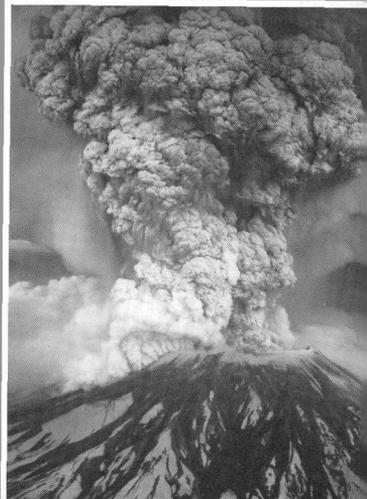


Volcanoes of the United States



Front and back cover (clockwise from top photograph on front) Augustine Volcano, Alaska, 1986; Mount St. Helens, Washington, 1980; Kilauea Volcano, Hawaii, 1983; Mount Spurr, Alaska, 1992; Mono-Inyo Craters Volcanic Chain inside Long Valley Caldera, California.

Volcanoes of the United States

by Steven R. Brantley



Mount Shasta, California, has erupted at least 10 times in the past 3,400 years and at least 3 times in the past 750 years. *(Photograph by Lyn Topinka.)*

Introduction

Few natural forces are as spectacular and threatening, or have played such a dominant role in shaping the face of the Earth, as erupting volcanoes. Volcanism has built some of the world's greatest mountain ranges, covered vast regions with *lava* (molten rock at the Earth's surface), and triggered explosive eruptions whose size and power are nearly impossible for us to imagine today. Fortunately, such calamitous eruptions occur infrequently. Of the 50 or so volcanoes that erupt every year, however, a few severely disrupt human activities. Between 1980 and 1990, volcanic activity killed at least 26,000 people and forced nearly 450,000 to flee from their homes.

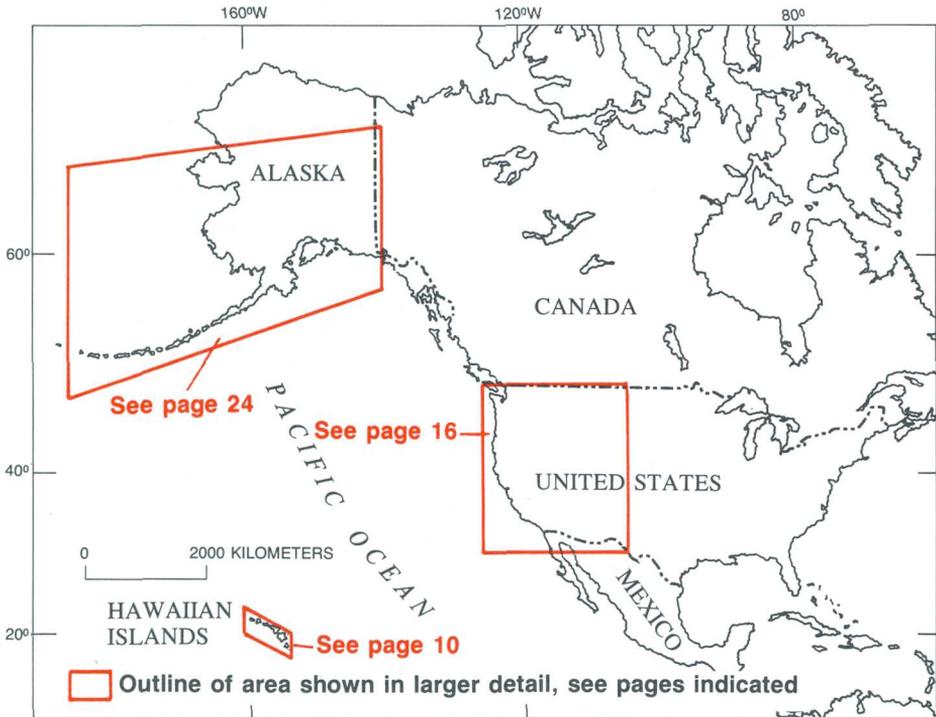
Though few people in the United States may actually experience an erupting volcano, the evidence for earlier volcanism is preserved in many rocks of North America. Features seen in volcanic rocks only hours old are also present in ancient volcanic rocks, both at the surface and buried beneath younger deposits. A thick ash deposit sandwiched between layers of sandstone in Nebraska, the massive granite peaks of the Sierra Nevada mountain range, and a variety of volcanic layers found in eastern Maine are but a few of the striking clues of past volcanism. With this perspective, an erupting volcano is not only an exciting and awesome spectacle in its own right but a window into a natural process that has happened over and over again throughout Earth's history.

The Earth's crust, on which we live and depend, is in large part the product of millions of once-active volcanoes and tremendous volumes of *magma* (molten rock below ground) that did not erupt but instead cooled below the surface. Such persistent and widespread volcanism has resulted in many valuable natural resources throughout the world. For example, volcanic ash blown over thousands of square kilometers of land increases soil fertility for forests and agriculture by adding nutrients and acting as a mulch. Groundwater heated by large, still-hot

magma bodies can be tapped for geothermal energy. And over many thousands of years, heated groundwater has concentrated valuable minerals, including copper, tin, gold, and silver, into deposits that are mined throughout the world.

The United States ranks third, behind Indonesia and Japan, in the number of historically active volcanoes (that is, those for which we have written accounts of eruptions). In addition, about 10 percent of the more than 1,500 volcanoes that have erupted in the past 10,000 years are located in the United States. Most of these volcanoes are found in the Aleutian Islands, the Alaska Peninsula, the Hawaiian Islands, and the Cascade Range of the Pacific Northwest; the remainder are widely distributed in the western part of the Nation. A few U.S. volcanoes have produced some of the largest and most dangerous types of eruptions in this century, while several others have threatened to erupt.

Map of United States showing areas where active volcanoes are located and shown later in more detail.

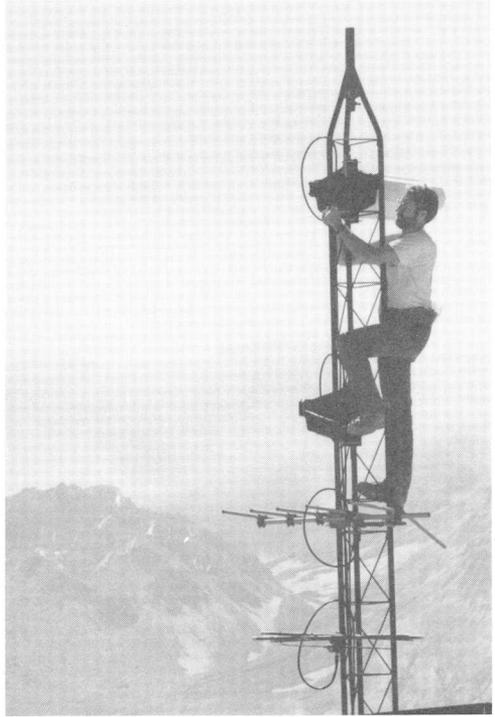
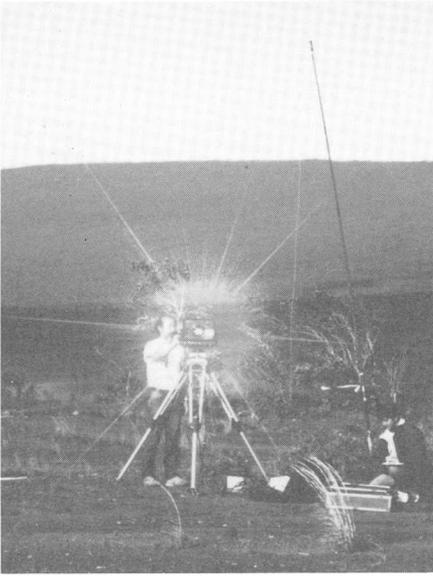


Scientists at the U.S. Geological Survey (USGS) engage in a variety of research activities in order to reduce the loss of life and property that can result from volcanic eruptions and to minimize the social and economic turmoil that can result when volcanoes threaten to erupt. These activities include studies of the physical processes before, during, and after a volcanic eruption, assessments of volcano hazards, and public outreach to translate scientific information about volcanoes into terms that are meaningful to the public and public officials.

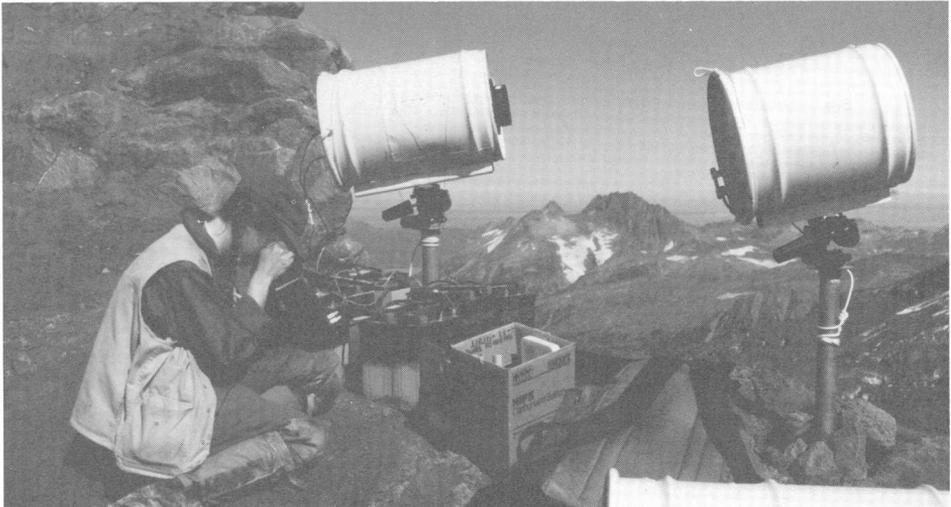
Monitoring volcanoes for signs of activity, another vital component, is carried out by USGS earth scientists at three volcano observatories, which were established to study active volcanoes in Hawaii (1912), the Cascades (1980), and Alaska (1988). These researchers record earthquakes, survey the surfaces of volcanoes, map volcanic rock deposits, and analyze the chemistry of volcanic gas and fresh lava to detect warning signs of impending activity and determine the most likely type of activity that will affect areas around a volcano. During the past 10 years, several warnings of eruptions were issued by the USGS and monitoring of recently active volcanoes in the United States was expanded. Predicting the time and size of volcanic eruptions, however, remains a difficult challenge for scientists.

Scientist collects lava sample from lava flow entering the sea on Kilauea Volcano.
(*Photograph by J.D. Griggs.*)



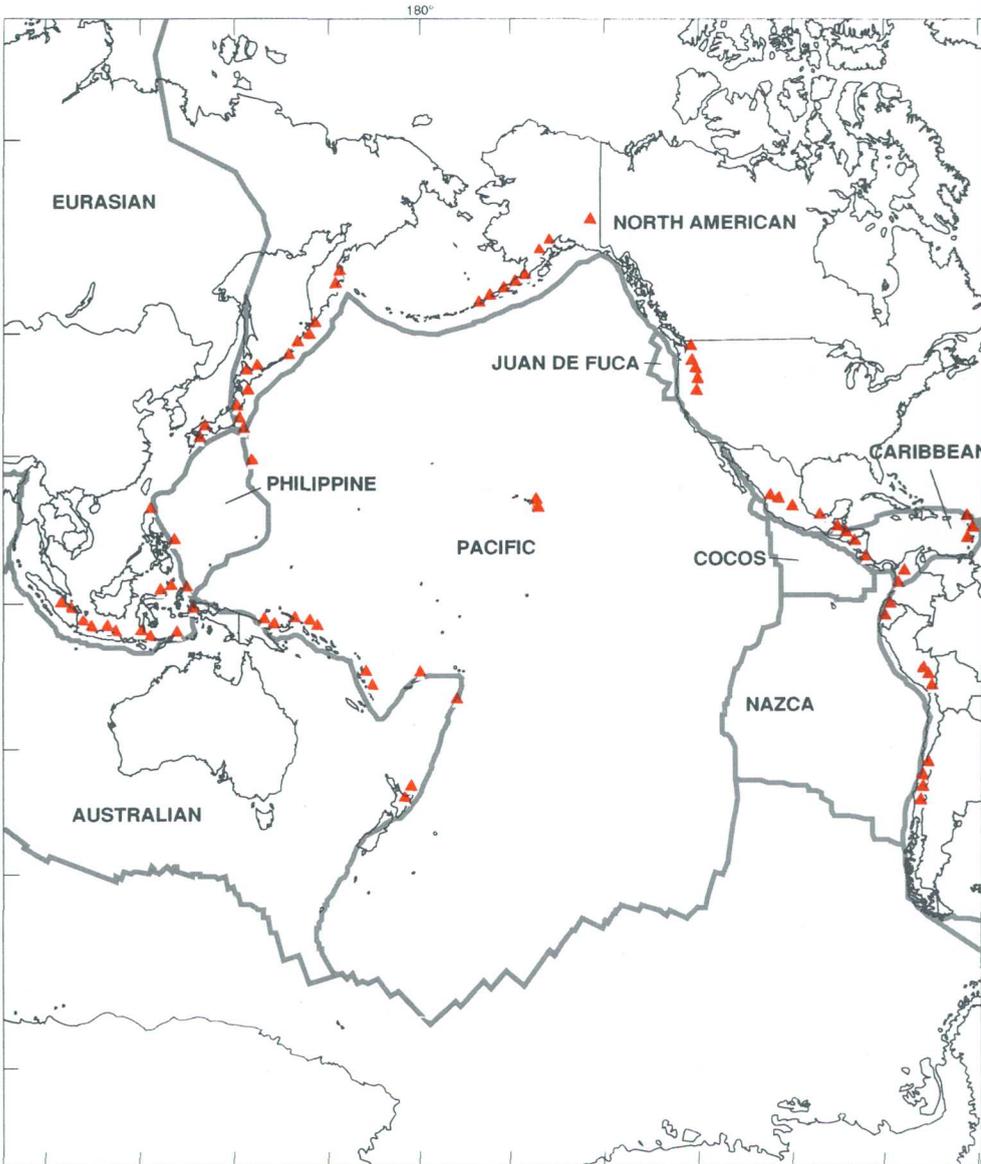


Scientists conducting field studies on active volcanoes in the United States.



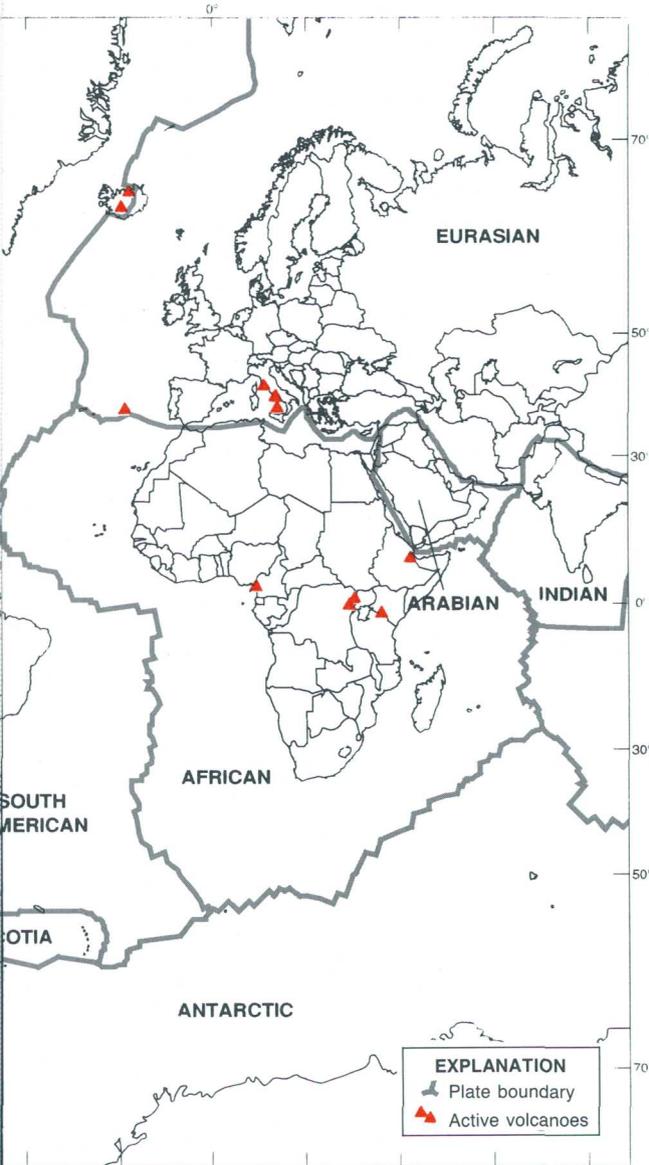
Volcanoes and the Theory of Plate Tectonics

Volcanoes are not randomly distributed over the Earth's surface. Most are concentrated on the edges of continents, along island chains, or beneath the sea forming long mountain ranges. More than half of the world's active



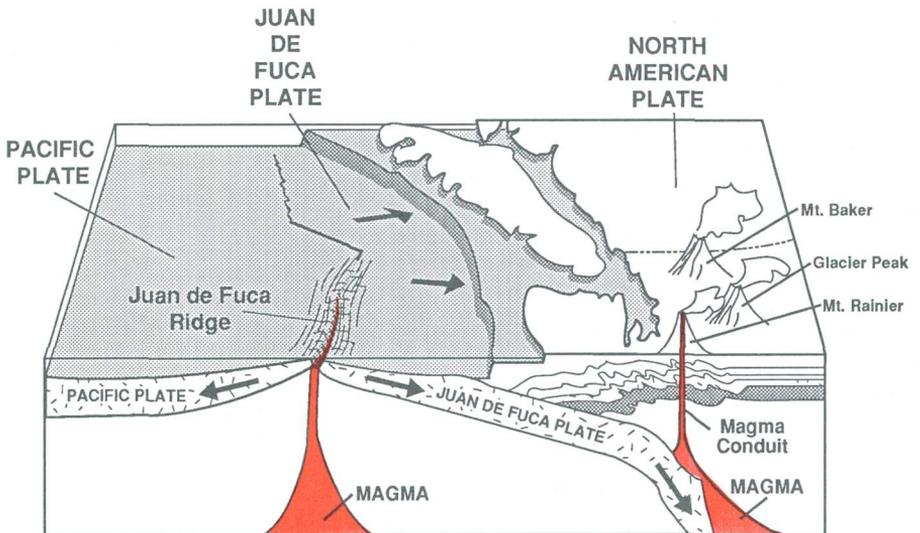
volcanoes above sea level encircle the Pacific Ocean to form the circum-Pacific “Ring of Fire.” In the past 25 years, scientists have developed a theory—called plate tectonics—that explains the locations of volcanoes and their relationship to other large-scale geologic features.

According to this theory, the Earth’s surface is made up of a patchwork of about a dozen large



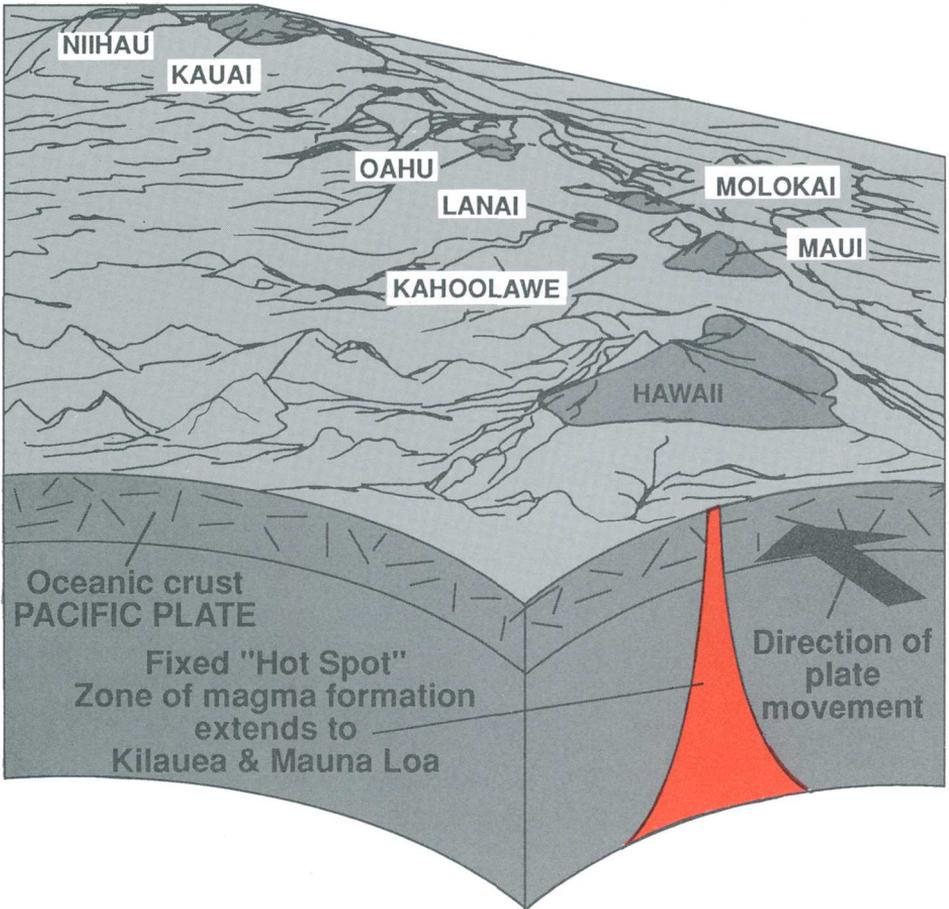
Major tectonic plates of the Earth. Only a few of the Earth’s active volcanoes are shown. (Sketch by Ellen Lougae.)

plates that move relative to one another at speeds from less than one centimeter to about ten centimeters per year (about the speed at which fingernails grow). These rigid plates, whose average thickness is about 80 kilometers, are spreading apart, sliding past each other, or colliding with each other in slow motion on top of the Earth's hot, pliable interior. Volcanoes tend to form where plates collide or spread apart, but they can also grow in the middle of a plate, as for example the Hawaiian volcanoes.



The boundary between the Pacific and Juan de Fuca Plates is marked by a broad submarine mountain chain about 500 km long, known as the Juan de Fuca Ridge. Young volcanoes, lava flows, and hot springs were discovered in a broad valley less than 8 km wide along the crest of the ridge in the 1970's. The ocean floor is spreading apart and forming new ocean crust along this valley or "rift" as hot magma from the Earth's interior is injected into the ridge and erupted at its top.

In the Pacific Northwest, the Juan de Fuca Plate plunges beneath the North American Plate. As the denser plate of oceanic crust is forced deep into the Earth's interior beneath the continental plate, a process known as *subduction*, it encounters high temperatures and pressures that partially melt solid rock. Some of this newly formed magma rises toward the Earth's surface to erupt, forming a chain of volcanoes above the subduction zone.

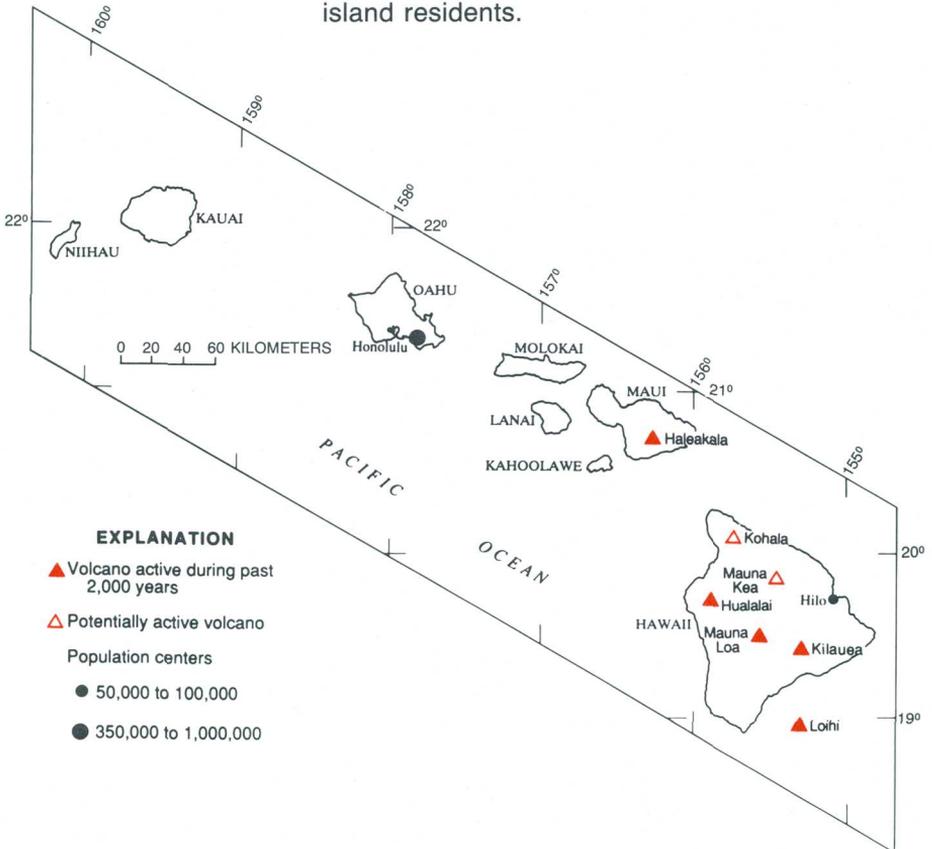


Located in the middle of the Pacific Plate, the volcanoes of the Hawaiian Island chain are among the largest on Earth. The volcanoes stretch 2,500 km across the north Pacific Ocean and become progressively older to the northwest. Formed initially above a relatively stationary "hot spot" in the Earth's interior, each volcano was rafted away from the hot spot as the Pacific Plate moves northwestward at about 9 cm per year. The island of Hawaii consists of the youngest volcanoes in the chain and is currently located over the hot spot.

Recent Eruptions From U.S. Volcanoes

Hawaiian volcanoes

Few places on Earth allow closer or more dramatic views of volcanic activity than Mauna Loa and Kilauea volcanoes on the island of Hawaii. Their frequent but usually non-explosive eruptions make them ideal for scientific study. Kilauea's eruptions are so intensely monitored that scientists have assembled a detailed picture of the volcano's magma reservoir "plumbing" system and how it behaves before and during eruptions. Studies of these volcanoes and the surrounding ocean floor continue to improve our understanding of the geologic history of the Hawaiian Island chain and the ability of scientists to determine volcanic hazards that threaten island residents.



Eruptions of Hawaiian volcanoes are typically non-explosive because of the composition of the magma. Almost all of the magma erupted from Hawaii's volcanoes forms dark gray to black volcanic rock (called *basalt*), generally in the form of lava flows and, less commonly, as fragmented lava such as volcanic bombs, cinders, pumice, and ash. Basalt magma is more fluid than the other types of magma (andesite, dacite, and rhyolite). Consequently, expanding volcanic gases can escape from basalt relatively easily and can propel lava high into the air, forming brilliant fountains sometimes called "curtains of fire."

Lava, whether erupted in high fountains or quietly pouring out, collects to form flows that spread across the ground in thin broad sheets or in narrow streams. The fluid nature of basalt magma allows it to travel great distances from the *vent* (the place where lava breaks ground) and tends to build volcanoes in the shape of an inverted warrior shield, with slopes less than about 10 degrees. Volcanoes with this kind of profile are called *shield volcanoes*.

Hawaiian volcanoes erupt at their summit calderas and from their flanks along linear rift zones that extend from the calderas. *Calderas* are large steep-walled depressions that form when a volcano's summit region collapses, usually after a large eruption empties or partly empties a reservoir of magma beneath the volcano. *Rift zones* are areas of weakness within a volcano that extend from the surface to depths of several kilometers. Magma that erupts from the flank of a volcano must first flow underground through one of the volcano's rift zones, sometimes traveling more than 30 kilometers from the summit magma reservoir before breaking the surface.

Mauna Loa. Rising more than 9,000 meters from the seafloor, Mauna Loa is one of the world's largest active volcanoes; from its base below sea level to its summit, Mauna Loa is taller than Mount Everest. It has erupted 15 times since 1900, with eruptions lasting from less than 1 day to as many as 145 days.

The most recent eruption began before dawn on March 25, 1984. Brilliant lava fountains lit the night-time sky as fissures opened across the floor of the caldera. Within hours, the summit activity stopped and lava began erupting from a series of vents along the northeast rift zone. When the eruption stopped 3 weeks later, lava flows were only 6.5 kilometers from buildings in the city of Hilo. Mauna Loa erupts less frequently than Kilauea, but it produces a much greater volume of lava over a shorter period of time.

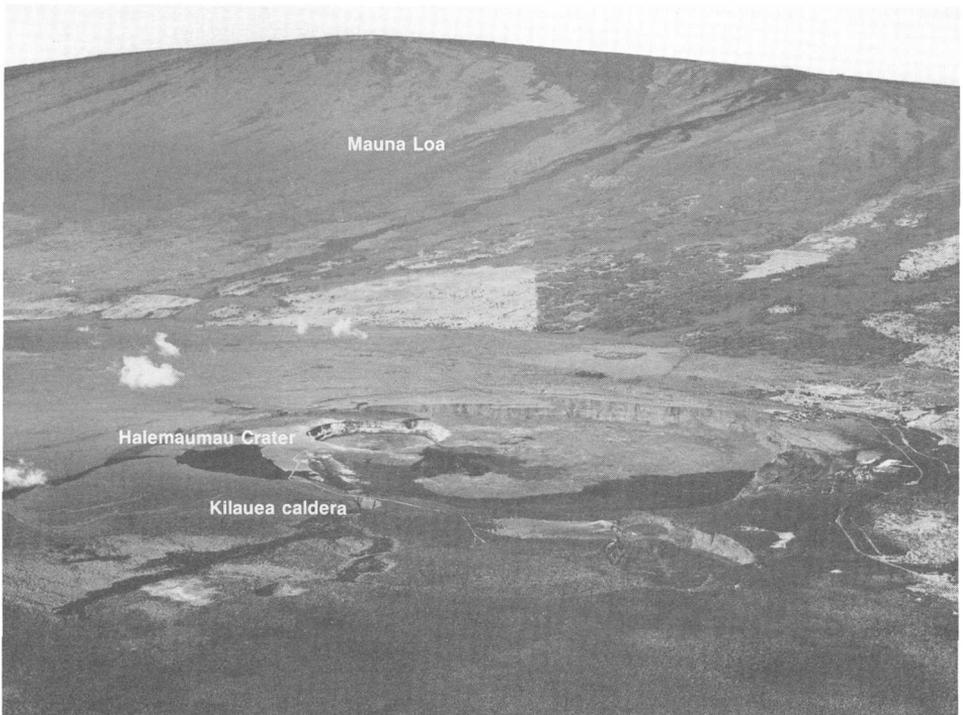


Lava fountains erupt from along Mauna Loa's rift zone. Fountains are about 25 meters high. (Photograph by J.D. Griggs.)

Kilauea Volcano. Kilauea's longest rift-zone eruption in historical time began on January 3, 1983. A row of lava fountains broke out from its east rift zone about 17 kilometers from the summit caldera; within a few months, the activity settled down to a single vent. Powerful fountain-ing episodes hurled molten rock 450 meters into the air and built a cone of lava fragments that quickly became the tallest landmark on the rift zone.

The eruption changed style abruptly in July 1986 when lava broke out through a new vent. Instead of regular episodes of high lava fountain-ing, lava spilled continuously onto Kilauea's surface. The steady outpouring of lava formed a lake of molten rock that became perched atop a small shield volcano. By June 1991, the shield was about 60 meters tall and 1,600 meters in diameter, and lava from the eruption had covered 75 square kilometers of forest and grassland, added 120 hectares of new land to the island, and destroyed 179 homes.

Aerial view of Hawaii's two most active volcanoes, Kilauea and Mauna Loa. (Photograph by J.D. Griggs.)

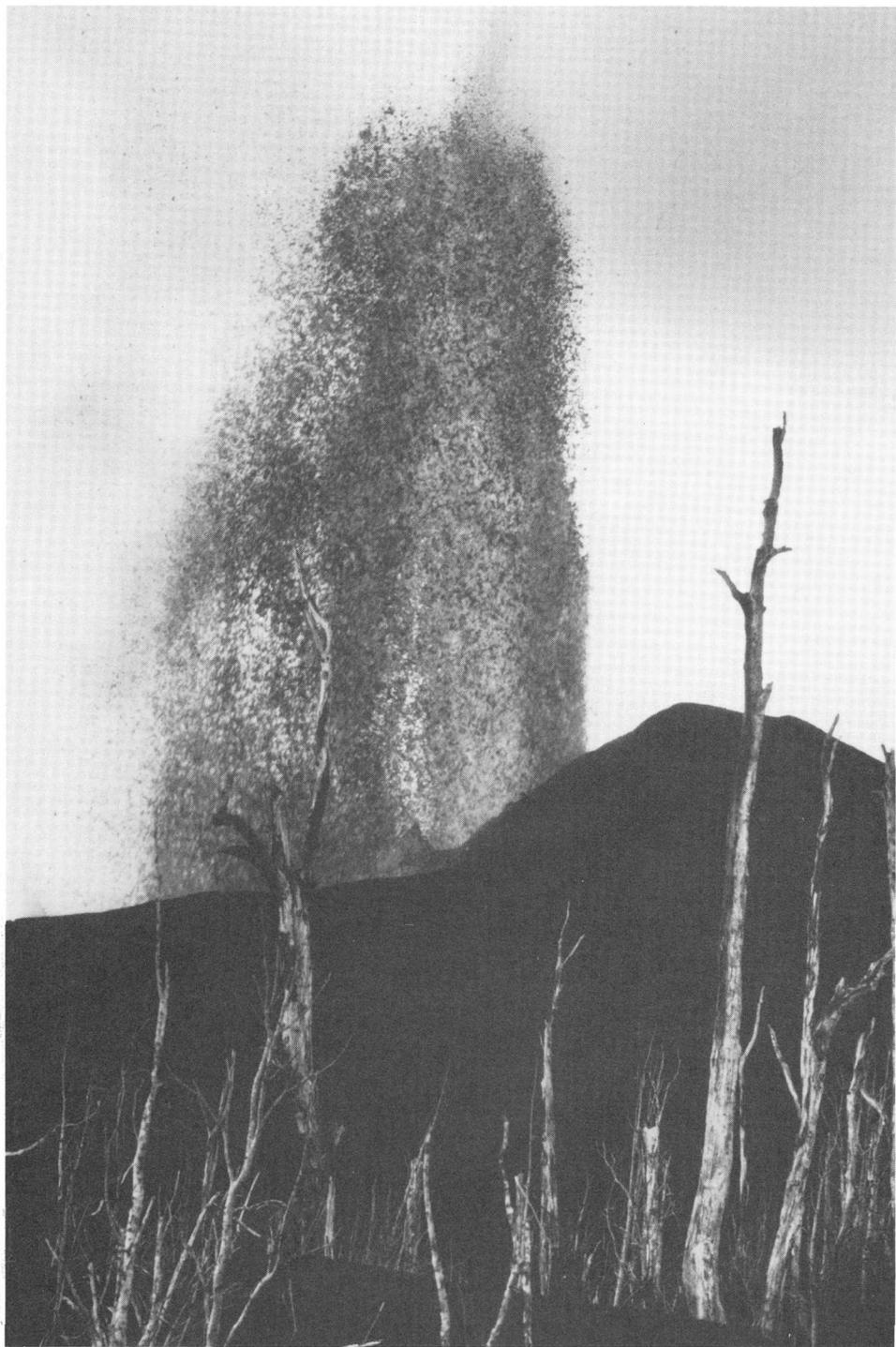


Although most of Kilauea's historical rift eruptions were much briefer, prolonged eruptive activity in the east rift zone from 1969 to 1974 formed a similar shield, Mauna Ulu (Hawaiian for "Growing Mountain"), and an extensive lava field on the volcano's south flank. The geologic record shows that such large-volume eruptions from the rift zones and the summit area, covering large parts of Kilauea's surface, have occurred many times in the recent past. In fact, about 90 percent of Kilauea's surface is covered with lava flows that are less than 1,100 years old.

Most eruptions at Kilauea can be viewed at close range, but a few historical eruptions were dangerously explosive. Fast-moving mixtures of ash and gas, called *pyroclastic surges*, raced across the summit area and into the southwest rift zone during an eruption in 1790. Footprints preserved in a layer of ash 30 kilometers southwest of the summit probably include those of a party of Hawaiian warriors and their families who were crossing the volcano when the eruption struck. An estimated 80 of the 250 people were killed by suffocating clouds associated with the pyroclastic surges. A smaller explosive eruption in 1924 from Halemaumau Crater in Kilauea summit caldera, which killed a photographer who was too close, hurled rocks weighing as much as 8 tons as far as 1 kilometer.

The volcanic cone of Pu'u O'o, named after an extinct Hawaiian bird, towers above an active lava lake (background). (Photograph by J.D. Griggs.)



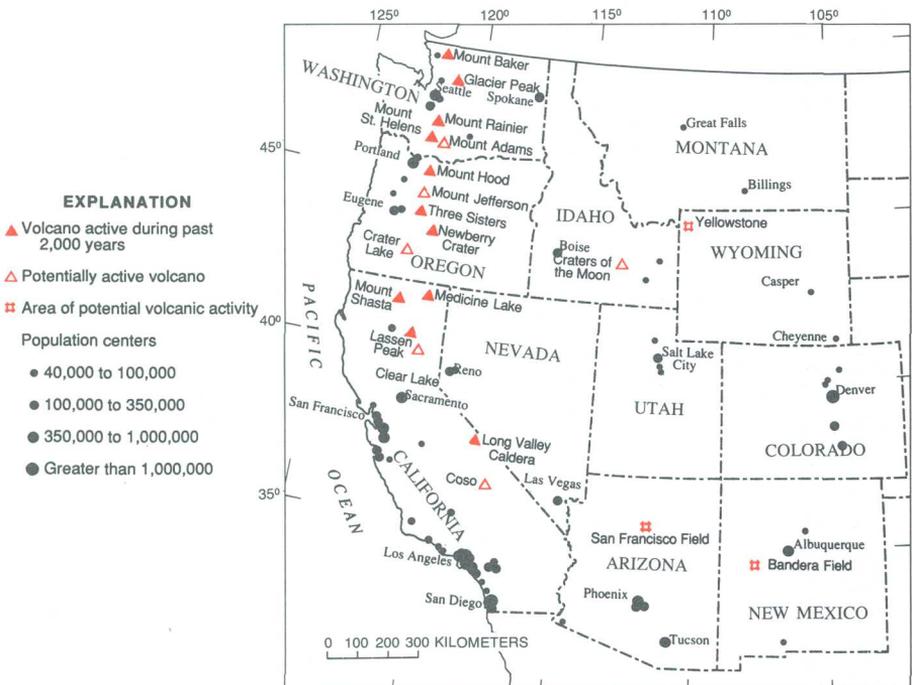


Lava fountain erupting from Pu'u O'o cone. Forty-four episodes of such fountaining between 1983 and 1986 built the cone 255 meters tall. (*Photograph by J.D. Griggs.*)

Cascade volcanoes

Volcanoes of the Cascade Range erupt far less frequently than Kilauea and Mauna Loa, but they are more dangerous because of their violently explosive behavior and their proximity to populated and cultivated areas in Washington, Oregon, and California. The 1980 eruption of Mount St. Helens in southwest Washington dramatically illustrated the type of volcanic activity and destruction these volcanoes can produce. Scientific studies of the eruption of Mount St. Helens and the eruptive histories of other Cascade volcanoes continue to improve public awareness and understanding of these potentially dangerous peaks.

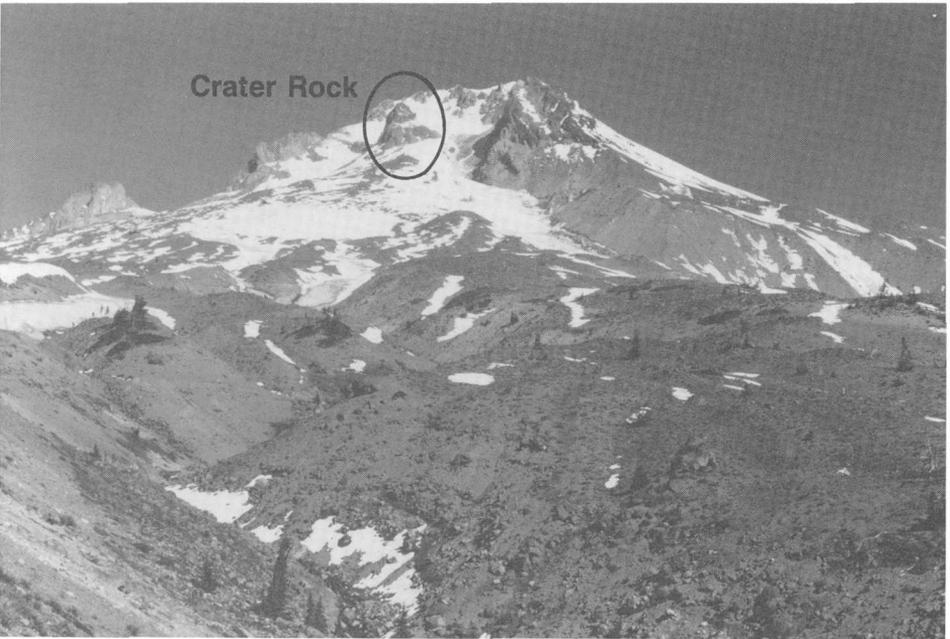
In contrast to Kilauea, Cascade volcanoes erupt a variety of magma types that generate a wide range of eruptive behavior and build steep-sided cones known as *composite volcanoes*. In addition to basalt, andesite and dacite magmas are common.



These magmas are so highly viscous, or sticky, that expanding volcanic gases cannot easily escape from them. This causes a tremendous build-up in pressure, often leading to extremely explosive eruptions. During such eruptions, magma is shattered into tiny fragments (chiefly ash and pumice) and ejected thousands of meters into the atmosphere or even the stratosphere. Under the force of gravity, sometimes these fragments sweep down a volcano's flanks at speeds of more than 100 kilometers per hour, mixing with air and volcanic gases to form *pyroclastic flows*. Rock fragments can also mix with water in river valleys to form *lahars* (volcanic debris flows and mudflows) that destroy everything in their paths.

Andesite and dacite magmas also erupt to form lava flows. Because these lavas are more viscous ("stickier") than basalt, they tend to form thicker flows that travel shorter distances from the vent; consequently, andesite and dacite lavas typically build tall cones with steep slopes of more than 20 degrees.

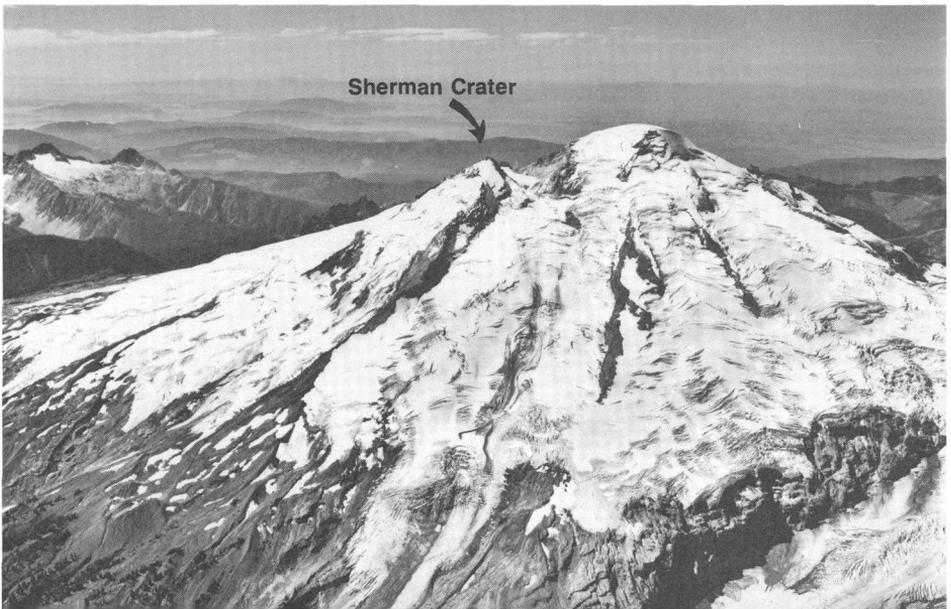
Mt. Hood, Oregon. Eruptions from the volcano about 1,800 and 200 years ago from the Crater Rock lava dome formed a broad apron of rock debris on the volcano's south side. (Photograph by Lyn Topinka.)



Mount Baker, Washington. Eyewitness reports of small ashy plumes and active steam vents on Mount Baker dating as far back as the mid-1800's were clear evidence that the ice-covered volcano had one of the most active geothermal systems among Cascade volcanoes. When new fumaroles and unusually dark vapor plumes appeared abruptly in March 1975, however, people in the Northwest became concerned about an impending eruption and possible avalanches and lahars from Sherman Crater, a vent just south of Mount Baker's summit. Despite a tenfold increase in the release of heat by the volcano during the next 12 months, which resulted in extensive changes to the ice cover in Sherman Crater and produced minor releases of ash, no eruption occurred. The thermal activity was not accompanied by earthquakes, which generally precede most eruptions, and since 1976, the volcano has not showed additional signs of activity.

The increased thermal activity between 1975 and 1976 prompted public officials and Puget Power to temporarily close public access to the popular Baker Lake recreation area and to lower the reservoir's water level by 10 meters. Significant avalanches of debris from the Sherman Crater area could have swept directly into the reservoir, triggering a disastrous wave that would have caused loss of life and damage to the reservoir.

Mount Baker viewed to the west. Increased fumarolic activity occurred in Sherman Crater (left of summit) during the mid-1970's.





Mount Rainier, Washington. Mount Rainier has not produced a significant eruption in the past 500 years, but scientists consider it to be one of the most hazardous volcanoes in the Cascades. Mount Rainier has 26 glaciers containing more than five times as much snow and ice as all the other Cascade volcanoes combined. If only a small part of this ice were melted by volcanic activity, it would yield enough water to trigger enormous lahars.

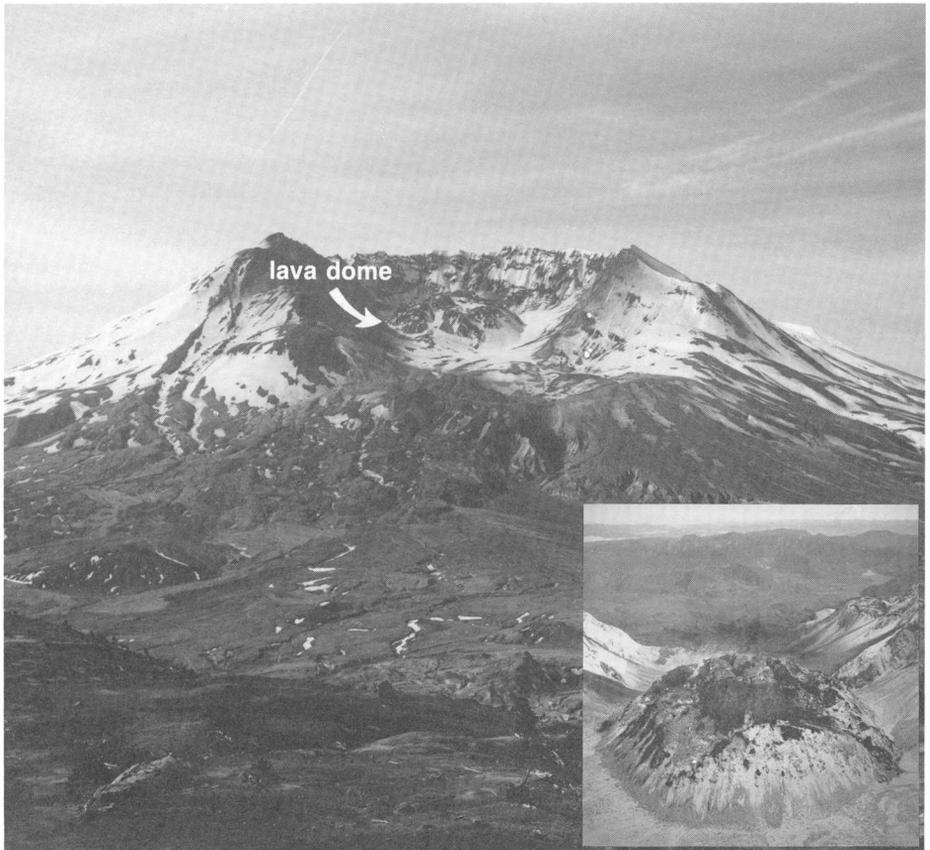
Mount Rainier's potential for generating destructive mudflows is enhanced by its great height above surrounding valleys and its "soft" interior. The volcano stands about 3,000 meters above river valleys leading from its base. Volcanic heat and ground water have turned some of the volcano's originally hard lava into soft clay minerals, thereby weakening its internal structure. These conditions make Mount Rainier extremely susceptible to large landslides. Several have occurred in the past few thousand years, one as recently as about 600 years ago. These landslides, apparently containing great volumes of water, quickly turned into lahars as they rushed down river valleys.

Mount Rainier towers 3,000 meters above the surrounding valleys, all of which have been swept by lahars during the past 10,000 years. Future eruptions will probably trigger similar lahars. *(Photograph by David Wieprecht.)*

Mount St. Helens, Washington. The catastrophic eruption on May 18, 1980, was preceded by 2 months of intense activity that included more than 10,000 earthquakes, hundreds of small *phreatic* (steam-blast) explosions, and the outward growth of the volcano's entire north flank by more than 80 meters. A magnitude 5.1 earthquake struck beneath the volcano at 08:32 on May 18, setting in motion the devastating eruption.

Within seconds of the earthquake, the volcano's bulging north flank slid away in the largest landslide in recorded history, triggering a destructive, lethal lateral blast of hot gas, steam, and rock debris that swept across the landscape as fast as 1,100 kilometers per hour. Temperatures within the blast reached as high as 300 degrees Celsius. Snow and ice on the volcano melted, forming torrents of water and rock debris that

Mount St. Helens crater and lava dome viewed from the north, 1990. **Inset:** Close view of lava dome with new lava extrusion on top (snow-free part) from the south, 1986. (Photographs by Lyn Topinka.)

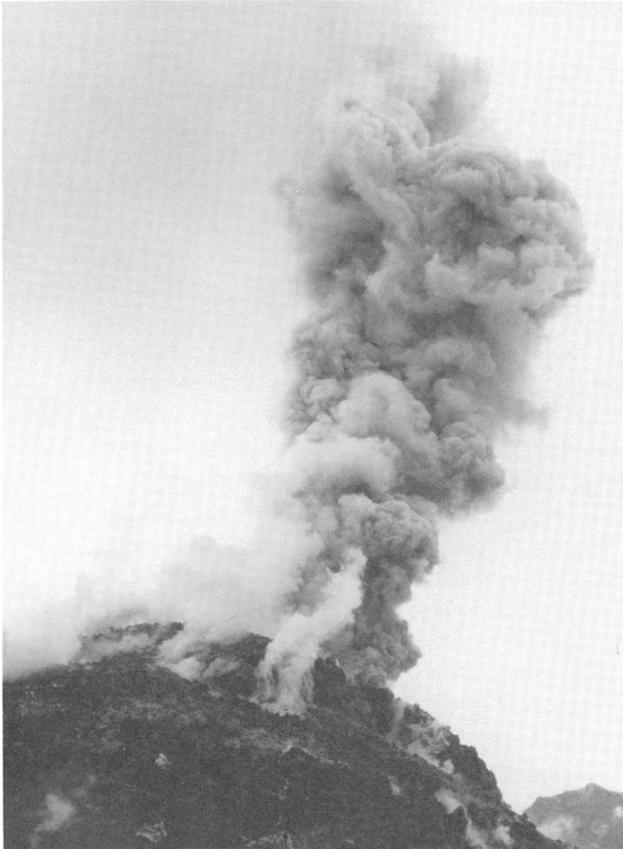




Top: Stand of timber in the process of being harvested was instead knocked over by the lateral blast. An estimated 4 million board feet of timber was destroyed.

(Photograph by H.H. Kieffer.)

Bottom: Small eruption of gas and ash from the lava dome caused by violent release of volcanic gas or the geyser-like flashing of superhot ground water to steam. *(Photograph by Dan Dzurisin.)*



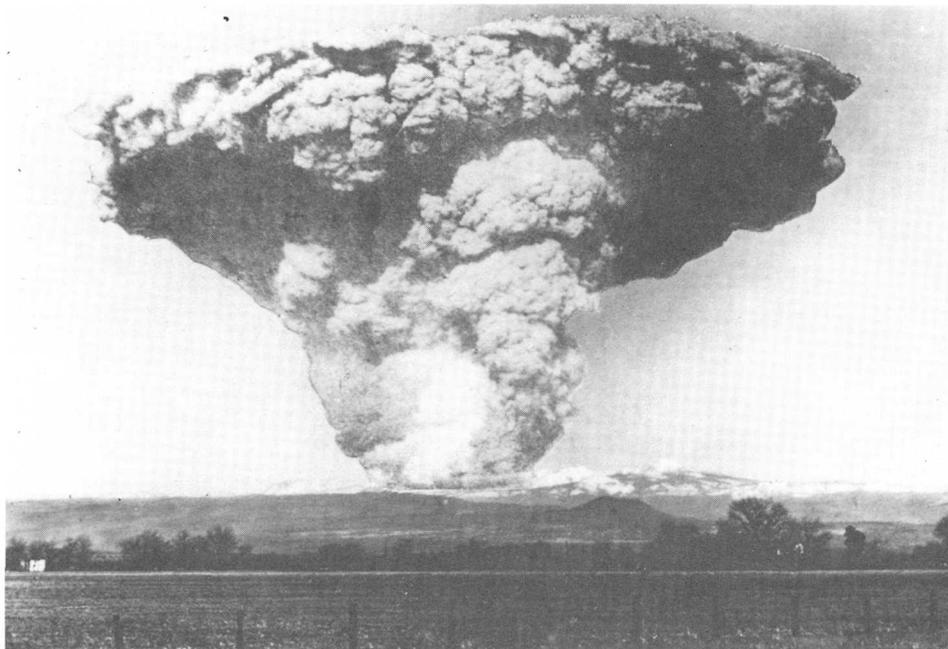


Mount St. Helens towers above the chaotic landslide deposit that fills a former valley to a depth of as much as 195 meters. Note many small hills atop the landslide, called "hummocks" by geologists. (Photograph by Lyn Topinka.)

swept down river valleys leading from the volcano. Within minutes, a massive plume of ash thrust 19 kilometers into the sky, where the prevailing wind carried about 520 million tons of ash across 57,000 square kilometers of the Western United States.

The well-documented landslide at Mount St. Helens has helped geologists to recognize more than 200 similar deposits at other volcanoes in the world, including several other Cascade peaks. Geologists now realize that large landslides from volcanoes are far more common than previously thought—seventeen such volcanic landslides have occurred worldwide in the past 400 years. Consequently, when scientists evaluate the types of volcanic activity that may endanger people, giant landslides are now included, in addition to other types of volcanic activity such as lava flows, pyroclastic flows, lahars, and falling ash.

Following the 1980 explosive eruption, more than a dozen extrusions of thick, pasty lava built a mound-shaped lava dome in the new crater. The dome is about 1,100 meters in diameter and 250 meters tall.



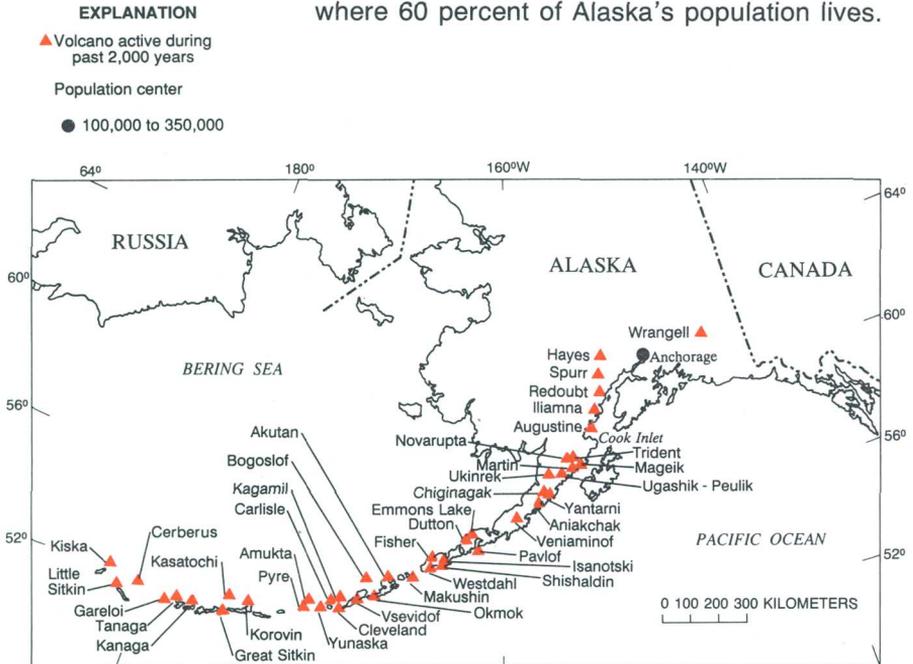
Lassen Peak, California. Long before the recent activity of Mount St. Helens, a series of spectacular eruptions from Lassen Peak between 1914 and 1917 demonstrated the explosive potential of Cascade volcanoes. Small phreatic explosions began on May 30, 1914, and were followed during the next 12 months by more than 150 explosions that sent clouds of ash as high as 3 kilometers above the peak. The activity changed character in May 1915, when a lava flow was observed in the summit crater. A deep red glow from the hot lava was visible at night 34 kilometers away. On May 19, an avalanche of hot rocks from the lava spilled onto snow and triggered a lahar that extended more than 15 kilometers from the volcano.

The most destructive explosion occurred on May 21, when a pyroclastic flow devastated forests as far as 6.5 kilometers northeast of the summit and lahars swept down several valleys radiating from the volcano. An enormous ash plume rose more than 9 kilometers above the peak, and the prevailing winds scattered the ash across Nevada as far as 500 kilometers to the east. Lassen Peak continued to produce smaller eruptions until about the middle of 1917.

Giant mushroom-shaped ash cloud of May 22, 1915, viewed from 80 kilometers west of Lassen Peak. (Photograph provided by National Park Service.)

Alaskan volcanoes

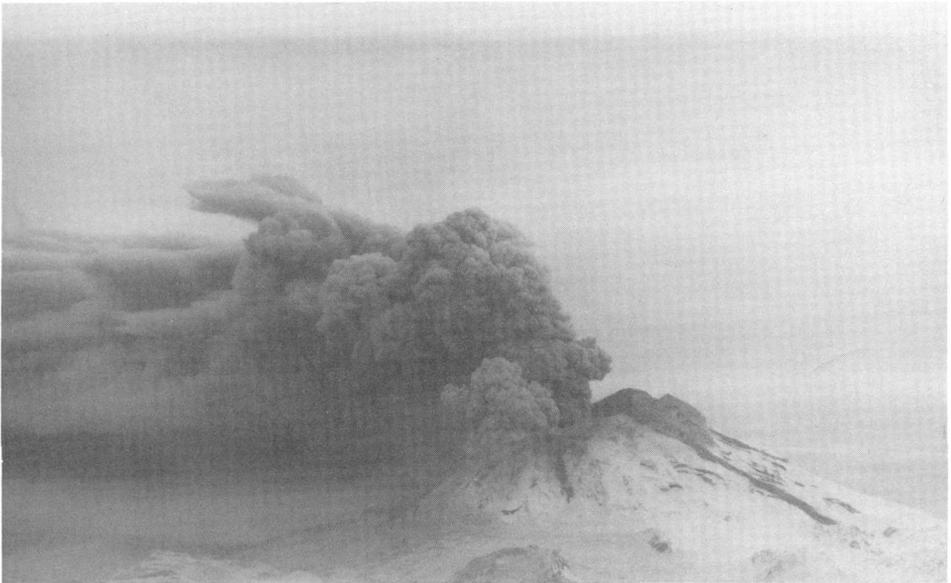
The Alaska Peninsula and the Aleutian Islands have about 80 major volcanic centers that consist of one or more volcanoes. Recent violent eruptions have demonstrated that volcanic hazards do exist in some areas of Alaska, even though it is sparsely populated. Alaskan volcanoes have produced one or two eruptions per year since 1900. At least 20 catastrophic caldera-forming eruptions have occurred in the past 10,000 years; the awesome eruption of 1912 at Novarupta in the Katmai National Monument is the most recent. Scientists are particularly concerned about the volcanoes whose eruptions can affect the Cook Inlet region, where 60 percent of Alaska's population lives.



Redoubt Volcano. Redoubt Volcano erupted for the fourth time this century on December 14, 1989. Following several days of strong explosive activity, a series of lava domes grew in Redoubt's summit crater during the next four months. Most of the domes were destroyed by explosions or collapsed down the volcano's north flank. Some of these events triggered small pyroclastic flows that melted snow and ice on the volcano to form lahars in Drift River Valley, which empties into Cook Inlet 35 kilometers away.

Ash produced by the eruptions severely affected air traffic enroute to Anchorage, Alaska's largest city and a major hub of domestic and international commercial air traffic. Many domestic carriers suspended service to Alaska following major explosive events, and several international carriers temporarily rerouted flights around Alaska. On December 15, a jetliner enroute to Japan encountered an ash cloud while descending into Anchorage. The plane quickly lost power in all four engines and lost 4,000 meters in altitude

Redoubt Volcano, Alaska, erupting on December 16, 1989. (Photograph by National Park Service.)





Lava dome in the summit crater of Redoubt Volcano, which grew between April 21 and June 1990. (Photograph by David Wieprecht.)

before the pilots were able to restart the engines. The aircraft landed safely in Anchorage, but it sustained more than \$80 million in damage.

Lahars generated during the eruption threatened an oil-storage facility located on the banks of Drift River. Oil is pumped from more than a dozen wells in Cook Inlet to the facility and then loaded onto tankers, which dock just offshore. A lahar on January 2 flooded part of the facility with nearly a meter of water, forcing its shut-down until workers could restore power. This and subsequent lahars prompted the Cook Inlet Pipeline Company to temporarily halt oil production from some oil wells and reduce the amount of oil stored at the facility between tanker loadings.



Rock from the lava dome of Redoubt Volcano deposited in a river valley by a lahar during an eruption on January 8, 1990. When found 6 days later, the temperature of the rock was still 145°C. (Photograph by C. Dan Miller.)

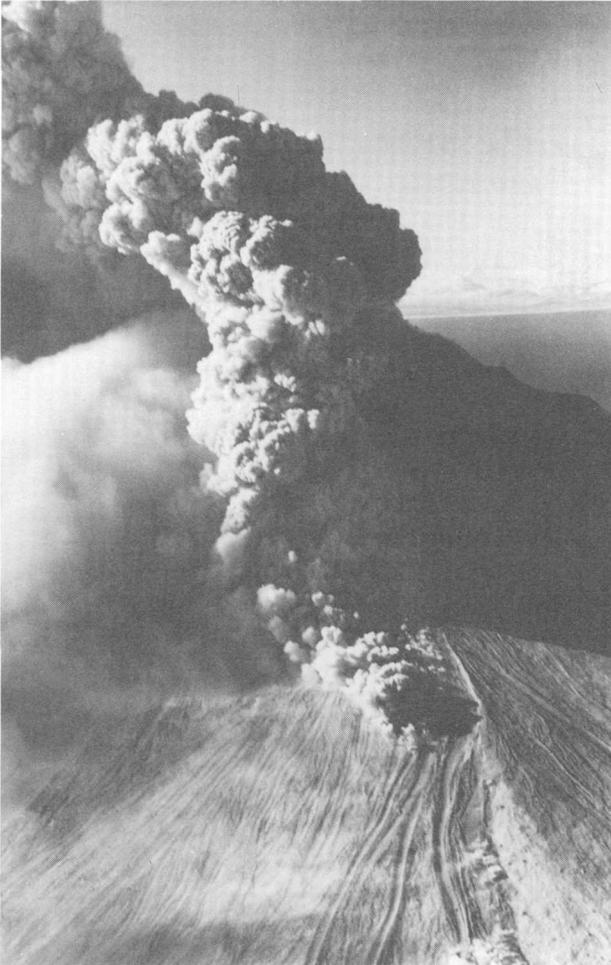
Augustine Volcano. One of the most active volcanoes in Cook Inlet is Augustine, whose symmetrical cone rises 1,254 meters above the sea. Since Captain James Cook discovered and named it in 1778, Augustine has erupted in 1812, 1883, 1935, 1963-64, 1976, and 1986. Curiously, the quiet intervals between these eruptions apparently have shortened from 70 to 10 years.

Augustine's 1986 eruption was similar to the pattern of events observed in 1976. After eight months of earthquake activity beneath the volcano, a violent explosion began on March 26. Billowing ash plumes rose more than 10 kilometers above the vent, pyroclastic flows sped down the volcano's flanks into the sea, and ash spread throughout Cook Inlet. A second stage began April 23, when lava began erupting near the volcano's summit and added about 25 meters to the top of the existing lava dome. Small pyroclastic flows accompanied growth of the dome.

Steam plume rises from lava dome atop Augustine Volcano on April 30, 1986.
(*Photograph by M.E. Yount.*)



Scientists were worried that this eruption might trigger a giant landslide from Augustine's steep upper cone, which could enter the sea to create a *tsunami* (powerful seismic sea wave). At least 12 landslides are known to have occurred at Augustine. The most recent slide took place at the onset of the 1883 eruption when a part of the volcano's summit collapsed into the sea. Within one hour, a tsunami as high as 9 meters crashed ashore on the coast of the Kenai Peninsula 80 kilometers away. No one was killed and property damage was only minor because the tsunami hit at low tide. Subsequent eruptions have rebuilt a steep cone of overlapping lava domes similar to the cone that existed just before the 1883 landslide.



Pyroclastic flow descending the upper flanks of Augustine Volcano. (Photograph by M.E. Yount.)

Novarupta, Katmai National Monument. The largest eruption in the world this century occurred in 1912 at Novarupta on the Alaska Peninsula. An estimated 15 cubic kilometers of magma was explosively erupted during 60 hours beginning on June 6—about 30 times the volume erupted by Mount St. Helens in 1980! The expulsion of such a large volume of magma excavated a funnel-shaped vent 2 kilometers wide and triggered the collapse of Mount Katmai volcano 10 kilometers away to form a summit caldera 600 meters deep and about 3 kilometers across. Extrusion of the lava dome, called Novarupta, near the center of the 1912 vent marked the end of the eruption.

Little was known about the spectacular effects of this great eruption until 1916, when a scientific expedition sponsored by the National Geographic Society visited the area. To their amazement, they found a broad valley northwest of Novarupta marked by a flat plain of loose, “sandy” ash material from which thousands of jets of steam were hissing. The eruption had produced pyroclastic flows that swept about 21 kilometers down the upper Ukak River valley. The thickness of the resulting pumice and ash deposits in the upper valley is not known but may be as great as 200 meters. In 1916, the deposits were still hot enough to boil water and form countless steaming fumaroles; hence the expedition named this part of the Ukak River the “Valley of Ten Thousand Smokes.”

Trident Volcano. Eruptions of andesitic lava flows between 1953 and 1960 built a new cone on Trident’s southwest flank, adding yet another to the volcano’s older complex of three overlapping cones (hence the name Trident). A huge cloud of rising ash was seen on February 15, 1953, in the direction of Katmai National Monument; 3 days later clear weather permitted U.S.

Navy pilots to spot a blocky lava flow emerging from Trident's southwest flank. Slow extrusion of lava during the next 4 months built an irregularly shaped lava dome about 1.5 kilometers long and 600 meters tall. Trident continued to erupt intermittently through 1960, generating three lava flows as long as 4.5 kilometers from the same vent and numerous ash-producing explosive eruptions.



Novarupta lava dome, Mt. Katmai, and Trident Volcano, Alaska. The dome is 380 meters in diameter and occupies a small part of the vent from which about 15 cubic kilometers of magma was erupted in 1912 (dashed line marks approximate outline of vent). (Copyrighted photograph reprinted with permission, Aero Map US Inc., August 21, 1987.)



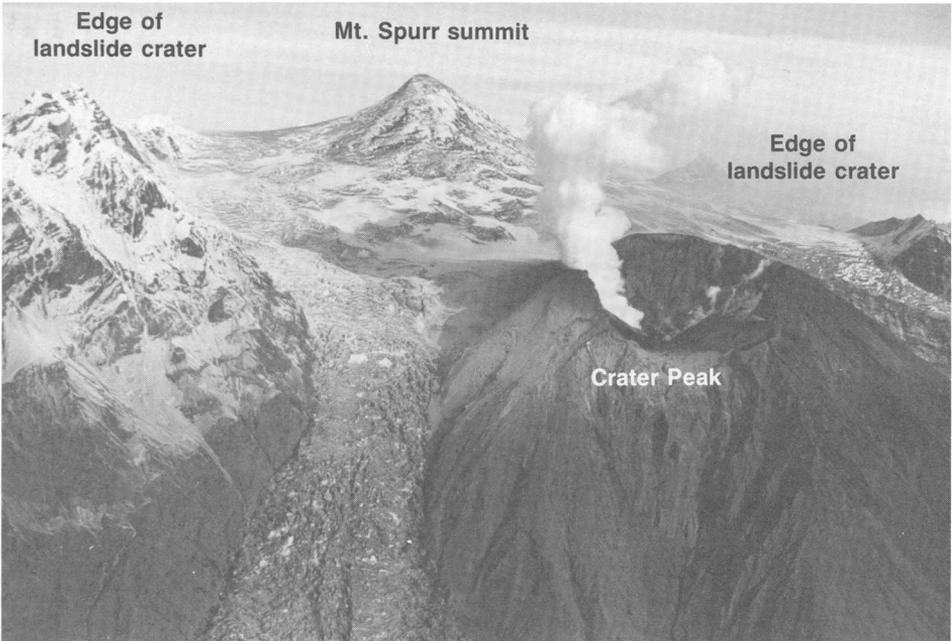
Small steam plume rises from a cinder cone within the summit caldera of Mount Veniaminof, Alaska. The large pit in the ice formed when lava (dark area) flowed beneath the ice and melted it. (Photograph by M.E. Yount.)

Mount Veniaminof. Mount Veniaminof is a massive composite volcano with a summit caldera about 8 kilometers in diameter. Since its formation about 3,700 years ago, the caldera has filled with ice to a depth of at least 60 meters. Between June 1983 and January 1984, a series of small explosions, lava fountains, and lava flows erupted from a small cinder cone within the caldera. The explosions hurled molten lava from the cinder cone, and lava flows melted a pit about 1.5 kilometers in diameter in the ice near the base of the volcano. Water from the melting ice formed a temporary lake.

Mount Spurr. The summit cone of Mount Spurr consists of a large lava dome built in the center of a horseshoe-shaped crater formed earlier by a large landslide. At the southern edge of this ancient crater is a younger, more active cone known as Crater Peak. Scientists have determined that Crater Peak is the source for at least 35 ash layers found in the Cook Inlet area, all of which were erupted in the past 6,000 years. Until recently, a warm turquoise-colored lake partially filled its crater.

A series of explosive eruptions from Crater Peak on June 27, 1992, generated ash plumes as high as about 14 kilometers, small pyroclastic

flows that swept down the south and east sides of the cone, and small lahars. The reawakening of Crater Peak followed nearly a year of increased earthquake activity, which escalated further on June 26, less than 1 day before its first eruption. Not all of the explosive episodes were preceded by a change in seismicity beneath the volcano, a condition that required scientists to maintain a 24-hour watch for extended periods of time in order to issue sudden reports and warnings of eruptive activity. The west side of Cook Inlet received a light to moderate ashfall during the largest explosive episode on August 18; Anchorage was blanketed with about 3 millimeters of ash, causing the Anchorage International Airport to close for a few hours. During an eruption at night on September 17, a spectacular display of lightning and incandescent ballistics and pyroclastic flows were witnessed by hunters who camped about 18 kilometers to the southeast; a faint glow above Crater Peak was also visible from as far away as Anchorage.

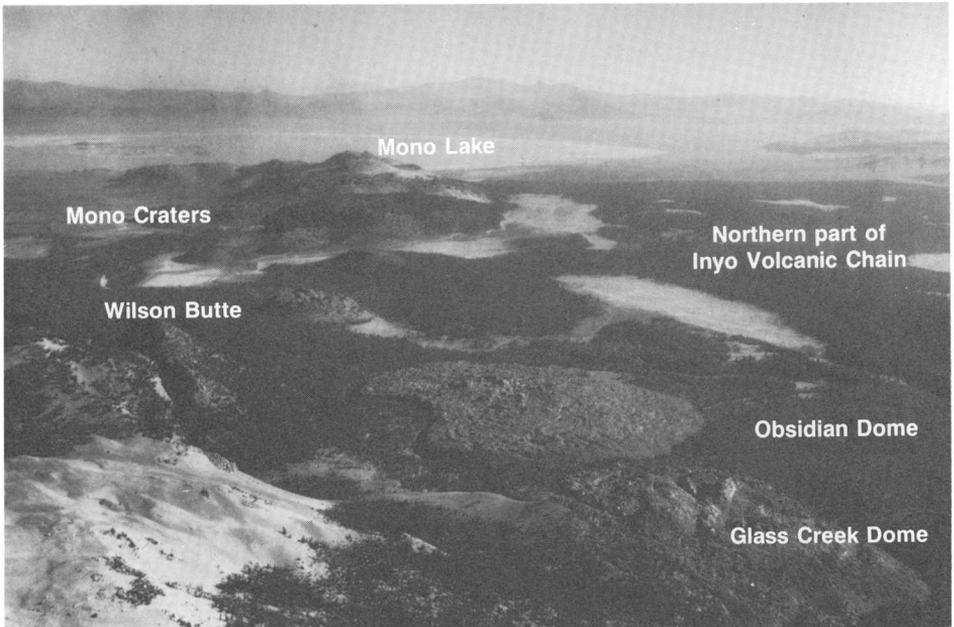


Steaming Crater Peak, a satellite vent on the south side of Mount Spurr volcano, produced three explosive eruptions in 1992. (Photograph by Cynthia Gardner.)

Restless calderas

The largest and most explosive volcanic eruptions eject tens to hundreds of cubic kilometers of magma onto the Earth's surface. When such a large volume of magma is removed from beneath a volcano, the ground subsides or collapses into the emptied space, to form a huge depression called a caldera. Some calderas are more than 25 kilometers in diameter and several kilometers deep.

Calderas are among the most spectacular and active volcanic features on Earth. Earthquakes, ground cracks, uplift or subsidence of the ground, and thermal activity such as hot springs, geysers, and boiling mud pots are common at many calderas. Such activity is caused by complex interactions among magma stored beneath a caldera, ground water, and the regional build-up of stress in the large plates of the Earth's



Aerial view of the Mono-Inyo Craters Volcanic Chain, California. Several eruptions occurred along both chains as recently as about 550 to 600 years ago. (Photograph by C. Dan Miller.)



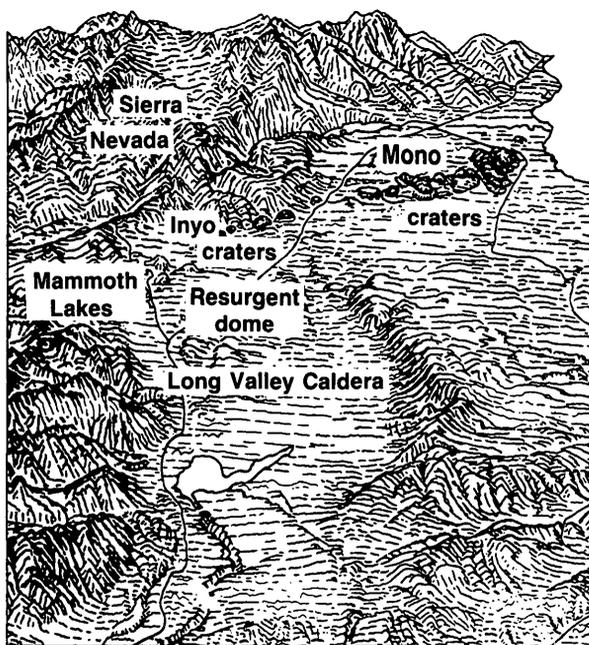
crust. Significant changes in the level of activity at some calderas are common; these new activity levels can be intermittent, lasting for months to years, or persistent over decades to centuries. Although most caldera unrest does not lead to an eruption, the possibility of violent explosive eruptions warrants detailed scientific study and monitoring of some active calderas.

Recently, scientists have recognized volcanic unrest at two calderas in the United States, Long Valley Caldera in eastern California and Yellowstone Caldera in Yellowstone National Park, Wyoming. Whether unrest at these calderas simply punctuates long periods of quiet or is the early warning sign of future eruptions is an important but still unanswered question.

Yellowstone River plummets through the famous Grand Canyon of Yellowstone. Carved by the river, the "yellow" rocks of the canyon are rhyolite lava flows that have been altered by hot water. The lava flows were erupted after the most recent caldera-forming eruption about 600,000 years ago.

Long Valley Caldera, California. Long Valley Caldera lies on the eastern front of the Sierra Nevada, about 300 kilometers east of San Francisco. A huge explosive eruption about 700,000 years ago formed the caldera and produced pyroclastic flows that traveled 65 kilometers from the vent and covered an area of about 1,500 square kilometers. Ash from the caldera-forming eruption fell as far east as Nebraska. Within the past 40,000 years, eruptions have been restricted to a linear zone of vents, including the Mono-Inyo Craters Volcanic Chain, that extends about 50 kilometers north from the northwest part of the caldera.

This volcanic chain consists of many vents that have erupted in the past several thousand years. Eruptions from vents as recently as 550 years ago produced lava flows, pyroclastic flows, and ash, all of rhyolitic composition. Geologic mapping shows that some eruptions were preceded by ground cracking, suggesting that the ground was pulled apart or stretched as magma neared the surface.



Sketch of Long Valley Caldera and the Mono-Inyo Craters Volcanic Chain in central California, viewed from the southeast. (Sketch by Tau Rho Alpha.)

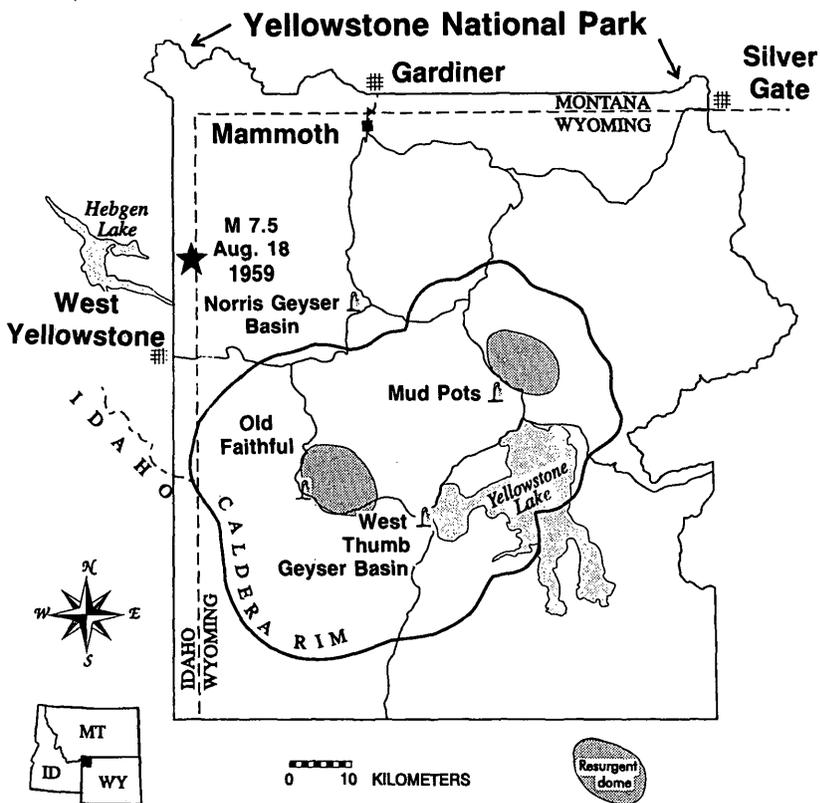
Three moderate earthquakes south of the caldera and one beneath the caldera on May 25-26, 1980, marked the beginning of unrest that continues into the 1990's. Swarms of earthquakes beneath the caldera, changes in several hot springs, and the formation of new springs have occurred since 1980. Precise surveys have also shown that the central part of the caldera has risen by more than 50 centimeters since 1975. This unrest is probably related to the stretching (east-west extension) of the Earth's crust that is known to be occurring in the region around the caldera, and it probably also involves the rise of magma beneath the caldera. Scientists do not know if this unrest will lead to volcanic activity, but the geologically recent eruptions along the Mono-Inyo Craters Volcanic Chain suggest that future eruptions are possible.



South Inyo Crater, Long Valley Caldera, California. Explosive eruptions formed the crater about 500 years ago. (Photograph by Steven R. Brantley.)

Yellowstone Caldera, Yellowstone National Park, Wyoming. Yellowstone Caldera is one of the largest and most active calderas in the world. The spectacular geysers, boiling hot springs, and mud pots that have made Yellowstone famous—and even the strikingly beautiful Grand Canyon of Yellowstone through which the Yellowstone River plunges—owe their existence to the tremendous volcanic forces that have affected the region during the past 2 million years. Cataclysmic eruptions 2.0, 1.3, and 0.6 million years ago ejected huge volumes of rhyolite magma; each eruption formed a caldera and extensive layers of thick pyroclastic-flow deposits. The youngest caldera is an elliptical depression, nearly 80 kilometers long and 50 kilometers wide, that occupies much of Yellowstone National Park. The caldera is buried by several extensive rhyolite lava flows erupted between 75,000 and 150,000 years ago.

Map of most recent Yellowstone Caldera and its main thermal features. After the caldera formed, many vents erupted thick rhyolite lava flows, and the central part of the caldera was pushed upward to form resurgent domes. The star marks the magnitude 7.5 Hebgen Lake earthquake.





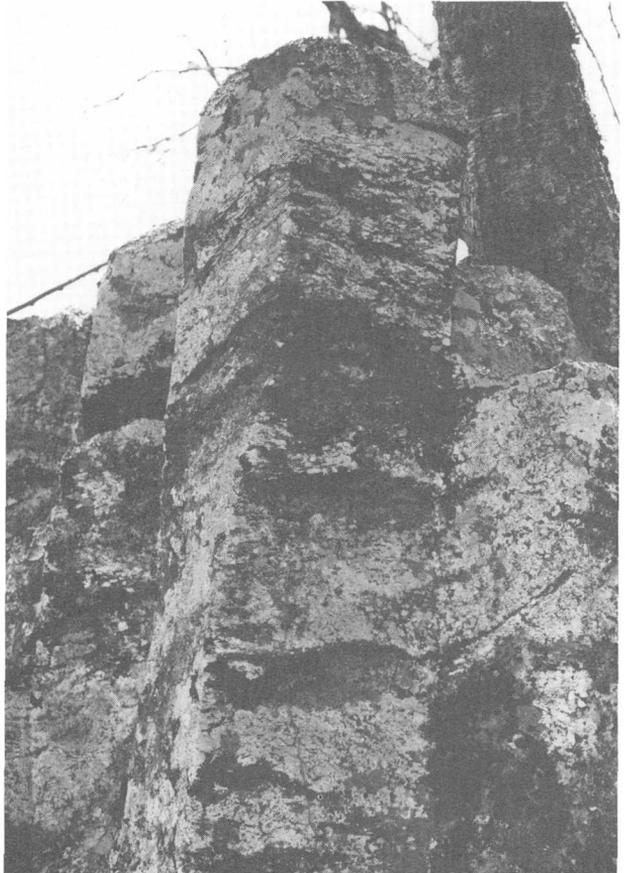
The Earth's crust beneath Yellowstone National Park is still restless. Precise surveys have detected an area in the center of the caldera that rose by as much as 86 centimeters between 1923 and 1984 and then subsided slightly between 1985 and 1989. Scientists do not know the cause of these ups and downs but hypothesize that they are related to the addition or withdrawal of magma beneath the caldera, or to the changing pressure of the hot ground water system above Yellowstone's large magma reservoir. Also, Yellowstone National Park and the area immediately west of the Park are historically among the most seismically active areas in the Rocky Mountains. Small-magnitude earthquakes are common beneath the entire caldera, but most are located along the Hebgen Lake fault zone that extends into the northwest part of the caldera. A magnitude 7.5 earthquake occurred along this zone in 1959.

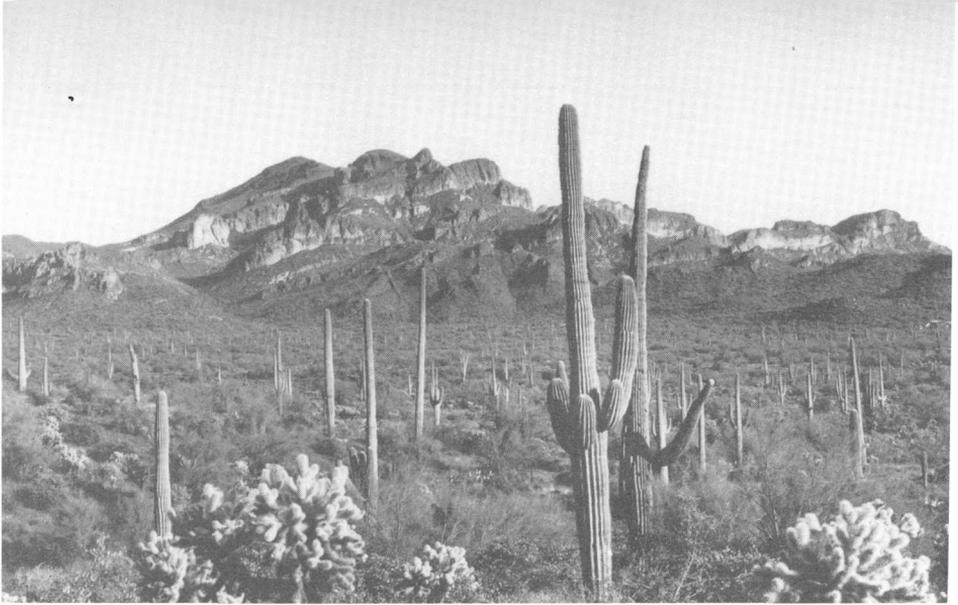
Castle Geyser erupting a column of hot water, Yellowstone National Park. (Photograph by Steven R. Brantley.)

Active Volcanoes: Windows Into the Past

Molten rock has erupted onto the surface of the Earth throughout its 4.5-billion-year history. Although many of these ancient rocks were removed by erosion, volcanic deposits can be found beneath younger rocks in many parts of the United States. To a geologist, such long-lasting volcanic rocks look like those formed by today's active volcanoes. Many ancient volcanic rocks, however, change somewhat with time, as they become firmly consolidated, buried by younger deposits, and sometimes folded and faulted by the continuous shifting of the Earth's crust. Even minerals of volcanic rocks may change, if after burial they encounter high pressures and temperatures.

Columnar jointing in an ancient lava flow in the Blue Ridge Mountains, Shenandoah National Park, Virginia. The flow that contains the columns is one of an extensive series of lava flows, each averaging about 200 feet thick, that poured over the land more than 570 million years ago. Columns form as cooling or shrinkage joints when a hot lava flow cools quickly; the columns form perpendicular to the cooling surface. These columns are about .5 meter in diameter. (Photograph by J.C. Reed, Jr.)





Most active volcanoes are built on older volcanic deposits erupted from ancient volcanoes, and visitors to the present-day volcanoes walk or drive across these products of past volcanism. For example, anyone driving across the Cascade Range, sunbathing at Waikiki, or fishing on the Alaska Peninsula is there because old volcanic rocks form the landscape.

One step further back in time from today's active volcanoes are people who picnic in the White Mountains of New Hampshire, enjoy the autumn colors in the Blue Ridge of Shenandoah National Park, and hike in the rugged Big Bend National Park of Texas. Many of the rocks in these areas were formed by eruptions or by intrusion of magma into the Earth's crust many millions of years ago. Because volcanic activity has been so important in shaping the Earth, watching active volcanoes today provides a window through which we can glimpse and reconstruct the early volcanic history of our planet.

As we increase our knowledge about volcanic processes, by studying volcanoes erupting today as well as those that have lain dormant for hundreds to thousands of years, we increase our ability to predict when and how volcanoes will erupt. Accurate predictions, presented in terms that are meaningful to public officials, will minimize the number of lives lost and the social and economic upheaval that an eruption can cause.

Thick layers of volcanic rocks form the Superstition Mountains, located about 60 kilometers east of Phoenix, Arizona. The consolidated deposits of pyroclastic flows, lava flows and domes, and lahars in the Superstition Mountains and adjacent areas testify to a period of intense volcanism about 17 to 25 million years ago in central Arizona. (*Photograph by D.W. Peterson.*)

Glossary

Andesite	A volcanic rock containing 53–63% silica with a moderate viscosity when in a molten state.
Ash	Fragments less than 2 millimeters in diameter of lava or rock blasted into the air by volcanic explosions.
Basalt	A volcanic rock consisting of less than 53% silica with a low viscosity when in a molten state.
Caldera	A large volcanic depression, commonly circular or elliptical when seen from above.
Composite volcano	A steep-sided volcano composed of many layers of volcanic rocks, usually of high-viscosity lava and fragmented debris such as lahar and pyroclastic deposits.
Dacite	A volcanic rock containing 63–68% silica with a high viscosity when in a molten state.
Dome	A steep-sided mound that forms when viscous lava piles up near a volcanic vent. Domes are formed by andesite, dacite, and rhyolite lavas.
Fumarole	A vent that releases volcanic gases, including water vapor (steam).
Lahar	A flowing mixture of water and rock debris that forms on the slopes of a volcano, sometimes referred to as debris flow or mudflow. The term comes from Indonesia.
Lava	Molten rock that erupts from a vent or fissure; see magma.
Magma	Molten rock that contains dissolved gas and crystals, formed deep within the Earth. When magma reaches the surface, it is called lava.
Phreatic eruption	A type of volcanic explosion that occurs when water comes in contact with hot rocks or ash near a volcanic vent, causing steam explosions.
Pumice	A light-colored volcanic rock containing abundant trapped gas bubbles formed by the explosive eruption of magma. Because of its numerous gas bubbles, pumice commonly floats on water.
Pyroclastic flow	A hot, fast-moving and high-density mixture of ash, pumice, rock fragments, and gas formed during explosive eruptions.
Pyroclastic surge	Same process as pyroclastic flow but of much lower density.
Rhyolite	A volcanic rock containing more than 68% silica with a very high viscosity when in a molten state.
Shield volcano	A volcano shaped like an inverted warrior's shield with long gentle slopes produced by eruptions of low-viscosity basaltic lava.
Silica	The molecule formed of silicon and oxygen (SiO_2) that is the basic building block of volcanic rocks and the most important factor controlling the fluidity of magma. The higher a magma's silica content, the greater its viscosity or "stickiness."
Vent	The opening at the Earth's surface through which volcanic materials (magma and gas) escape.
Volcano	A vent in the surface of the Earth through which magma erupts and also the landform that is constructed by the erupted material.
Volcanic landslide	The downslope movement of soil, rock debris, and sometimes glacial ice, with or without water, from the flank of a volcano.



Scientist surveying lava dome at Redoubt Volcano. (Photograph by G. McGimsey.)

The metric units used in this publication can be converted to English units by using the approximate conversions given below:

Length

1 kilometer 0.6 of a mile
1 meter 39.37 inches
1 centimeter 0.4 inch
1 millimeter 0.04 inch

Area

1 sq. kilometer 0.4 sq. mile
1 sq. meter 1.2 sq. yards
1 sq. centimeter 0.155 sq. inch

Temperature

To convert °Celsius to °Fahrenheit, multiply °C by 1.8 and add 32.
To convert °Fahrenheit to °Celsius, subtract 32 from °F and divide the result by 1.8.

Further Reading

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