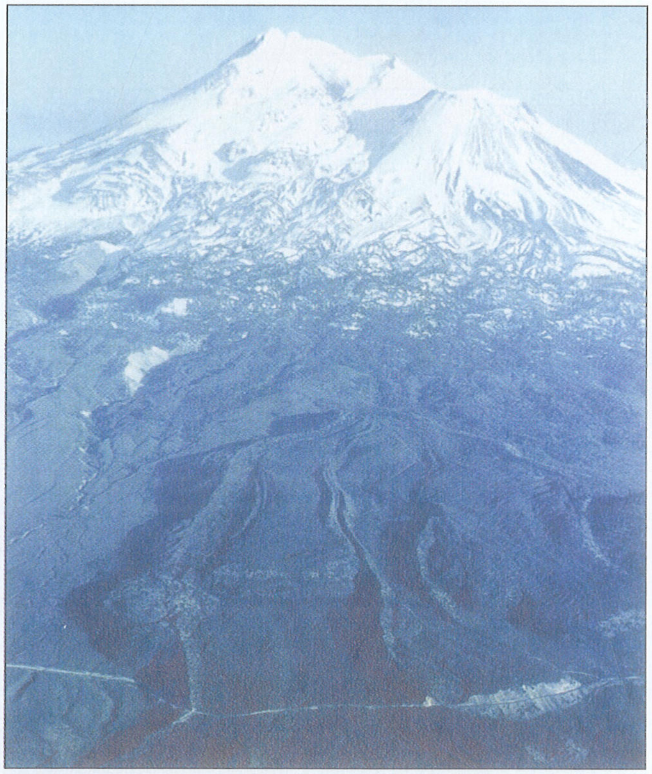


Figure 7.16 View from the north to Mount Shasta and Shastina. Note the network of roads being used to develop towns on top of lava flows, lahars, and debris avalanche deposits. Note the debris avalanche deposit that flowed from photo center to base of photo.

160 km (100 mi) away. Mount Shasta is an active volcano, erupting 11 times in the last 3,400 years, including at least three times in the last 750 years. Its last eruption was probably in 1786.

The Mount Shasta area is a beautiful place to live, and the towns along the volcano base are growing. But how wise is this? The lower slopes of Mount Shasta are broad and smooth, allowing pyroclastic flows to spread widely as they move down the volcano flank (figure 7.17). Lahars are more prone to flow through valleys, and towns lie there (figure 7.18). The rock record gives further reason to pause and consider whether or not to build here. Figure 7.19 shows the distribution of a 300,000-year-old avalanche deposit that extends 43 km (27 mi) out from the volcano base. This catastrophic event deposited eight times more debris than Mount St. Helens did in 1980. This jumbled mass near Mount Shasta is the foundation for three towns and one large reservoir.

Would it be advisable to draw park boundaries around the hazardous Cascade Range volcanoes and not allow towns to be built there? Volcanologists Dwight Crandell, Donal Mullineaux, and Meyer Rubin point out that

> *The potential risk from future eruptions may be low in relation to the lifetime of a person or to the life expectancy of a specific building or other structure. But when dwelling places and other land uses are established, they tend to persist for centuries or even millennia.*

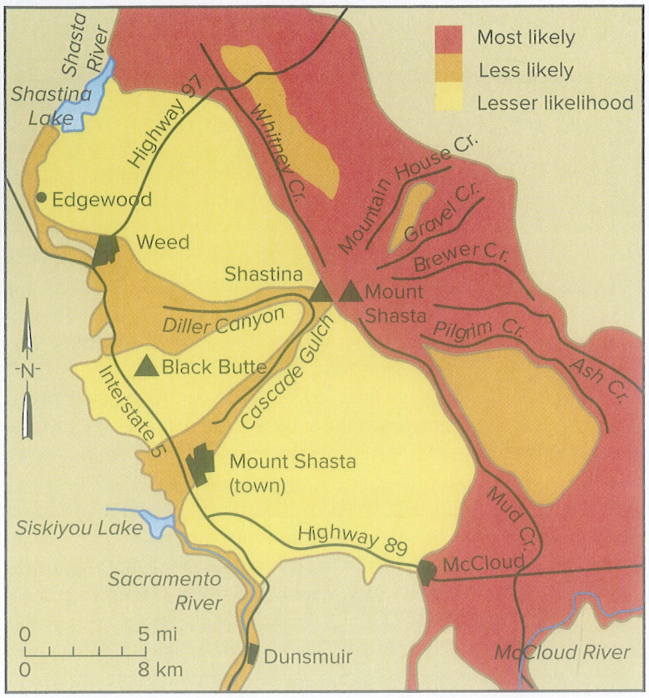


Figure 7.18 Map of the Mount Shasta–Shastina area showing the most likely paths for lahars. These volcanic mudflows tend to occupy the same river bottom flatlands where towns are built.

Source: D. R. Crandell and D. R. Nichols, "Volcanic Hazards at Mt. Shasta," 1989, US Geological Survey.

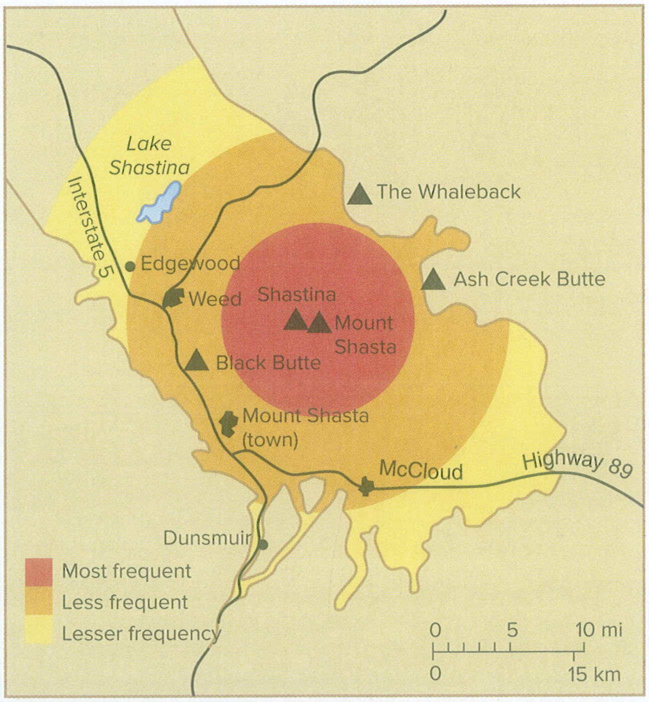


Figure 7.17 Map of the Mount Shasta–Shastina region, showing the areas most susceptible to lateral blasts and pyroclastic flows. Note the growing towns within the danger zones.

Source: D. R. Crandell and D. R. Nichols, "Volcanic Hazards at Mt. Shasta," 1989, US Geological Survey.

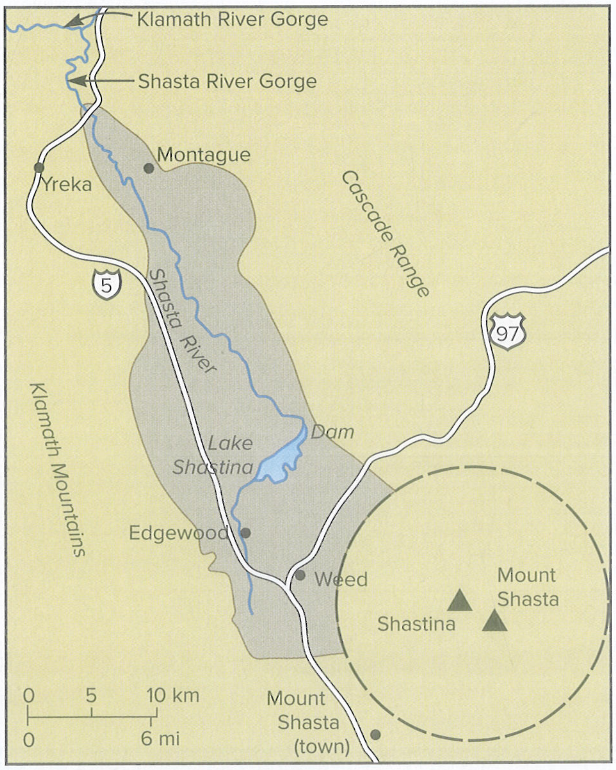


Figure 7.19 Map of a 300,000-year-old debris avalanche deposit at the base of Mount Shasta. The amount of material is eight times greater than the amount erupted at Mount St. Helens in 1980. It forms the foundation for three towns and one reservoir. See this avalanche deposit in the front center of figure 7.16.

In Greater Depth

Rapid Assembly and Rise of Magma

As 2 May 2008 began, a 5.2M earthquake shook southern Chile. Less than four hours later, Chaiten Volcano blew magma, ash, and steam 21 km (13 mi) up into the atmosphere in a Plinian eruption. The magma was rhyolite, the most viscous type. Unexpectedly, this stickier-than-toothpaste magma had risen 5 km (3 mi) in less than four hours, then erupted explosively. Apparently the earthquake opened **fissures** (cracks) to the magma reservoir that caused a pressure drop, triggering the eruption.

Volcanic events beginning and exploding so quickly bring into question how much warning time would there be before a super-eruption, a caldera-forming eruption. The volumes of magma extruded during super-eruptions are huge compared to recent events (figure 7.20). With thousands of years between caldera eruptions, it has seemed that long lengths of time would be necessary to accumulate a huge new body of magma; however, it now seems that it could occur in historical lengths of time rather than requiring geologic time spans. Study of chemically zoned mineral crystals such as quartz at Yellowstone, Wyoming; plagioclase at Santorini, Greece; and olivine at Irazu in Costa Rica have distinguished pre-eruptive from eruptive processes. The mineral cores, their interiors, may be thousands of years old but their outermost layer may be less than 100 years old. This indicates that long-existing magma bodies may be rather quickly recharged and/or disturbed to connect and mobilize existing batches of magma that surpass the threshold conditions needed for a super-eruption (see figure 6.15).

It appears that viscous magma does not just rest as a liquid reservoir but instead is stored as a mostly solid, crystalline mush. This magma can spend as much as 99% of its time at a temperature too cool to erupt but hot enough for a change in state to initiate amalgamation and rapid rise. The old resting magma could be activated by (1) an injection of new, hot, fresh magma, or (2) fracturing by fault movements that connect isolated magma bodies and reduce pressure on them. Once activated these viscous magmas can rise rapidly—very rapidly. It is not yet known whether magma ascent rates correlate with explosivity.

The potential for a supervolcano, a caldera eruption in our lifetimes seems intuitively unlikely, but it is not scientifically unreasonable. Two candidate sites for a super-eruption are Yellowstone National Park, USA, and Campi Flegrei, Naples, Italy.

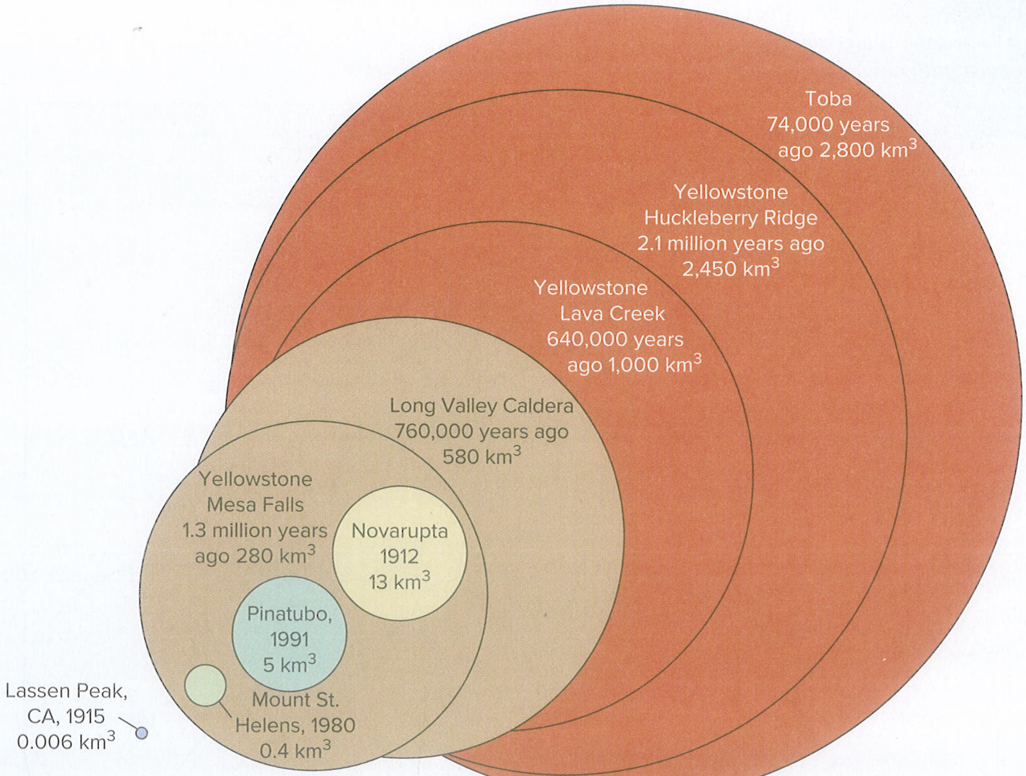


Figure 7.20 Volumes of magma erupted during some events described in the text. Note: 1 km^3 = 0.239 mi^3.
Source: After USGS.

Volcanic Processes and Killer Events

Volcanoes can kill in numerous ways (figure 7.21). They can burn you with a pyroclastic flow, slam and suffocate you with a lahar, batter and drown you with tsunami, poison you with gas, hit you with a pyroclastic bomb, fry you with a lava flow, or kill you with indirect events such as famine.

THE HISTORIC RECORD OF VOLCANO FATALITIES

Volcanoes operate all around the world. How many people do they kill? Which volcanic processes claim the most lives? The lack of written records for some time intervals and in some parts of the world makes these questions difficult to answer. Volcanologists Tom Simkin, Lee Siebert, and Russell Blong have studied the questions and given approximate answers. About 275,000 people have been killed by volcanic action during the past 500 years (figure 7.22). A dozen or so volcanic processes have done the killing (table 7.1). We will now individually examine some of the killer processes. As we do so, note that several of these each resulted in thousands of deaths (figure 7.22).

PYROCLASTIC ERUPTIONS

Explosive volcanic eruptions shatter magma into pieces by gas bubble growth and blast the fragmented magma as pyroclasts up to the surface and into the atmosphere. The pyroclasts may be brought back to the ground as **pyroclastic falls, pyroclastic flows,** and **pyroclastic surges.**

Pyroclastic Falls

During an explosive eruption, airborne pyroclasts fall down on the landscape with particles ranging in size from ash to bombs to huge blocks. The pyroclastic fall is similar to cannon bombardments during war, and it results in about 2% of volcanic deaths.

Pyroclastic Flows

Few experiences on Earth are as frightening as having a super-hot, turbulent cloud of ash, gas, and air come rolling toward you at high speed. History records numerous instances of pyroclastic flows killing thousands of people at each event.

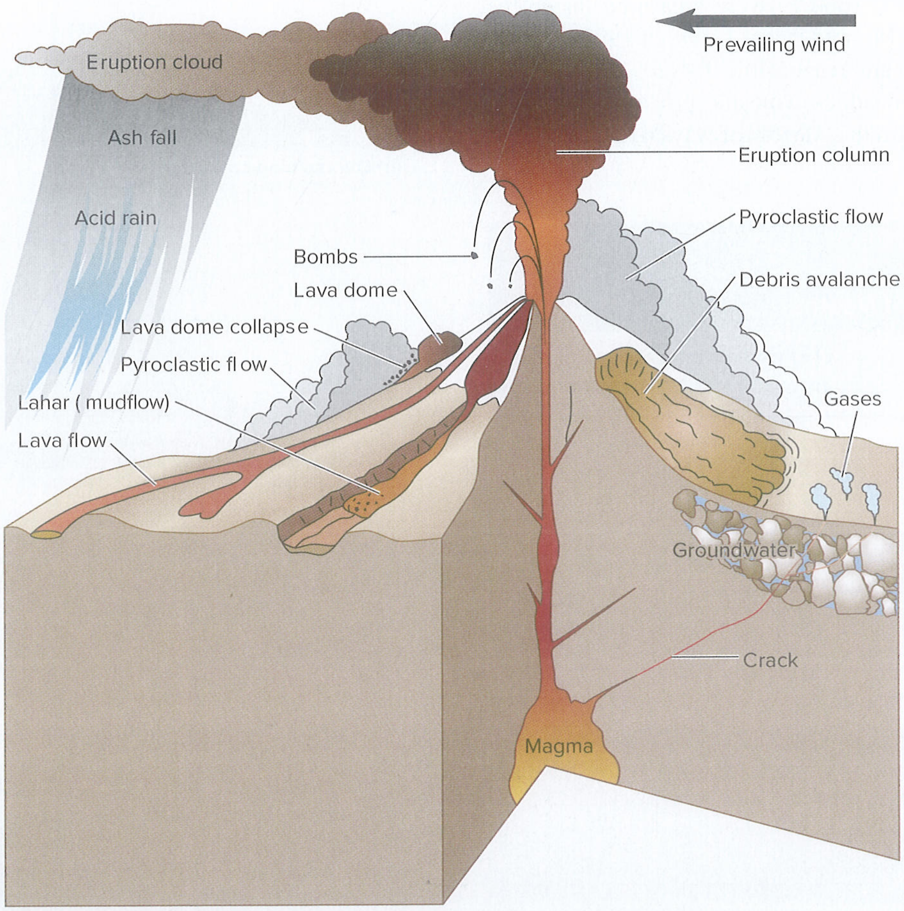


Figure 7.21 Volcanoes operate many life-threatening natural processes.
Source: US Geological Survey Fact Sheet 002–97 (1997).

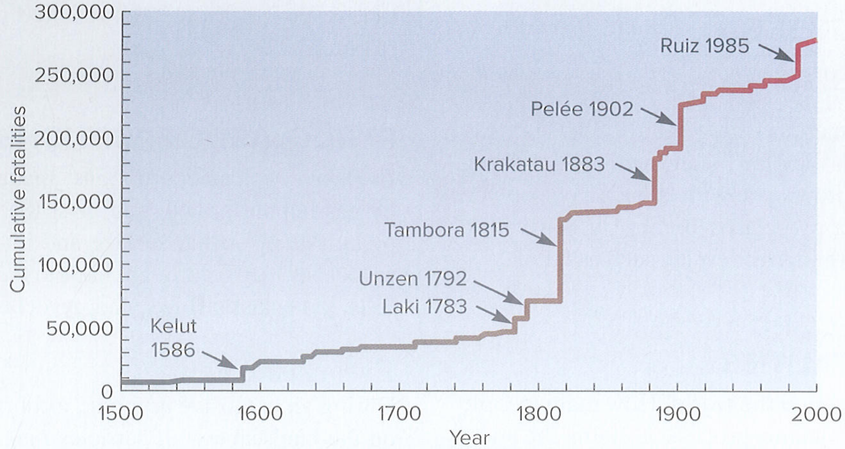


Figure 7.22 Cumulative fatalities from volcanoes during 500 years, 1500 to 2000.
Source: Data from T. Simkin, L. Siebert, R. Blong, Science 291:255 (2001).

A pyroclastic flow is an overwhelming mixture of hot hunks of magma, volcanic ash, volcanic gas, and mixed-in air that flows downslope at speeds greater than 10 m/sec (22 mph) and may exceed 100 m/sec (225 mph). Pyroclastic flows derive their energy from the volcanic eruption, gas expansion within the flowing mass, and the pull of gravity. Temperatures of 350°C (660°F) were measured inside the volcanic ash cloud at Mount Unzen, Japan, in 1992.

Pyroclastic flows are responsible for 29% of volcanic deaths; they are the deadliest volcanic process (table 7.1). Pyroclastic flows begin in a variety of ways (figure 7.23).

TABLE 7.1
Volcanic Causes of Deaths

	275,000 Deaths	530 Volcanic Events
Pyroclastic flow	29%	15%
Tsunami	21%	5%
Lahar	15%	17%
Indirect (famine)	23%	5%
Gas	1%	4%
Lava flow	<1%	4%
Pyroclastic fall (bombs)	2%	21%
Debris avalanche	2%	3%
Flood	1%	2%
Earthquake	<1%	2%
Lightning	<1%	1%
Unknown	7%	20%

Source: Data from T. Simkin, L. Siebert, R. Blong, "Volcano Fatalities" in Science 291:255 (2001).

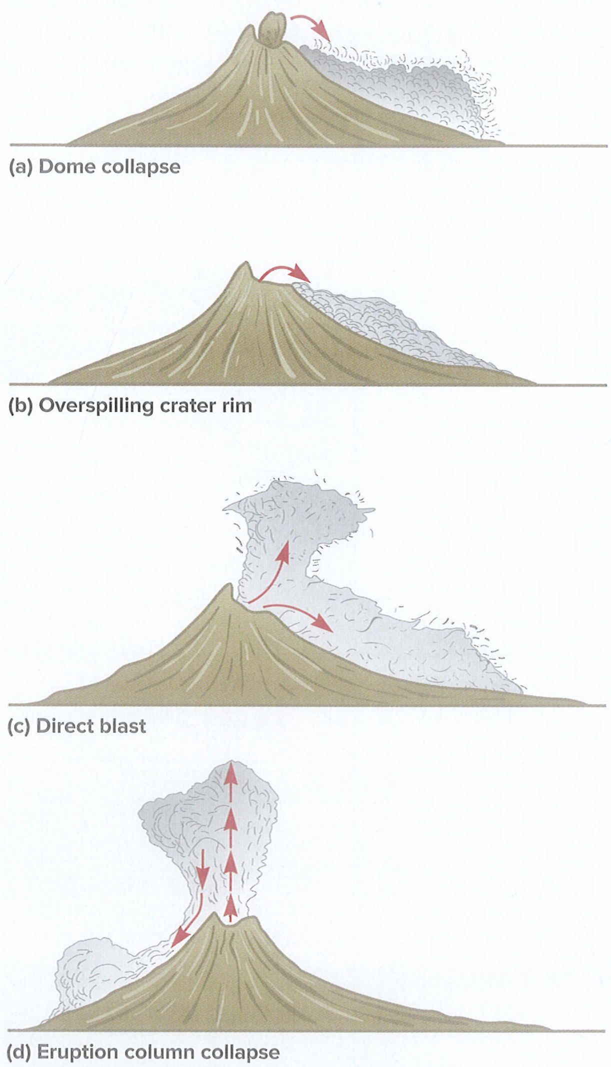


Figure 7.23 Ways of generating pyroclastic flows: (a) dome collapse as at Mount Unzen, 1991; (b) overspilling of crater rim as at Mont Pelée, 1902–1903; (c) direct blast as at Mount St. Helens, 1980, and Mount Pinatubo, 1991; (d) eruption column collapse as at Mount Mayon, 1984.

A Classic Disaster

Mont Pelée, Martinique, 1902

The Caribbean island of Martinique in the West Indies was colonized by the French in 1635. The tropical climate was superb for growing sugarcane to help satisfy the world's growing appetite for the sweetener. On the north end of Martinique is a 1,350 m (4,430 ft) high volcano. The French called the volcano Pelée, meaning "peeled" or "bald," to describe the bare area where volcanism had destroyed all plant life during the eruptions of 1792 and 1851. By coincidence, the pronunciation of the French word *Pelée* is the same as the Polynesian word *Pele* used in Hawaii to denote the goddess of volcanoes and fire.

In early spring of 1902, Vulcanian activity began. The crater atop Mont Pelée began filling with extremely viscous magma, displacing boiling lake waters through a V-shaped notch (figure 7.24). The extraordinarily sticky magma kept plugging the crater. At times, superhot pyroclastic flows would spill out of the crater; at other times, they would blast out. By late April, it was obvious to most people that this problem might get bigger. About 700 rural folks were migrating each day into St. Pierre, a city of picturesque, early 17th-century buildings that normally was home to 25,000 residents. Another 300 people a day were leaving St. Pierre, which lay only 10 km (6 mi) from Mont Pelée. At a little past noon on 5 May, a large pyroclastic flow sped down the Riviére Blanche, destroying the sugar mill and 40 people. This further increased the anxiety level in St. Pierre. But there was an election coming up on 10 May, and the governor did not want everyone scattered from the island's largest city because that would likely change the election results. Governor Mouttet and his wife went to St. Pierre and used the militia to preserve order and halt the exodus of fleeing people. Bad decision. There was no election on 10 May anyway; all the voters, including the governor, died on 8 May (figure 7.25).

On the morning of 8 May 1902, a massive volume of gas-charged, ultrasticky magma had risen to the top of the crater. At about 7:50 a.m., witnesses heard sharp blasts that sounded like thousands of cannons being fired as trapped gas bubbles exploded and shattered magma into fine pieces. This spectacular pyroclastic flow moved as a red-hot avalanche of incandescent gases and glowing volcanic fragments (then called **nuée ardente,** which is French for "glowing cloud"). The mass moved as solid particles of magma suspended in gas. Its energy came from (1) the initial blast, (2) gravity, and (3) gas continuing to escape from the pieces of airborne magma, creating a "popcorn" effect. The momentum of the flow was aided and its friction reduced by internal turbulence and air mixed into the flow as it moved downward and outward. The temperature at the crater is estimated to have been about 1,200°C (2,200°F), and the glowing cloud was still hotter than 700°C (1,300°F) when it hit St. Pierre. The coarsest and heaviest part of the pyroclastic flow moved down the Riviére Blanche. The associated gas-ash clouds expanded in width and overwhelmed St. Pierre (see figure 7.24).

How was the town of St. Pierre destroyed? The pyroclastic flow moved with hurricane speeds of about 190 km/hr (115 mph),

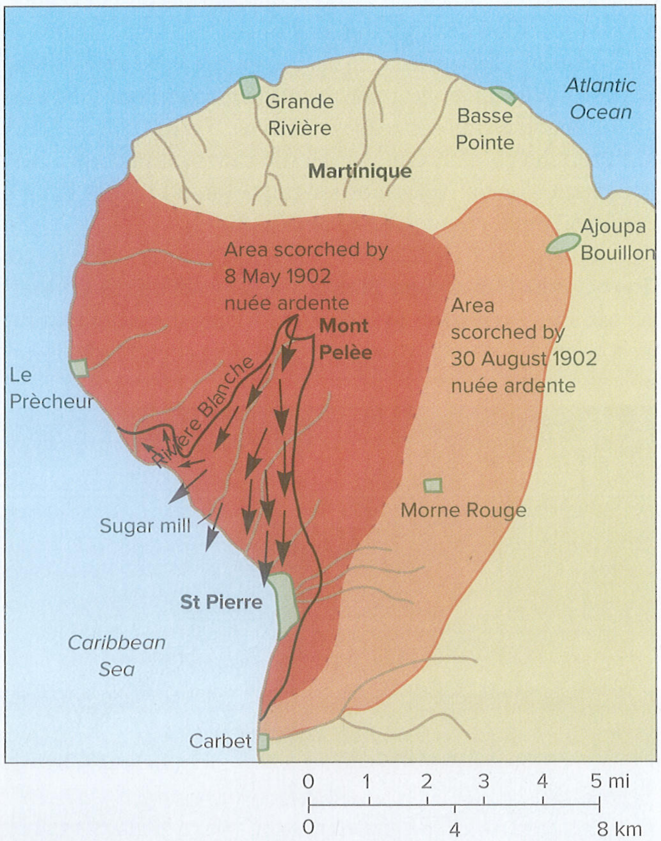


Figure 7.24 Map of Mont Pelée showing areas scorched by the largest pyroclastic flows of 1902.

Figure 7.25 The pyroclastic flow–charred remains of St. Pierre, May 1902. Mont Pelée is in the background.

Source: Library of Congress, Prints and Photographs Division [LC-USZ62-76173] but it was much denser than a hurricane because of its contained ash. The flow lifted roofs, knocked down most walls perpendicular to its path, twisted metal bars, and wrapped sheets of metal roofing around the scorched trunks of trees. Within the space of a couple of minutes, St. Pierre turned from a verdant tropical city to burned-out ruins covered by a foot of grey ash. Muddy ash also plastered any walls and tree trunks that were still standing.

What killed the people? Death was quick and came from one of three causes: (1) physical impact, (2) inhaling superhot gases, or (3) burns. The refugee-swollen population of St. Pierre was more than 30,000; only two people are known to have survived. One was Auguste Ciparis, a 25-year-old murderer locked in a stone-hut jail without windows and with only a small barred grating in his door. When hot gases entered his cell, he fell to the floor, suffering severe burns on his back and legs. Four days later, he was rescued; he then spent the rest of his life showing his scarred body at circus sideshows as "the prisoner of St. Pierre." The other survivor was a man inside the same house where his family members died.

Was it safe to be on a boat in the harbor? No. The fiery hot cloud did not stop when it hit the water. Of 18 boats in the harbor, only the British steamship *Roddam* survived, though it was badly burned and two-thirds of its crew were dead.

Pyroclastic flows continued rolling out of Mont Pelée. St. Pierre was overwhelmed again on 20 May, but it no longer mattered. On 30 August, a pyroclastic flow moved toward the southeast and scorched Morne Rouge and four other towns, killing another 2,000 people. Despite these tragic events, at present the area is fully settled once again.

Dome Collapse A growing lava dome provides a unique combination of steady magma supply and the upward lift of unstable, overhanging topography. Big hunks of lava dome frequently break off and create pyroclastic flows (see figure 7.23a). At Mount Unzen in Japan, between 1991 and 1994, more than 7,000 dome collapses were recorded.

In May 1991, the lava dome in Mount Unzen began a growth spurt that attracted international attention. As the unstable lava dome grew and towered 90 m (300 ft) above the crater rim, 15,000 residents were evacuated from villages and tea plantations around the mountain's base. As residents left, journalists and volcanologists arrived to record the numerous collapses of 200 to 300 ft high masses from the lava dome and watch the debris run downslope as glowing pyroclastic flows. At 4:09 p.m., on 3 June 1991, a much larger than usual mass fell off the lava dome and rolled downslope at about 60 mph, killing 44 observers, including the famed French volcano photographers, Maurice and Katya Krafft. All the deaths occurred in previously evacuated areas.

Overspilling Crater Rim A volcano crater may have its lake turned into a cauldron of boiling water, or the crater may fill with magma. If the crater overfills, hot water and magma can pour over the rim and flow downslope (see figure 7.23b). This happened numerous times on Mont Pelée in Martinique in 1902.

Direct Blast In some eruptions, a pyroclastic flow may simply form as a direct blast from the volcano. In 1980, as a landslide moved down Mount St. Helens, the decrease in pressure on magma inside the volcano caused a tremendous direct blast (see figure 7.23c). The direct blast traveled 150 m/sec (335 mph) and overwhelmed everything it encountered—lakes, trees, people.

Eruption Column Collapse At its greatest power, a volcano may send its eruption column of hot pyroclastic material, hot gas, and intermixed air high up into cooler air, providing time for heat to dissipate and for pyroclasts to cool and be spread far and wide. A dangerous phase of the eruption can occur in those moments when less energy is fed into the eruption column and the column begins to collapse, sending clouds of hot gases, ash, and pumice flowing as ground-hugging deadly pyroclastic flows (see figure 7.11).

Since 1616, more than 1,500 people have been killed during 40 recorded deadly eruptions of the subduction-caused stratovolcano Mount Mayon in the Philippines. In 1984, a series of Vulcanian eruptions sent magmatic debris 10 km (6 mi) into the atmosphere several times. Partial collapses of the eruption column sent pyroclastic flows rolling down the mountain slope at velocities ranging from 50 to 100 km/hr (30 to 60 mph) (figures 7.23d and 7.26).

Pyroclastic Flows over Water Can a pyroclastic flow travel across a body of water to kill you? Or does the water absorb heat from the hot, gas-rich cloud quickly enough to eliminate

Figure 7.26 Pyroclastic flows formed as collapses from the vertical eruption column flow downhill, Mayon Volcano, Philippines, 1984.
Chris G. Newhall/U.S. Geological Survey

its ability to kill? A body of water does *not* eliminate the hazard. During the 1883 eruptions of Krakatau in Indonesia, one remarkable blast on 27 August sent out a hot, gaseous pyroclastic flow that raced across the sea surface of the Sunda Straits for 40 km (25 mi) to reach the coastal province of Katimbang on Sumatra (see figure 8.20). It flowed onshore with enough heat to fatally burn more than 2,000 people.

Pyroclastic Surges

Pyroclastic surges occur when more steam and less pyroclastic material combine to produce a more-dilute, less-dense, high-velocity flow. Because of their low density, surges are not as easily controlled by topography. Some volcanic eruptions that involve magma and water interaction produce ground-hugging surges that may flow in all directions simultaneously as ring-shaped base surges. The deadliest pyroclastic surge in modern times occurred in Mexico on 4 April 1982.

El Chichón Volcano sits in a remote part of Chiapas, the southernmost state in Mexico (figure 7.27a). The volcano had been dormant for at least 550 years and was not considered an imminent hazard. March 1982 was a month of numerous earthquakes leading up to 29 March, when an unexpected six-hour-long Plinian eruption blasted 1.4 km^3 of rock and magma into the atmosphere. The volcano had changed (figure 7.27b). The eruption was surprising and the pyroclastic debris settling from the atmosphere was uncomfortable, but the Plinian event was not enough to drive the rural farmers and villagers from their land. The next five days were calming for the residents, as only minor volcanic activity occurred. But suddenly, on 4 April, a pyroclastic surge flowed radially outward for 8 km (5 mi), overrunning nine villages and killing 2,000 people. Everyone within 8 km of the volcano, in any direction, was killed by the base surge. Following the surge, a Plinian column shot up 20 km (12 mi). On the same day, there were two more base surges and Plinian columns, but the last two base surges did not matter; everyone was already dead. In addition, the Plinian columns injected sulfur dioxide (SO_2) into the upper atmosphere, and the whole world felt the effect as global climate cooled (see figure 12.24).

TSUNAMI

Volcanic tsunami can be created when some of the huge amounts of energy produced during volcanic eruptions are injected into large water bodies. Volcanic processes that generate tsunami include caldera collapse into the ocean; undersea eruptions; and travel of pyroclastic flows, lahars, and debris avalanches into the sea. Volcano-generated tsunami have been responsible for 21% of volcano-caused deaths.

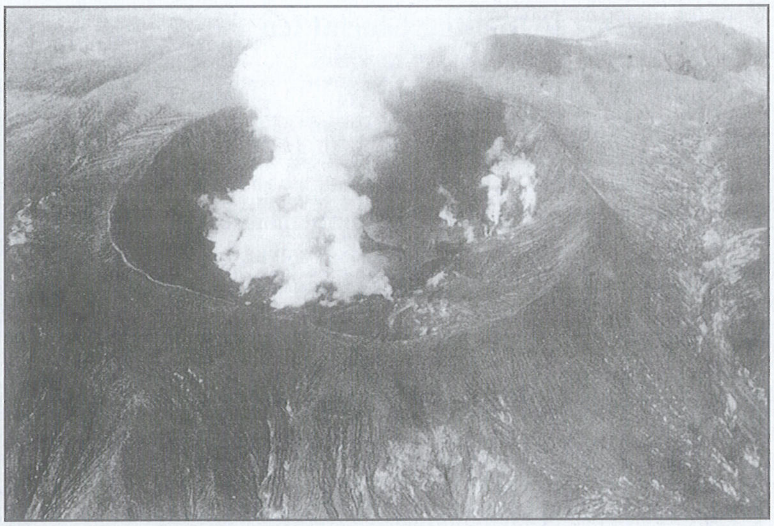
Caldera Collapse

The collapse of Krakatau Volcano in 1883 killed more than 36,000 people. The volcanic eruptions directly killed less than 10% of the people; more than 90% of the fatalities were due to volcano-caused tsunami. The 1883 and 2018 Krakatau tsunami are discussed in detail in chapter 8.

LAHARS

Lahars are volcanic mudflows and volcanic debris flows that are fluid when moving, but begin to solidify soon after stopping. These pyroclast-carrying flows can travel at speeds up to 65 km/hr (40 mph). The combination of water plus loose pyroclasts plus steep slopes plus the pull of gravity produces lahars. The word *lahar* comes from Indonesia and entered the scientific language after the deadly flows from the volcano Kelut in 1586 (see figure 7.22).

(a)



(b)

Figure 7.27 El Chichón, Chiapas, Mexico. (a) *Before:* In September 1981, the lava dome–plugged volcano was not considered a big hazard. (b) *After:* During one week in 1982, the lava dome was destroyed, leaving a 1 km (0.6 mi) diameter crater.

(a) Courtesy René Canul D. (b) *Source:* Robert I. Tilling/US Geological Survey

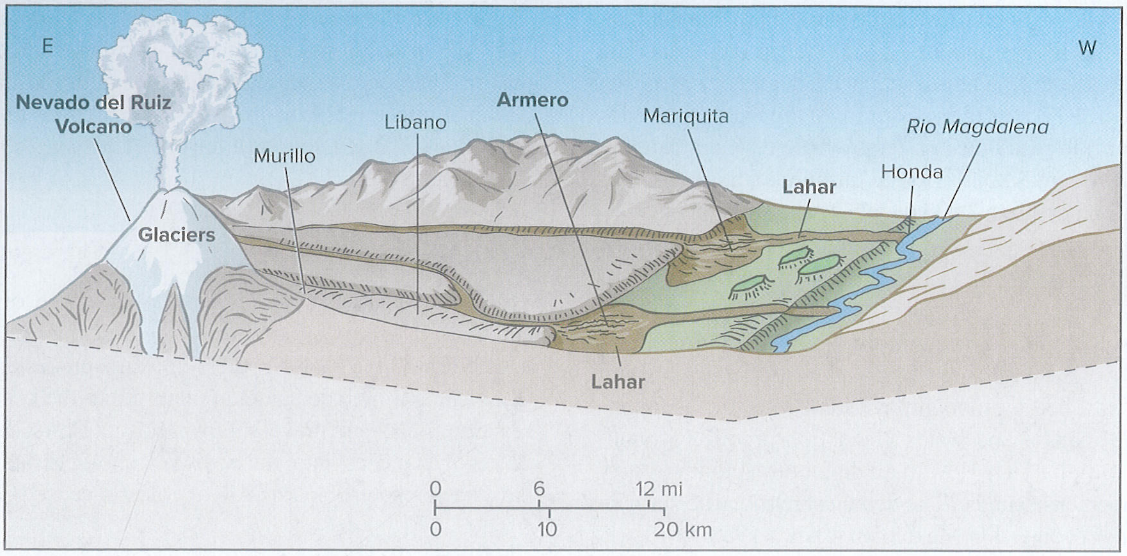


Figure 7.28 An eruption of Nevado del Ruiz in 1985 dropped hot pyroclastic debris onto glaciers, resulting in lahars.
Source: US Geological Survey.

Lahars may occur as *primary* events during volcanic eruptions or as *secondary* events months or years after eruption. When steep slopes are covered with loose pyroclasts, it takes only the addition of water to create lahars. Water may be available as a crater lake during eruption, such as at Kelut Volcano, or it may come later from heavy rainfalls or melting glacial ice.

Lahars Due to Heavy Rainfall

The eruptions of Mount Pinatubo in the Philippines in June 1991 featured stupendous Vulcanian events (see figure 6.3). On 15 June 1991, Typhoon Yunya with its heavy rainfall passed over the erupting volcano, sending voluminous lahars downslope and through the cities below (see figure 6.32).

Lahars Due to Melting Glacial Ice

Does it take a huge eruption to kill a lot of people? No. Nevado del Ruiz in Colombia rises to an elevation of 5,400 m (more than 17,700 ft). A 19 km^2 (7 mi^2) area on top of the mountain is covered by an ice cap 10 to 30 m (30 to 100 ft) thick with an ice volume of about 337 million m^3. In November 1985, continuous harmonic tremors (earthquakes) foretold a coming eruption. On 13 November, at 9:37 p.m., a Plinian column rose several miles high. Hot pyroclastic debris began settling onto the ice cap, causing melting. By 10 p.m., condensing volcanic steam, ice melt, and pyroclastic debris combined to send lahars down the east slopes into Chinchina, destroying homes and killing 1,800 people.

But the worst was yet to come. Increasing eruption melted more ice, sending even larger lahars flowing down the canyons to the west and onto the floodplain of the Rio Magdalena (figure 7.28). At 11 p.m., the first wave of cool lahars reached the city of Armero and its 27,000 residents. These lahars had traveled 45 km (28 mi) from the mountaintop, dropping more than 5,000 m (16,400 ft) in elevation. In the steep-walled canyons, the lahars moved at rates up to 45 km/hr (28 mph), slowing as they flowed out onto the flatter land below.

A few minutes after 11 p.m., roaring noises announced the approach of successive waves of warm to hot lahars. Most of Armero, including 22,000 of its residents, ended up buried beneath lahars 8 m (26 ft) thick (figure 7.29). The 22,000 unlucky people were either crushed or suffocated by the muddy lahars.

But 5,000 people did escape. How? They were higher up the slopes. A memorable video showed a man's talking head, which appeared to be resting on top of the mudflows; the man was caught by lahars and buried to his chin as he tried to escape upslope. One step slower and he would have been completely buried and suffocated. But with a bit of digging, he was freed, shaken but unharmed.

Figure 7.29 Most of the town of Armero, Colombia, and 22,000 of its residents lie beneath lahars up to 8 m (26 ft) thick.
Source: Darrell G. Herd/U.S. Geological Survey

Figure 7.30 Mount Rainier looms on the skyline behind the Seattle-Tacoma region.
Lyn Topinka/U.S. Geological Survey

The volcanic eruption at Nevado del Ruiz was actually rather minor. Had there not been an ice cap to melt, no harm would have been done. The November 1985 lahars were a virtual rerun of the events that occurred in that area 140 years earlier, in February 1845. The same places were buried by the same types of lahars. In 1845, the death toll was about 1,000, but because Colombia's population has grown, the dead in 1985 numbered about 24,000.

Mount Rainier, Washington—On Alert

Should the Seattle-Tacoma metropolitan region be concerned about lahars? Yes. Nevado del Ruiz showed that a small eruption on a glacier-capped volcano can be big trouble. Mount Rainier is the tallest of the Cascade Range volcanoes, at 4,393 m (14,410 ft). It stands 2,150 to 2,450 m (7,000 to 8,000 ft) above its adjacent areas and is a beautiful sentinel readily seen from throughout the Seattle-Tacoma urban region (figure 7.30). Yet Mount Rainier is number one on the danger list of many U.S. volcanologists because of its (1) great height, (2) extensive glacial cap, (3) frequent earthquakes, and (4) active hot-water spring systems, which have weakened the mountain internally. Mount Rainier can be described as 33.6 mi^3 of structurally weak rock capped by 1 mi^3 of snow and ice; this volcanic mountain is inherently unstable. Mount Rainier is a national park and cannot be densely developed, but it nonetheless presents distinct threats to heavily populated areas. The mountain itself may fail in a massive avalanche, and/or rapidly melted ice can cause floods or lahars. Mount Rainier supports the largest glacier system of any mountain in the lower 49 states. This ice can be melted by magma moving up inside the mountain, even without active volcanism.

The rock record shows numerous far-reaching lahars in the last several thousand years (figure 7.31). The Osceola mudflow moved about 5,600 years ago, flowing more than 120 km (75 mi) down the White River valley before spreading out onto the Puget Sound lowlands and into Puget Sound. It covers an area greater than 100 mi^2 to depths over 20 m (70 ft). The Osceola mudflow began as a water-saturated avalanche during summit eruptions of Mount Rainier. It transformed into a clay-rich lahar within 2 km (1.2 mi) of travel as it carried 3.8 km^3 (0.9 mi^3) of material at velocities up to 45 mph out across the Puget Sound lowlands. The affected area is now home to about 100,000 people. A repeat of an Osceola-size lahar could kill thousands of people. To visualize what could happen, see the 1985 lahar in Armero, Colombia (see figure 7.29); the Osceola event was 40 times larger than the Armero lahar.

The Electron mudflow is only 500 years old; it flowed down the Puyallup River valley for 48 km (30 mi) and also out onto the Puget Sound lowlands. Today, the region is a desirable place to live; the population is growing rapidly and building homes on top of these lahar deposits. Mount Rainier's next major eruption may bring staggering property damage and deaths.

Warnings are possible before lahars reach towns. Moving lahars may be detected in the upper reaches of valleys near Mount Rainier by acoustic flow monitors (AFMs). An AFM is a seismometer that records ground vibrations at different frequencies than those generated by earthquakes or most volcanic activity. An AFM concentrates on

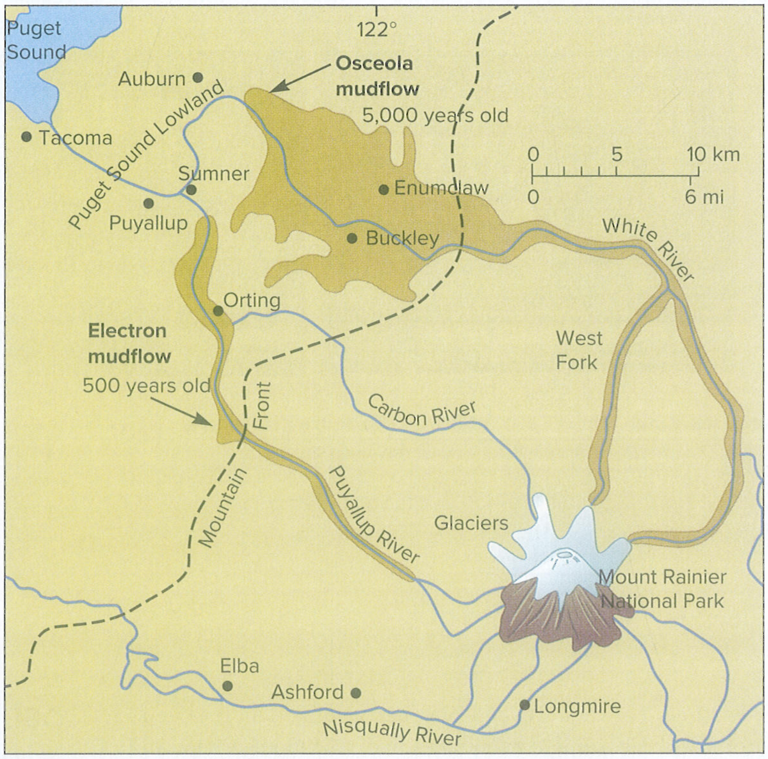


Figure 7.31 Map showing the area covered by two of the many lahars that have flowed from Mount Rainier.
Source: D. R. Crandell and D. R. Mullineaux, "Volcanic Hazards at Mt. Rainier, Washington", 1967, in US Geological Survey Bulletin 1238.

Side Note

Death at Ashfall, Nebraska

Ten million years ago, the area around Ashfall, Nebraska, held water holes within a savanna setting, a warm, flat grassland similar to some classic wildlife areas in Africa today. Large herds of animals migrated to the water holes to drink: three-horned deer, giant camels, three-toed horses, oreodonts, four-tusked elephants, weasels, bear dogs, rhinoceroses, and many more species. Their daily routines changed for the worse one day when a huge volcanic eruption blasted forth 1,500 km (930 mi) away. The eruption came from what is now the Yellowstone hot spot, but 11.93 million years ago, it was located in Idaho (see figure 6.39). Winds carried volcanic ash from Idaho and blanketed Nebraska with a layer of ash about 1 ft thick. After its initial deposition, local winds picked up and blew ash around in gray blizzards. Large amounts of reworked ash settled in the water holes, filling some with ash layers adding up to a total thickness of 4 m (13 ft).

What effects can cool, loose, ultrafine volcanic ash have on life? All the animals inhaled volcanic ash for days, weeks, and months, causing health problems. The high magnification of a scanning electron microscope reveals that volcanic ash is composed of sharp, jagged, angular pieces of glass and rock (figure 7.32), which are irritants inside living bodies. Breathing becomes difficult, and respiratory problems develop. Fossil bones of large animals at Ashfall show irregular growth, evidence that they were not getting enough oxygen to grow normal bones.

Fossil preservation at Ashfall is superb, with whole animal skeletons still joined together as they were in life. The layers of fossil-containing ash show the death sequence. In the lowest ash layer are the remains of the first to die—birds and turtles. In overlying ash layers are the fossils of musk deer and small carnivores. Some of the next animals to perish were the horses and camels. A herd of about 100 rhinoceroses kept returning to the water holes, kicking up and breathing volcanic ash clouds each time, until they too died (figure 7.33). Their fossils include a mother rhino who died before her suckling youngster lying next to her. As ash continued to blow about, it ultimately buried the water hole death sites. You can see the herds of animals, partially excavated and available for viewing, at Ashfall Fossil Beds State Historical Park in Antelope County, Nebraska.

Figure 7.33 Skeletons of rhinoceroses killed 10 million years ago by breathing fine volcanic ash for days, Ashfall, Nebraska.
Pat Abbott

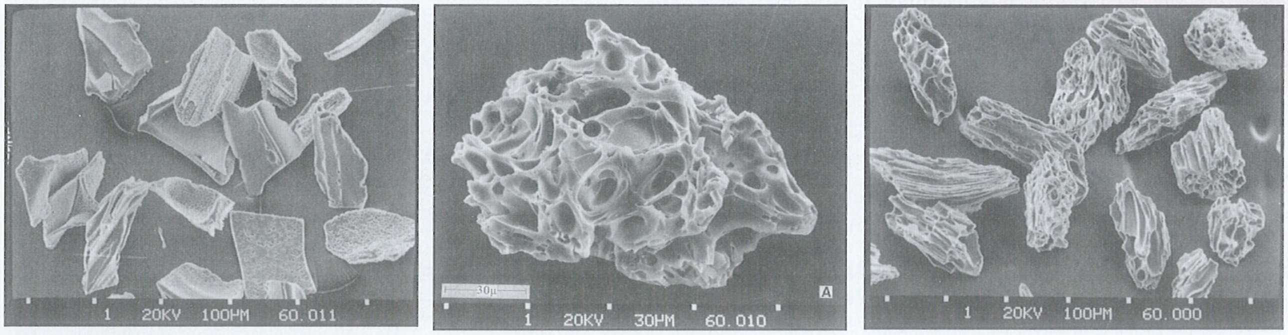


Figure 7.32 Volcanic ash in scanning-electron microscope photos. (a) Glass shards from walls around gas bubbles exploded during eruption of Yellowstone caldera 2.1 million years ago. Tic marks at bottom are 0.001 mm. (b) A single glass particle from 1980 Mount Saint Helens eruption. Voids and holes are from gas bubbles. Length of particle is 0.03 mm. (c) Tiny glass shards with many gas-bubble holes from Rockland Ash exploded 600,000 years ago from Brokeoff Volcano northwest of Lassen, California. Tic marks at bottom are 0.001 mm.
Source: Photos by Robert Oscarson, Janet Slate, USGS, Glen Izett, USGS, Denver (Ret.), as marked, and A. M. Sarna-Wojcicki

vibrations between 10 and 300 hertz (Hz), whereas seismometers recording earthquakes and volcanoes commonly focus on waves between 0.5 and 20 Hz. When data from AFMs cross critical values, they are transmitted by radio to emergency centers, and they can also trigger automatic warning devices.

DEBRIS AVALANCHES

A tall stratovolcano is a beautiful sight and appears to be a mountain of strength. In reality, though, many centuries of forceful intrusions of magma into stratovolcanoes riddle them with fractures, creating planes of weakness. Hot water and gases rising through fractures chemically decompose the volcanic rock over time and weaken it. The fractures and rotten rock can lead to massive failures: **sector collapses** that flow downslope as debris avalanches (see Mount Shasta photo in figure 7.16 and map in figure 7.19). A debris avalanche deposit is composed of huge blocks of the volcano within a matrix of finer-grained material (see sector collapse of north side of Mount St. Helens in figure 7.9c and debris avalanche material choking the Toutle River in figure 7.14).

A volcano sector collapse may be triggered by the injection of fresh magma that inflates a volcano; by forceful expansion of water in contact with magma inside a volcano; or by an earthquake. Debris avalanches are responsible for 2% of volcano-caused deaths.

INDIRECT—FAMINE

Volcanoes affect humans not only directly, but also indirectly. Volcanism can reduce agricultural output, weaken or kill livestock, and weaken humans, setting the stage for famine.

Laki, Iceland, Fissure Eruption of 1783

During the summer of 1783, the greatest lava eruption of historic times poured forth near Laki in Iceland. After a week of earthquakes, on the morning of 8 June 1783, a 25 km (16 mi) long fissure opened, and basaltic lavas gushed for 50 days at 5,000 m^3/sec. To better appreciate this volume of magma, consider that North America's mightiest river, the Mississippi, empties into the Gulf of Mexico at about three times this volume. When the eruption ended, an area of 565 km^2 (218 mi^2) was buried beneath 13 km^3 (3 mi^3) of basaltic lavas. The volume of ash and larger airborne fragments totaled another 0.3 km^3.

The 50 days of eruption were accompanied by the release of an enormous volume of gases that enshrouded Iceland and much of northern Europe in a "dry fog" or blue haze or **vog.** This haze was rich in SO_2 (one of the visible components of today's urban smog) and an unusually large amount of fluorine. The gases slowed the growth of grasses and increased their fluorine content. An Icelandic farmer named Jon Steingrimmson wrote:

> *The hairy sand-fall and sulfurous rain caused such unwholesomeness in the air and in the earth that the grass became yellow and pink and withered down to the roots. The animals that wandered around the fields got yellow-colored feet with open wounds, and yellow dots were seen on the skin of the newly shorn sheep, which had died.*

The volcanic gases helped kill 75% of Iceland's horses and sheep and 50% of the cattle. The resulting famine weakened the Icelandic people, and about 20% of the population (10,000 people) died. In today's world of instant communication and rapid air transport, these deaths would have been avoided.

Tambora, Indonesia, 1815

The most violent and explosive eruption of the last 200 years was another Indonesian event; it came from Tambora Volcano on Sumbawa Island in April 1815. After three years of moderate activity, on 5 April, a Plinian eruption column shot up 33 km (20 mi) and carried out 12 km^3 (2.9 mi^3) of pumice in just two hours. On 10 April, an even more powerful Plinian eruption blasted up to 44 km (27 mi) high for three hours. The magma exited with so much force that it eroded and widened the vent in the volcano, thus cutting off the focused energy that drove the Plinian column. The eruption column stopped, and the widened vent lay open; with its insides exposed, the volcano now spilled its guts. On 11 April, about 50 km^3 (12 mi^3) of magma poured out of the caldera in overwhelming pyroclastic flows. The week-long eruption saw about 150 km^3 (36 mi^3) of magma burst forth. Tambora once stood 4,000 m (13,000 ft) high, but now its elevation was reduced to 2,650 m (8,700 ft) with a 6 km (3.7 mi) wide caldera that was over 1 km (0.6 mi) deep. The volcanic explosions were audible 2,600 km (1,600 mi) away, and volcanic ash fell 1,300 km (800 mi) from Tambora. On Sumbawa Island, pyroclastic flows killed at least 10,000 people. They also destroyed the feudal kingdoms of Sanggar and Tambora, leading to the erasure of the Tambora language, the easternmost Austro-Asiatic language.

The eruption of Tambora was responsible for an estimated 117,000 deaths: about 10% killed by the eruption and 90% dying slowly at the end of a chain reaction. Pyroclastic fallout devastated crops, which led to famine and weakened people, making them more susceptible to disease, and then the diseases killed them. But this was not just another Indonesian disaster. The Plinian eruptions of April 1815 so affected global climate that 1816 is known as "the year without a summer." The climatic effects of the eruption are discussed in chapter 12.

GAS

It is not just gas-powered magma that kills; gas can be deadly all by itself. Gases are a continuous product of volcanism but even nonerupting volcanoes can release significant volumes of gas.

Killer Lakes of Cameroon, Africa

Spreading centers commonly begin as three-armed rifts meeting at a triple junction (see figure 4.7). In northeast Africa, two rift arms have spread apart enough to create the Red Sea and the Gulf of Aden, while the third arm has failed, so far, to open the East African Rift Valley into another new ocean basin (see figure 4.5). **Failed rifts** that do not open up enough to become spreading centers are common (e.g., figure 7.34). If a rift fails to open a new ocean basin, must it stop all activity? No.

Cameroon sits near the equator in western Africa. It hosts a string of crater lakes running in a northeasterly trend. Prolific rainfalls fill the lakes and combine with the hot temperatures to cover the countryside with greenery. Lake Nyos is one of these crater lakes, filled with beautiful, deep-blue water. This topographically high crater is only several hundred years old. It was blasted into the country rock by

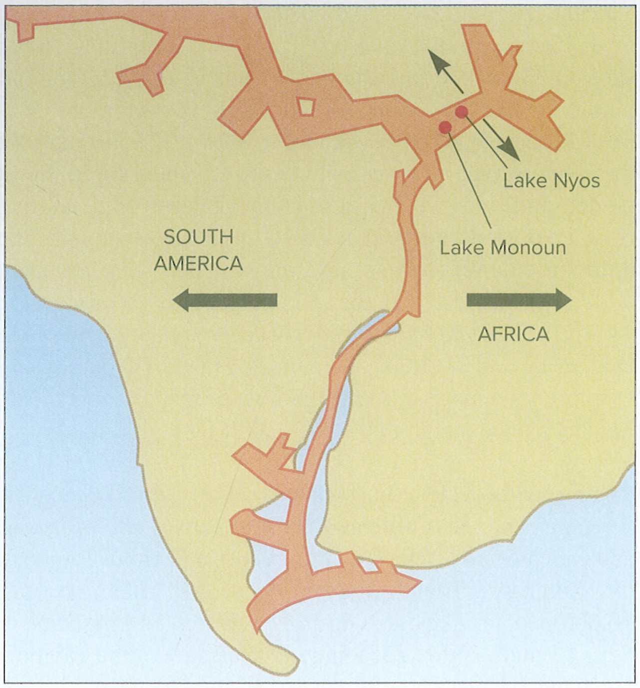


Figure 7.34 Schematic map of Africa and South America splitting apart 135 million years ago. Note the failed rift extending into Africa (upper-right corner).

explosions of volcanic gases and is 1,925 m (6,310 ft) across at its greatest width and as deep as 208 m (680 ft).

At about 9:30 p.m. on 21 August 1986, a loud noise rumbled through the Lake Nyos region as a gigantic volume of gas belched forth from the crater lake and swept down the adjacent valleys (figure 7.35). The dense, "smoky" rivers of gas were as much as 50 m (165 ft) thick and moving at rates up to 45 mph. The ground-hugging cloud swept outward for 25 km (16 mi). Residents of four villages overwhelmed by the gaseous cloud felt fatigue, light-headedness, warmth, and confusion before losing consciousness. After 6 to 36 hours, about half a dozen people awoke from their comas to find themselves in the midst of death: 1,700 asphyxiated people; 3,000 dead cattle; and not a bird or insect alive, nor any other animal. Yet the luxuriant plants of the region were unaffected.

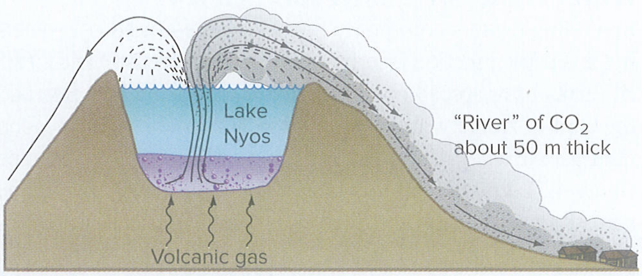


Figure 7.35 Schematic cross-section of Lake Nyos. Volcanic gas is absorbed by the deep-water layer. In 1986, when bottom water was disturbed, 0.15 km^3 of CO_2 gas erupted out of the lake and poured down river valleys for an hour or more in a 50 m thick cloud. Virtually all animal life was killed; plants were unaffected. Solid lines show gas flow; dashed lines are water drops.

Source: Diagram after Y. Zhang, 1996, Nature, 379, 57–59.

This shocking event raised numerous questions. What was the death-dealing gas? What was the origin of the gas? How did the gas accumulate into such an immense volume? What triggered the gas avalanche? Is this event likely to happen again?

What was the death-dealing gas? After a lot of effort to identify some exotic lethal gas or toxic substance as the cause of the tragedy, the killer gas turned out to be simply carbon dioxide. This is the same gas we drink in sparkling spring water, soda pop, and champagne. Its toxicity at Nyos is explained by the principle set forth in 1529 by the German physician Theophrastus von Hohenheim (Paracelsus). The principle of Paracelsus states: *the dose alone determines the poison.* A gas does not have to be poisonous, just abundant. Life in the Nyos region was subjected to the same conditions we recreate inside the fire-extinguisher cylinders in our buildings. Fire extinguishers are loaded with carbon dioxide, which does not put out flames directly; because CO_2 is heavier than air, it deprives fire of oxygen, thus causing flames to die out. Animal life in the Nyos area was extinguished in the same fashion.

What was the origin of the gas? It had a volcanic origin, leaking upward from underlying basaltic magma. A 1,600 km (1,000 mi) long string of volcanoes, the Cameroon volcanic line, trends northeastward through several Atlantic Ocean islands and then on land through northeastern Nigeria and northwestern Cameroon. Interestingly, this is the location of the triple junction of spreading centers that ripped apart this section of Gondwanaland, helping give the distinct outlines to the Atlantic margins of South America and Africa (figure 7.34). The two successful spreading arms are still widening the South Atlantic Ocean. The failed rift is occupied by the line of volcanism that includes the crater that forms Lake Nyos; it is not a volcanic mountain but a crater blasted through bedrock by largely gaseous explosions. The volcanic activity is not seafloor spreading per se; rather, it is a "wannabe" ocean basin that never made it but has not given up totally.

How did the gas accumulate into such an immense volume? Lakes by their nature are stratified bodies of water. Their water layers differ in density, one stacked on top of another. (This is a smaller-scale example of the density differentiation discussed for the whole Earth in chapter 2.) Carbon dioxide, given off by basaltic magma at depth, rises into the bottom waters of Lake Nyos, is dissolved into the heavier, lower water layer, and is held there under the pressure of the overlying water (figure 7.35). As the amount of CO_2 in the lake-bottom water increases, it becomes more unstable. When CO_2 bubbles form, they rise with increasing speed, setting off a positive feedback chain of events leading to more and more bubble formation and rise. Volcanologist Youxue Zhang calculated that the gas eruption was moving about 200 mph when it reached the lake surface. The event of 21 August 1986 released about 0.15 km^3 of gas in about one hour. It was like a large-scale erupting champagne bottle, where removal of the cork causes a decrease in pressure, allowing CO_2 to escape in a gushing stream. About 66% of the dissolved gases escaped. After the event, the lake level was 1 m lower, and the water was brown from mud and dead vegetation stirred up from the bottom.

What triggered the gas avalanche? Many suggestions have been made, including volcanic eruption, landslide, earthquake, wind disturbance, or change in water temperature with resultant overturn of lake-water layers. It is interesting to note that a similar event occurred two years earlier at Lake Monoun on 15 August 1984. This was a smaller event, but it killed 37 people. Both events were in August, the time of minimum stability in Cameroon lake waters. Is this a coincidence, or is this a normal overturning of lake water during the rainy season?

Is this event likely to happen again? Definitely. The Lake Nyos gas escape left behind 33% of the CO_2, and more is constantly being fed through the lake bottom. In about 20 years, the lake water could again be oversaturated with CO_2. The same loss of life will occur again unless remedial actions are taken. Degassing pipes have been installed to allow high-pressure gas to shoot out of the lake as a fountain of gassy water (figure 7.36). This could prevent the CO_2 concentrations from building up to explosive levels.

As this situation has become better known, other similar lakes have been recognized. For example, the giant Lake Kivu that straddles the border between Rwanda and Congo holds more than 350 times as much gas as Lake Nyos.

Figure 7.36 Future deadly gas eruptions are being stalled by venting the carbon dioxide gas in the lake-bottom water to the surface through a 200 m (650 ft) long pipe suspended down from a raft. The gas-rich water erupts 37 m (120 ft) up into the atmosphere and the gas simply blows away. There are no mechanical pumps involved here; the dissolved CO_2 powers the fountain.

Source: Bill Evans/USGS

LAVA FLOWS

Lava flows are common and impressive, but they are responsible for less than 1% of volcano-caused deaths. Why don't lava flows kill more people? Usually they move too slowly—but not always.

Nyiragongo, Zaire, 2002

As East Africa slowly rifts away from the African continent (see figure 4.5), magma rises to build stratovolcanoes such as Mount Nyiragongo in the East African Rift Valley. Nyiragongo has a long-lived lava lake in its summit crater. On 17 January 2002, lava flowed rapidly down the slopes of the volcano, killing more than 100 people living on the mountain. Upon reaching flatter ground, the lava flows slowed but moved relentlessly toward Lake Kivu. The city of Goma lay in the path of the oncoming lava: 500,000 residents plus uncounted thousands of civil war refugees from Rwanda lived there. Lava reached the lake, but it first flowed through the heart of Goma, destroying about 25% of the buildings and forcing the war refugees to flee again.

How were the lava flows able to catch and kill so many people? The lava had unusually low viscosity. In 1977, Nyiragongo lava flows had exceptionally low SiO_2 content, about 42%. (Compare this value to table 6.5.) The low-viscosity lava in 1977 flowed down the volcano slopes at about 60 km/hr (40 mph), killing an estimated 300 people.

An additional concern is the tremendous volume of carbon dioxide and methane gas held in the deep water of Lake Kivu. A large disruption of the bottom waters, as by an entering lava flow or eruption on the lake bottom, could cause a gas release affecting the 2 million people living along the shore of Lake Kivu.

VEIs of Some Killer Eruptions

Does the total energy involved in a volcanic eruption correlate well with number of deaths? Not necessarily. The volcanic explosivity index (VEI), in chapter 6, is a semi-quantitative approach to estimating the magnitude of explosive eruptions based on volume of material erupted and eruption-column height. Table 7.2 lists VEIs for some of the deadly events we have examined. Note that some of these events had low VEIs; they killed with a relatively small-volume pyroclastic flow, melted glacier ice, and gas escape without magma.

How frequent are eruptions at specific VEI magnitudes? Somewhere on Earth, a VEI 2 event occurs every few weeks, a VEI 3 happens several times a year, a VEI 4 erupts once or twice a year, a VEI 5 happens about once per decade, and a VEI 6 blasts forth once or twice a century. The bigger the eruptions, the less frequently they occur. As the human population continues its rapid growth, increasing numbers of people move into volcano hazard zones. The need for accurate prediction of eruptions is becoming ever more pressing.

TABLE 7.2

VEIs of Notable Volcanic Disasters (Volcanic Explosivity Index)

VEI	Volcano
8	Yellowstone, 600,000 years ago; Toba, 74,000 years ago
7	Tambora, 1815
6	Vesuvius, 79; Krakatau, 1883; Pinatubo, 1991
5	St. Helens, 1980
4	Pelée, 1902
3	Nevado del Ruiz, 1985
2	Kilauea, 2018
1	—
0	Lake Nyos, 1986

How much harm can a volcano do? The Indonesian volcano Toba may have driven the human race almost to extinction about 74,000 years ago. The eruption was a resurgent caldera event that ejected 2,800 km^3 (670 mi^3) of rock, magma, and ash in a mega-eruption with a VEI of 8 (table 7.2). The size of this eruption is equivalent to a combined 560 of the Mount Pinatubo eruptions in 1991 (see figure 7.20). The scar from the Toba eruption is the 100 km (60 mi) long Lake Toba lying near the equator at 2.5° North latitude on Sumatra. Low-latitude eruptions are the most dangerous because they spread debris around more of the world, as gases and fine ash choke the atmosphere and affect life globally.

DNA studies of humans alive today suggest we are descended from a small population of 1,000 to 10,000 people. The average rates of genetic mutation within our own DNA suggest that the time when human population was severely reduced was about the same time as the eruption of Toba. The regional devastation and global cooling of the climate caused by the Toba eruption may have made life so difficult that humans were almost forced into extinction.

Volcano Monitoring and Warning

Can we monitor the activity of a volcano and provide advance warning before a large eruption? Efforts to do so have met with both failure and success.

LONG VALLEY, CALIFORNIA

In the Long Valley–Mammoth Lakes area of California, abundant melting of crustal rock occurs, although no classic mantle plume exists there. About 767,000 years ago, several days of colossal eruptions blew out about 1,400 km^3 (335 mi^3) of rhyolitic magma, generating pyroclastic flows that covered an east-central California area greater than 1,500 km^2 (580 mi^2) with pyroclastic debris (called Bishop Tuff) up to hundreds of meters thick. One pyroclastic lobe flowed 65 km (40 mi) down the Owens Valley. After the magma blasted and poured out, the surface of the Earth dropped nearly 2 km (>1 mi) into the emptied magma reservoir forming the Long Valley caldera (figures 7.37 and 7.38). Afterwards, some remaining magma rose, causing the caldera floor to bulge up into a resurgent dome 400 m (1,300 ft) high (see figures 6.41d and 6.42).

It has been estimated that before the super-eruption, the magma body had a diameter of 19 km (12 mi), with its roof 8 km (5 mi) below the surface. Today, some estimates based on seismic waves suggest that the magma reservoir contains more than 1,000 km^3 (240 mi^3) of magma, with local concentrations of melt up to 27% of rock volume. If reactivated, this is enough magma to support a super-eruption.

Recent Events

Huge eruptions are rare, but these giant continental calderas have fairly frequent small eruptions. There were eruptions in Long Valley 600 years ago and in Mono Lake just 150 to 250 years ago. Today, the main magma body is about 10 km (6 mi) in diameter and its top is around 8 km (5 mi) deep (figure 7.39).

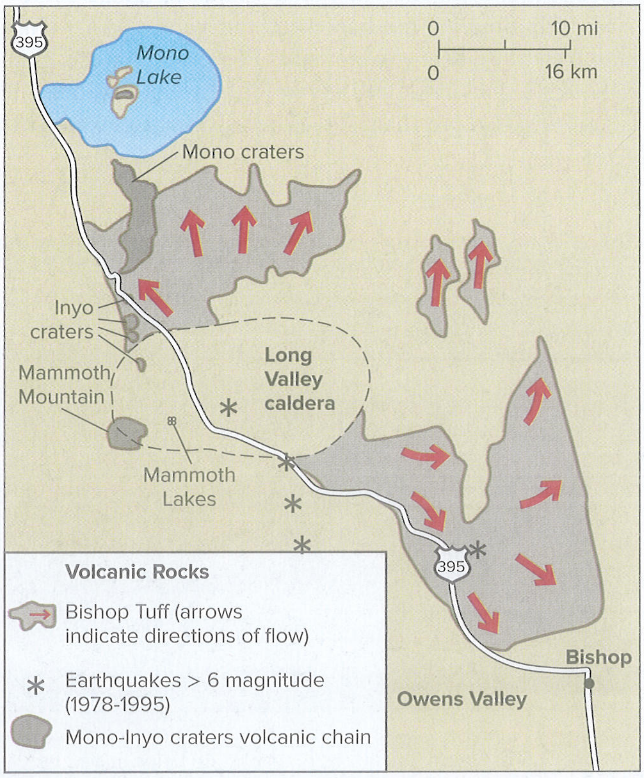


Figure 7.37 Map showing the Long Valley caldera formed by massive eruptions. The brown areas with red arrows are composed of Bishop Tuff, uneroded remains of pyroclastic debris from the last major eruption. The section of Highway 395 shown here lies just north of the section pictured in figure 5.24.

Figure 7.38 The large valley in the center and center-right is the caldera complex of Long Valley, California.

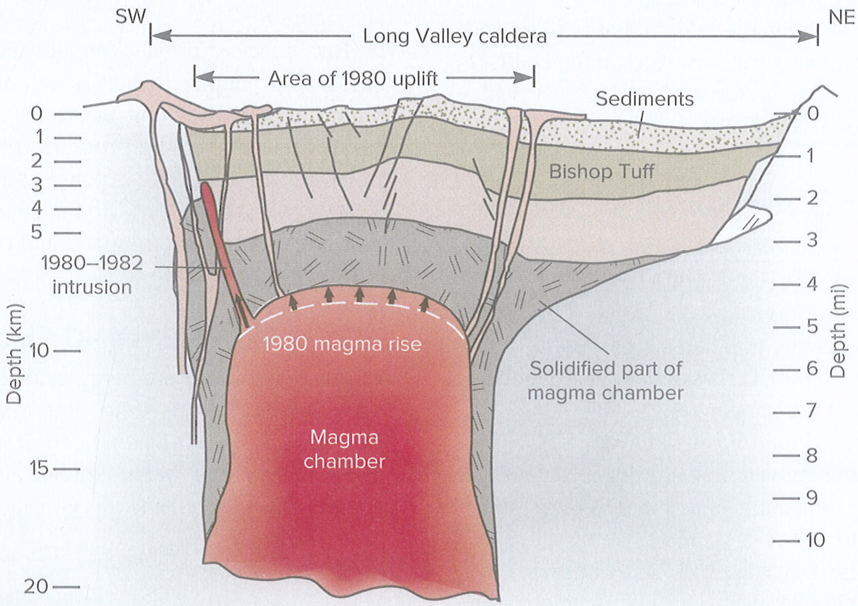


Figure 7.39 This cross-section oriented northeast–southwest through the Long Valley caldera shows the size and depth of the magma body. A tonguelike intrusion moved up the southern edge of the caldera in 1980–1982.

On 25–26 May 1980, one week after the catastrophic eruption of Mount St. Helens, Long Valley was shaken by numerous earthquakes within 48 hours: four of magnitude 6, dozens of magnitude 4 to 5, and hundreds of smaller seisms. In the resort town of Mammoth Lakes, foundations and walls cracked, chimneys fell, and pantry and store shelves dumped their goods. Monitoring by the U.S. Geological Survey showed the resurgent dome had risen 25 cm (10 in) in late 1979–early 1980 (see dome in figure 6.42). The dome rose another several inches by early 1982, accompanied by swarms of earthquakes. Some magma that was 8 km (5 mi) deep in 1980 had risen to within 3 km (2 mi) of the surface by 1982.

Was a volcanic eruption imminent? What should be done? The affluent town of Mammoth Lakes draws most of its income from tourism; it has a year-round population of 5,500 but adds another 20,000 during winter ski season. Would issuing a formal warning of volcanic hazard do good or harm? On 27 May 1982, the U.S. Geological Survey issued a Notice of Potential Volcanic Hazard, the lowest level of alert. House prices fell 40% overnight and tourist visits dropped dramatically. Home and business owners erupted, but the volcano did not.

In the early 1990s, trees on Mammoth Mountain began dying as large amounts of carbon dioxide (CO_2) rose up from the underlying magma and killed them. At the same time, small earthquakes resumed and the ground surface began rising. These phenomena can occur for decades or centuries; however, at large calderas, they do not always mean an eruption is imminent. Many residents remain angry about the "false alarm" of 1982, while many volcanologists and emergency planners are hesitant to issue another volcano warning. Residents are advised to follow the motto: prepare for the worst, but hope for the best.

To get a good view of the giant caldera that is Long Valley, look over your left shoulder as you ride up the chairlifts at the Mammoth Mountain ski resort. The big, dry valley below is the caldera (see figure 7.38).

MOUNT PINATUBO, PHILIPPINES, 1991

A volcano-warning success story occurred in the Philippines in 1991 before the climactic eruption of Mount Pinatubo on 15 June. The volcanic eruption was the largest in the 20th century to occur near a heavily populated area. Nearly 1 million people, including 20,000 U.S. military personnel and their dependents, lived in the danger zone.

In March 1991, Mount Pinatubo awoke from a 500-year-long slumber as magma moved upward from a depth of 32 km (20 mi), causing thousands of small earthquakes, creating three small steam-blast craters, and emitting thousands of tons of sulfur dioxide–rich gas. U.S. and Philippine volcanologists and seismologists began an intense monitoring program to anticipate the size and date of a major eruption. On 7 June, magma reached the surface but had lost most of its gas (like a stale glass of soda pop), so the magma simply

Figure 7.40 The 15 June 1991 Plinian-type eruption of Mount Pinatubo lasted 15 hours, sending pyroclastic flows downslope. VEI = 6.

Rick Hoblitt/U.S. Geological Survey

oozed out to form a lava dome (see figure 7.12). Then, on 12 June (Philippine Independence Day), millions of cubic meters of gas-charged magma reached the surface, causing large explosive eruptions. It was time to get out of the volcano's killing range! The message to speed up the evacuation spread quickly and loudly. Virtually every person, and every movable thing, left hurriedly. On 15 June, the cataclysmic eruption began (figure 7.40). It blew 5 km^3 (1 mi^3) of magma and rock up to 35 km (22 mi) into the atmosphere, forming an ash cloud that grew to more than 480 km (300 mi) across. The airborne ash blocked incoming sunlight and turned day into night. Pyroclastic flows of hot ash, pumice, and gas rolled down the volcano flanks (see figure 6.3) and filled valleys up to 200 m (660 ft) deep. Then, as luck would have it, a typhoon (hurricane) arrived and washed tremendous volumes of volcanic debris downslope as lahars (see figure 6.32).

How successful was the advance warning? Although almost 300 people died, it is estimated that up to 20,000 might have died without the forceful warnings. The scorecard for the monitoring program from March to June 1991 shows that a monitoring expense of about $1.5 million saved 20,000 lives and $500 million in evacuated property, including airplanes. What a dramatic and cost-effective success!

SIGNS OF IMPENDING ERUPTION

Several phenomena are being evaluated as signs of impending eruption. We need to determine if they are reliable enough to justify evacuating people out of a volcanic-hazard zone. Phenomena being studied include seismic waves, ground deformation, and gas emissions.

Seismic Waves

As magma rises up toward the surface, it causes rocks to snap and break, thus sending off short-period seismic waves (SP) with typical periods of 0.02 to 0.06 seconds. Magma on the move through an opened conduit generates longer-period seismic waves (LP) with periods of 0.2 to 2 seconds. In 1991, during the two weeks before Mount Pinatubo erupted, there were about 400 LP events a day coming from about 10 km (6 mi) deep. Apparently, the LP events were recording the arrival of new magma moving in and loading the volcano for eruption.

Further study shows that a volcano in action causes a variety of earthquakes that generate seismic waves with different periods. These seismic waves (acoustic emissions) produce a record similar to a symphony orchestra. Recognition of different seismic waves could develop into a way of forecasting eruptions. Volcanic processes include (1) creation and propagation of fractures in rock, (2) active injection and movement of magma, (3) degassing, and (4) changes in pore-fluid pressures. Seismic waves from volcanic activity include (1) high-frequency waves, (2) low-frequency waves, (3) very-low-frequency waves, (4) tremors of continuous low-frequency vibrations, and (5) hybrid mixtures. The goal is to relate each seismic-wave type to a specific volcanic activity. In effect, the work is like distinguishing the sound of the flute or the clarinet from the many sounds produced by a symphony orchestra.

Ground Deformation

The ground surface rises up and sinks down as magma moves up or withdraws. Ground deformation can be measured by tilt meters or strain meters placed in the ground and by electronic distance meters. In recent years, satellites have been using radar to measure movements of the ground over time. For example, between 1996 and 2000, a 15 km (9 mi) wide area on the flanks of the Three Sisters volcanoes in Oregon bulged upward 10 cm (4 in) as about 21 million m^3 of magma rose to within 6 to 7 km (3.7 to 4.3 mi) below the ground surface (figure 7.41). Now, global positioning system (GPS) stations have been set in the area to add more data about ground deformation. The more the ground rises, the more likely it is that some magma will break through to the surface and erupt.

Gas Measurements

As magma rises toward the surface, the pressure on it drops and dissolved gases escape. For example, at Mammoth Mountain next to the Long Valley caldera in California (see figure 7.37), CO_2 is escaping from the magma. In the 1990s, more than 1,000 tons a day were oozing through the surface, killing trees and causing worry about an impending eruption. Now, CO_2 releases have declined to about 300 tons a day, suggesting that an impending eruption is less likely. However, this interpretation could be misleading. In 1993, at Galeras Volcano in Colombia, a decrease in gas emissions was interpreted as meaning an eruption was less likely. But, in fact, it meant that the volcano had become plugged by its sticky magma, and gas pressure was building toward the eruption that killed seven volcanologists. So, either an increase or a decrease in gas emissions can be bad. More research must be done.

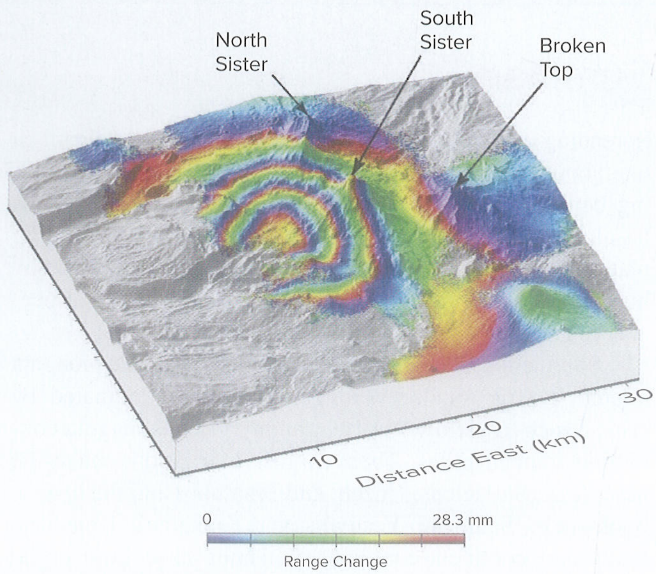


Figure 7.41 Uplift deformation of ground surface near Three Sisters volcanoes in central Oregon, 1 May 2001. Satellite radar interferometry image from InSAR (Interferometric Synthetic Aperture Radar) data.

Source: U.S. Geological Survey

VOLCANO OBSERVATORIES

As volcanoes continue to burst out with damaging and killing eruptions, many countries are responding by establishing and staffing volcano observatories to provide warnings before big eruptions. In the 20th century, the United States experienced powerful eruptions in four states: Alaska, California, Hawaii, and Washington. There are at least 65 active or potentially active volcanoes in the United States. Watching these volcanoes for signs of activity has led the U.S. Geological Survey to establish a Volcano Hazards Program that includes five volcano observatories: Alaska (AVO), California (CalVO), Cascades (CVO), Hawaiian (HVO), and Yellowstone (YVO). Each of these observatories maintains its own website to report current activity. Their observations are also presented using an alert system (table 7.3).

TABLE 7.3

Volcanic-Alert Levels, U.S. Geological Survey

Normal	Typical background activity of a volcano in a noneruptive state
Advisory	Elevated unrest above known background activity
Watch	Heightened/escalating unrest with increased potential for eruptive activity or minor eruption underway
Warning	Highly hazardous eruption underway or imminent

Summary

Spreading centers provide such ideal settings for volcanism that about 80% of all extruded magma occurs there. Spreading centers sit on top of the asthenosphere, which yields basaltic magma that rises to fill fractures between diverging plates. Basaltic volcanoes may be successfully colonized by humans both at spreading centers (e.g., Iceland) and at oceanic hot spots (e.g., Hawaii).

Subduction-zone eruptions involve basaltic magma altered by fractional crystallization and contaminated by crustal rock to yield water-rich, highly viscous magma containing trapped gases. Their explosive eruptions make the news (e.g., St. Helens, Unzen, and Pinatubo) and the history books (e.g., Santorini, Vesuvius, and Krakatau). Transform faults and continent-continent collisions have little or no volcanism associated with them.

The historic record tells of about 275,000 deaths by volcano in the last 500 years. The deadliest processes have been pyroclastic flows, tsunami, lahars, and indirect effects leading to famine. Gas-powered pyroclastic flows can move at speeds up to 150 mph with temperatures over 1,300°F and for distances over 30 mi; examples are Mont Pelée and El Chichón. Pyroclastic debris and water combine and flow downslope as lahars at speeds up to 30 mph and for distances up to 45 mi, killing thousands at Nevado del Ruiz and presenting a hazard to Seattle-Tacoma from Mount Rainier. Volcano-generated tsunami were mega-killers at Krakatau. Sectors of volcanic cones can collapse, producing giant debris avalanches that bury entire landscapes up to 30 mi away (e.g., Mount Shasta). Giant eruptions from continental calderas can erupt more than 1,000 times as much magma as a typical volcano (e.g., Long Valley).

A volcano may be active for millions of years, but centuries may pass between individual eruptions. The timescale of an active volcano must be considered by people living nearby.

It is possible to monitor a volcano and give advance warning of a major eruption. At Mount Pinatubo in the Philippines, early warning saved up to 20,000 lives before the 1991 eruption.

Terms to Remember

failed rift 197
fissure 188
jokulhlaup 178
nuée ardente 191
pyroclastic fall 189
pyroclastic flow 189
pyroclastic surge 189
sector collapse 197
vog 197

Questions for Review

1. How many years might one subduction zone operate? One volcano? How many years might pass between eruptions at an active volcano?
2. Explain why it is relatively safe to watch the eruption of a Hawaiian volcano but dangerous to watch a Cascade Range volcano.
3. What is sector collapse? What is a debris avalanche?
4. Draw a plate-tectonic map and explain the origin of the Cascade Range volcanoes.
5. Draw a series of cross-sections and explain the sequence of events in the Mount St. Helens eruption in 1980.
6. What volcanic processes have killed the most people in the last 500 years?
7. Name four ways of creating pyroclastic flows.
8. Why do pyroclastic flows travel so fast? How do they kill?
9. Is a Plinian eruption most dangerous when it is the strongest?
10. Can pyroclastic flows travel outward in all directions simultaneously? (See pyroclastic surges.)
11. How far can a pyroclastic flow travel over water and still be hot enough to kill people?
12. Draw a cross-section and explain how lahars form and move. How do they kill?
13. What four factors combine to produce lahars?
14. Explain the hazard that Mount Rainier presents to the Seattle-Tacoma region.
15. Draw a cross-section and explain the sequence of events at an African killer lake, such as Nyos.
16. How can an eruption with a low VEI (low magnitude explosivity) rating kill thousands of people?
17. How do the ages vary along a line of subduction-zone volcanoes compared to a line of hot-spot volcanoes?
18. What signs of impending eruption are produced by an active volcano?
19. What is column collapse? How does it generate pyroclastic flows?
20. What health hazards are associated with ash fall? What is the composition of most volcanic ash?

Questions for Further Thought

1. Is a Cascade Range volcano likely to have a major eruption during your lifetime?
2. Is it wise for towns near Mount Shasta to keep growing? What should be done about this situation?
3. Is it wise to build in river valleys below Mount Rainier, even tens of miles away?
4. Could a caldera-forming super-eruption occur during your lifetime? Where are possible sites for these events?