Department of the Interior/U.S. Geological Survey

Eruptions of Mount St. Helens: Past, Present, and Future

Eruptions of **Mount St. Helens:** Past, Present, and Future

by Robert I. Tilling

Cover photograph:
Steam plume rises from lava dome growing inside the large, amphitheater-like crater formed during the catastrophic eruption of May 18, 1980. Spirit Lake is in the foreground *(Photograph taken on May 18,1982, by Lyn Topinka).*

Inside front cover:
View of Mount St. Helens from north on May 17, 1980 *(Photograph by Harry Glicken).*

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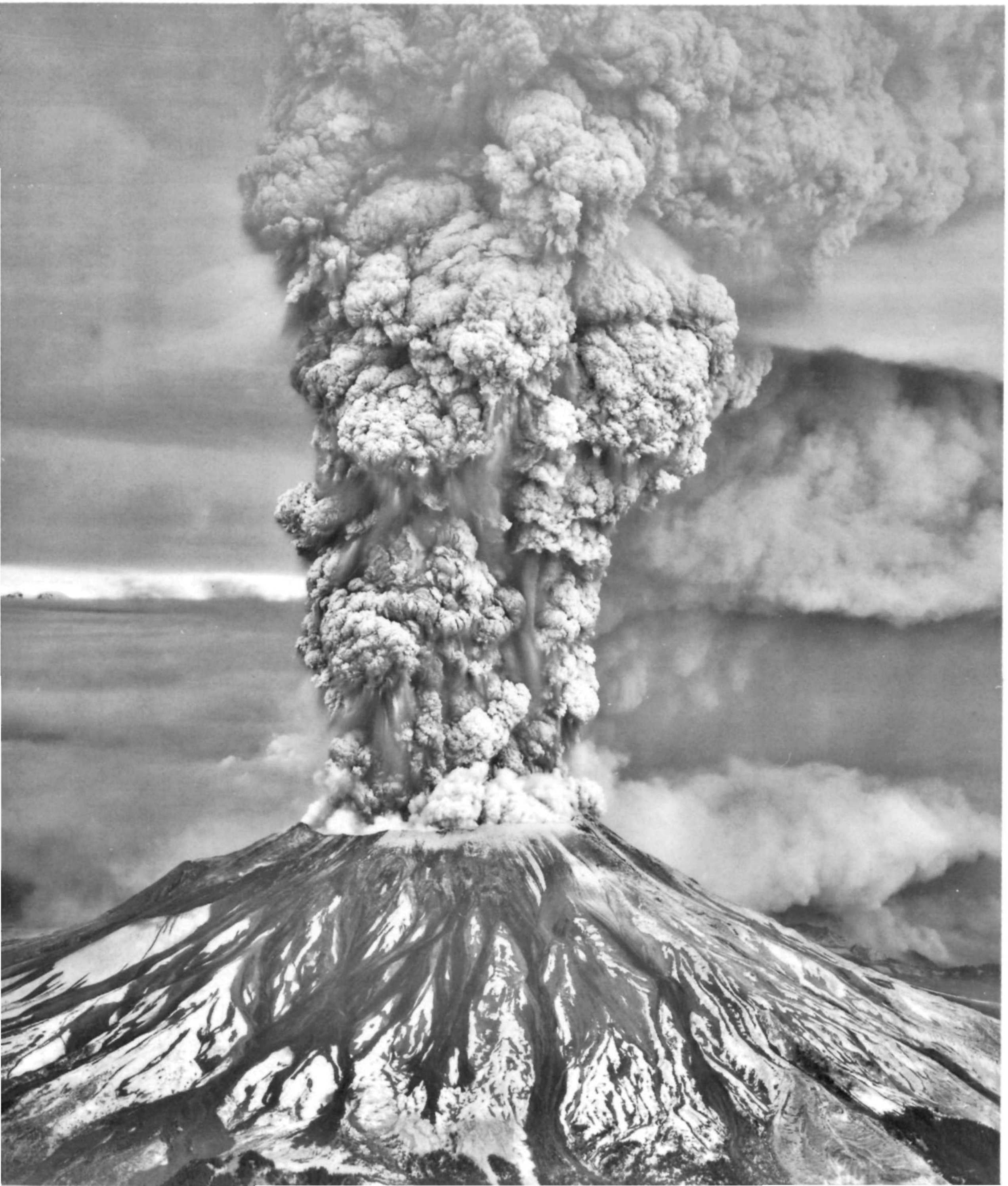


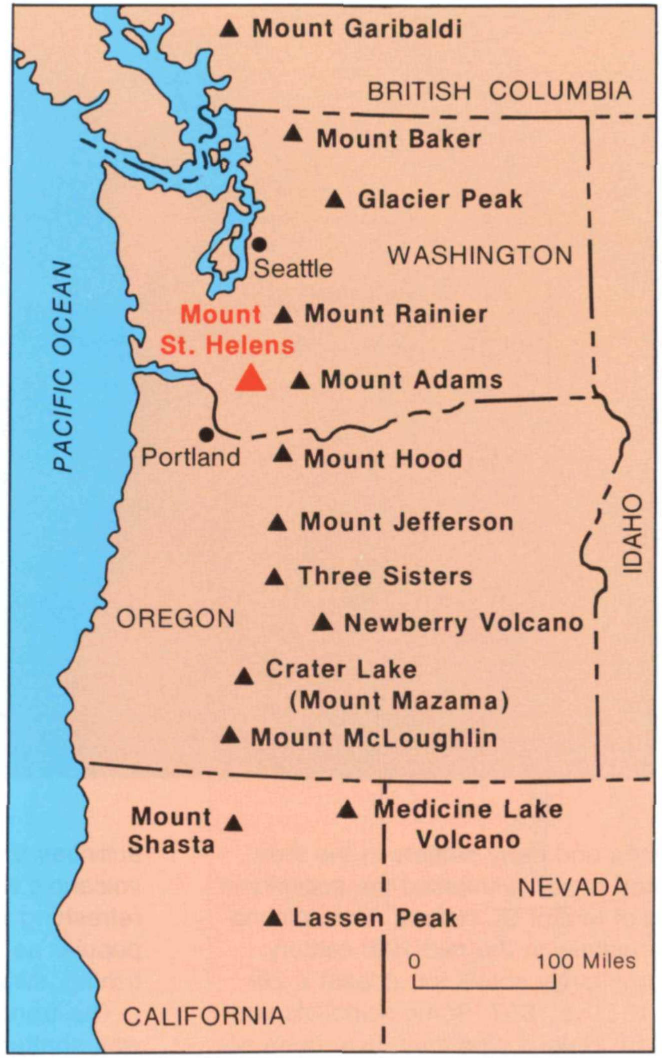
Preface

May 18, 1980. On that fateful day, Mount St. Helens Volcano in Washington exploded after 2 months of intense earthquake activity and intermittent, relatively weak eruptions. The cataclysmic eruption and events related to it caused the worst volcanic disaster in the history of the United States.

What happened on May 18 ranks among the most significant geologic events in the United States during the 20th century. The processes, effects, and products of the chain of events were the most intensively studied and photographically documented of any volcanic eruption in the world to date. The wealth of data on Mount St. Helens before, during, and after the May 18 eruption enabled geoscientists of the U.S. Geological Survey (USGS), the University of Washington, and other research institutions in the United States and abroad to put into perspective the devastating impact of suddenly unleashed volcanic energy. During 1981 and 1982, the results of many of these studies were published by the USGS in two comprehensive volumes, Professional Papers 1249 and 1250, both dedicated to the memory of David A. Johnston, a USGS volcanologist killed while making scientific observations on May 18. This booklet presents selected highlights of the volcano's past and present eruptive activity and speculates about its possible future behavior. Publications cited in the *Selected Readings* will provide more detailed discussions on topics that have been omitted or treated only briefly.

The climactic eruption of May 18, 1980, at about noon. The maximum height of the ash and gas column was about 12 miles *(Photograph by Austin Post).*

The active and potentially active volcanoes of the principal part of the Cascade Range of the Pacific Northwest. The northern end of the Cascades is Meager Mountain (British Columbia), about 55 miles north of Mount Garibaldi.



Introduction

Mount St. Helens, located in southwestern Washington about 50 miles northeast of Portland, Oregon, is one of several lofty volcanic peaks that dominate the Cascade Range of the Pacific Northwest; the range extends from Meager Mountain in British Columbia, Canada, to Lassen Peak in northern California. Geologists call Mount St. Helens a *stratovolcano* or *composite volcano,* a term for steep-sided, often symmetrical cones constructed of alternating layers of lava flows, ash, and other volcanic debris. Composite volcanoes tend to erupt explosively and pose considerable danger to nearby life and property. In contrast, the gently sloping *shield volcanoes,* such as those in Hawaii, typically erupt nonexplosively, producing fluid lavas that can flow great distances from the active vents. Although Hawaiian-type eruptions may destroy property, they rarely cause death or injury.

Before 1980, snow-capped, gracefully symmetrical Mount St. Helens was known as the "Fujiyama of America." Mount St. Helens, other active Cascade volcanoes, and those of Alaska comprise the North American segment of the circum-Pacific "Ring of Fire," a notorious zone that produces frequent, often destructive, earthquake and volcanic activity.

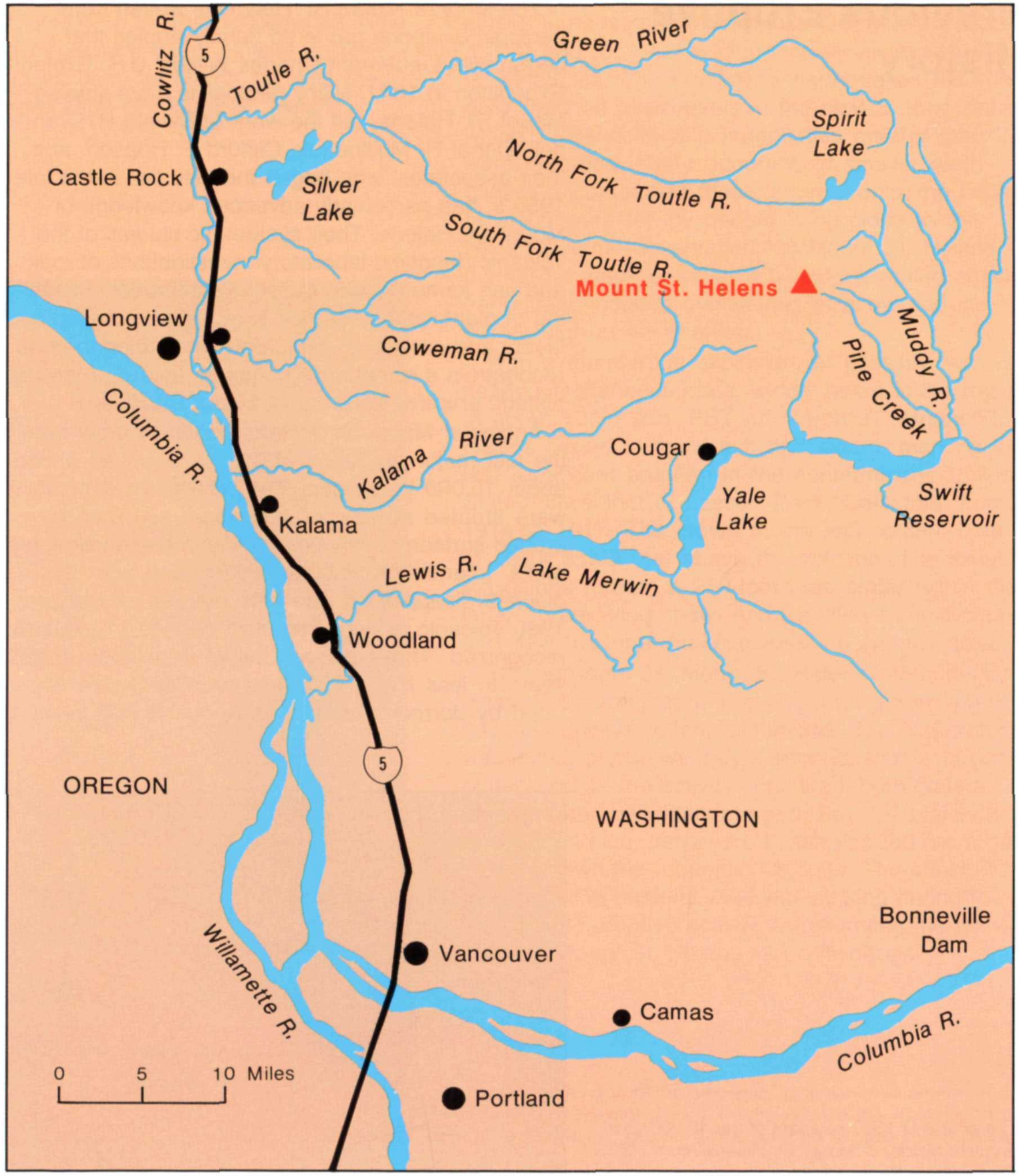
Some Indians of the Pacific Northwest called Mount St. Helens "Louwala-Clough," or "smoking mountain." The modern name, Mount St. Helens, was given to the volcanic peak in 1792 by Captain George Vancouver of the British Royal Navy, a seafarer and explorer. He named it in honor of a fellow countryman, Alleyne Fitzherbert, who held the title Baron St. Helens and who was at the time the British Ambassador to Spain. Vancouver also named three other volcanoes in the Cascades—Mounts Baker, Hood, and Rainier—for British naval officers.

Indians on the Cowlitz River watching an eruption of Mount St. Helens, as painted by Canadian artist Paul Kane following a visit to the volcano in 1847 *(Photograph courtesy of the Royal Ontario Museum).*

The local Indians and early settlers in the then sparsely populated region witnessed the occasional violent outbursts of Mount St. Helens. The volcano was particularly restless in the mid-19th century, when it was intermittently active for at least a 26-year span from 1831 to 1857. Some scientists suspect that Mount St. Helens also may have been active sporadically, but weakly, during the three decades before 1831. Although minor steam explosions may have occurred in 1898, 1903, and 1921, the mountain gave little or no evidence of being a volcanic hazard for more than a century after 1857. Consequently, the majority of 20th-century residents and visitors thought of Mount St. Helens not as a menace, but as a serene, beautiful mountain playground teeming with wildlife and available for leisure activities throughout the year. At the base of the volcano's northern flank, Spirit Lake, with its clear, refreshing water and wooded shores, was especially popular as a recreational area for hiking, camping, fishing, swimming and boating.

The tranquility of the Mount St. Helens region was shattered in the spring of 1980, however, when the volcano stirred from its long repose, shook, swelled, and exploded back to life. The local people rediscovered that they had an active volcano in their midst, and millions of people in North America were reminded that the active—and potentially dangerous—volcanoes of the United States are not restricted to Alaska and Hawaii.

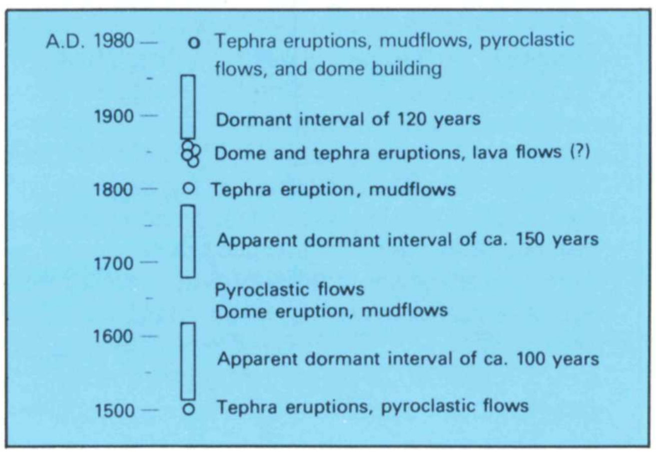
Sketch map showing the location of Mount St. Helens and the principal drainages and places mentioned in the text.



Previous Eruptive History

The story of Mount St. Helens is woven from geologic evidence gathered during studies that began with Lieutenant Charles Wilkes' U.S. Exploring Expedition in 1841. Many geologists have studied Mount St. Helens, but the work of Dwight R. Crandell, Donal R. Mullineaux, Clifford P. Hopson, and their associates, who began their studies in the late 1950's, has particularly advanced knowledge of Mount St. Helens. Their systematic studies of the volcanic deposits, laboratory investigations of rock and ash samples, and radiocarbon (carbon-14) dating of plant remains buried in or beneath the ash layers and other volcanic products enabled them to reconstruct a remarkably complete record of the prehistoric eruptive behavior of Mount St. Helens.

Ancestral Mount St. Helens began to grow before the last major glaciation of the Ice Age had ended about 10,000 years ago. The oldest ash deposits were erupted at least 40,000 years ago onto an eroded surface of still older volcanic and sedimentary rocks. Intermittent volcanism continued after the glaciers disappeared and nine main pulses of pre-1980 volcanic activity ("eruptive periods") have been recognized. These periods lasted from about 5,000 years to less than 100 years each and were separated by dormant intervals of about 15,000 years to only 200 years. A forerunner of Spirit Lake was born about 3,500 years ago, or possibly earlier, when eruption debris formed a natural dam across the valley of the North Fork of the Toutle River. The most recent of the pre-1980 eruptive periods began about A.D. 1800 with an explosive eruption, followed by several additional minor explosions and extrusions of lava, and ended with the formation of the Goat Rocks lava dome by 1857.



The post-A.D 1500 segment of the 40,000-year eruptive history of Mount St. Helens *(from USGS Professional Paper 1249).*

Mount St. Helens is the youngest of the major Cascade volcanoes, in the sense that its visible cone was entirely formed during the past 2,500 years, well after the melting of the last of the Ice Age glaciers about 10,000 years ago. Mount St. Helens' smooth, symmetrical slopes are little affected by erosion as compared with its older, more glacially scarred neighbors—Mount Rainier and Mount Adams in Washington, and Mount Hood in Oregon. As geologic studies progressed and the eruptive history of Mount St. Helens became better known, scientists became increasingly concerned about possible renewed eruptions. The late William T. Pecora, a former Director of the USGS, was quoted in a May 10, 1968, newspaper article in the *Christian Science Monitor* as being "especially worried about snow-covered Mt. St. Helens."

On the basis of its youth and its high frequency of eruptions over the past 4,500 years, Crandell, Mullineaux, and their colleague Meyer Rubin published in February 1975 that Mount St. Helens was the one volcano in the conterminous United States most likely to reawaken and to erupt "perhaps before the end of this century." This prophetic conclusion was followed in 1978 by a more detailed report, in which Crandell and Mullineaux elaborated their earlier conclusion and analyzed, with maps and scenarios, the kinds, magnitudes, and areal extents of potential volcanic hazards that might be expected from future eruptions of Mount St. Helens. Collectively, these two publications contain one of the most accurate forecasts of a violent geologic event.

Reawakening and Initial Activity

A magnitude 4.2 (Richter Scale) earthquake on March 20, 1980, at 3:47 p.m. Pacific Standard Time (PST), preceded by several much smaller earthquakes beginning as early as March 16, was the first substantial indication of Mount St. Helens' awakening from its 123-year sleep. Earthquake activity increased during the following week, gradually at first and then rather dramatically at about noon on March 25. The number of earthquakes recorded daily reached peak levels in the next 2 days, during which 174 shocks with magnitudes greater than 2.6 were recorded. Many hundreds of smaller earthquakes accompanied these larger events, the largest of which were felt by people living close to the volcano. Aerial observations of Mount St. Helens during the week of seismic buildup revealed small earthquake-induced avalanches of snow and ice, but no sign of an eruption.

With a thunderous explosion, or possibly two nearly simultaneous ones, widely heard in the region at about 12:36 p.m. PST on March 27, Mount St. Helens began to spew ash and steam, marking the first significant eruption in the conterminous United States since that of Lassen Peak, California, from 1914 to 1917. The crown of the ash column rose to about 6,000 feet above the volcano. The initial explosions formed a 250-foot-wide crater within the larger, preexisting snow- and ice-filled summit crater, and new fractures broke across the summit area.

Through April 21, Mount St. Helens intermittently ejected ash and steam in bursts lasting from a few seconds to several tens of minutes. The first crater was joined on the west by a second, slightly larger crater, and as the activity continued, both craters enlarged and ultimately merged. Several avalanches of snow and ice, darkened by ash, formed prominent streaks down the mountain's slopes. The effect of the prevailing easterly wind was striking during the March-April eruptive activity, transforming the snow-covered Mount St. Helens into a "two-tone" mountain.

A view to the north of the "two-tone" mountain—an appearance produced by prevailing easterly winds during the initial activity of Mount St. Helens. Mount Rainier is visible in background *(Photograph by Daniel Miller)*.

The ash blown out between March 27 and May 18 was derived entirely from the 350-year-old summit dome, shattered and pulverized by *phreatic* (steam-blast) processes driven by the explosively expanding, high-temperature steam and other gases. No *magma* (molten rock and contained gases) was tapped during the initial eruptions.

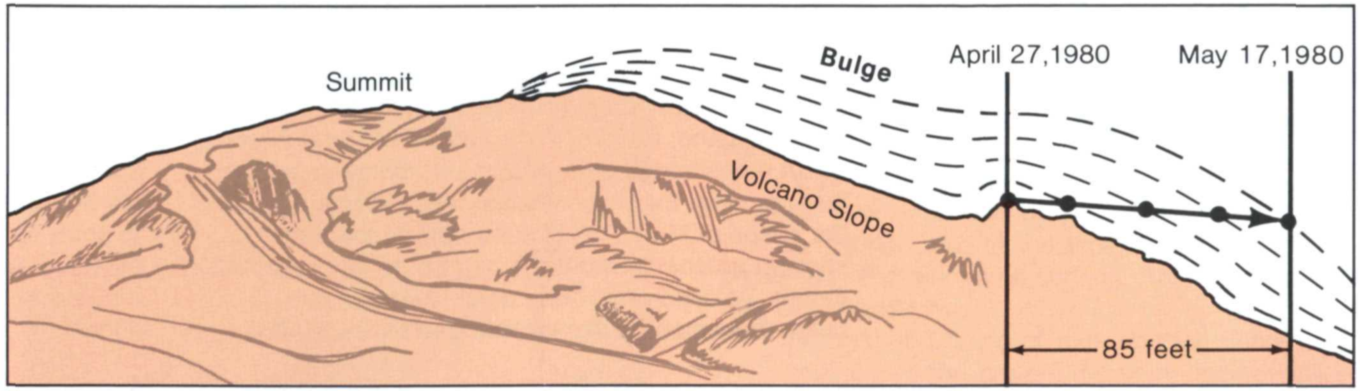
Intense earthquake activity persisted at the volcano during and between visible eruptive activity. As early as March 31, seismographs also began recording occasional spasms of *harmonic tremor,* a type of continuous, rhythmic ground shaking different from the discrete sharp jolts characteristic of earthquakes. Such continuous ground vibrations, commonly associated with eruptions at volcanoes in Hawaii, Iceland, Japan, and elsewhere, are interpreted to reflect subsurface movement of fluids, either gas or magma. The combination of sustained strong earthquake activity and harmonic tremor at Mount St. Helens suggested to scientists that magma and associated gases were on the move within the volcano, thereby increasing the probability of magma eruption.

Visible eruptive activity ceased temporarily in late April and early May. Small steam-blast eruptions resumed on May 7, continued intermittently for the next several days, and ceased again by May 16. During this interval, the forceful intrusion of magma into the volcano continued with no respite, as was shown by intense seismic activity and visible swelling and cracking of the volcano. The swelling was easily measurable and affected a large area on the north face of Mount St. Helens; this area became known as the "bulge," the initial growth of which probably began during the first eruption (March 27) or perhaps even a few days before. Through mid-May about 10,000 earthquakes were recorded. The earthquake activity was concentrated in a small zone less than 1.6 miles directly beneath the bulge on the north flank of Mount St. Helens.

A comparison of aerial photographs taken in the summer of 1979 with those taken during and after April 1980 showed that by May 12 certain parts of the bulge near the summit were more than 450 feet higher than before the magma intrusion began. Repeated measurements begun in late April with precise electronic instruments that shoot a laser beam to reflector targets placed on and around the bulge showed that it was growing northward at an astonishing rate of about 5 feet per day. The movement was predominantly horizontal—clear evidence that the bulge was not simply slipping down the volcano's steep slope. As the bulge moved northward, the summit area behind it progressively sank, forming a complex down-dropped block called a *graben*. These changes in the volcano's shape were related to the overall deformation that increased the volume of the mountain by 0.03 cubic mile by mid-May. This volume increase presumably corresponded to the volume of magma that pushed into the volcano and deformed its surface. Because the intruded magma remained below ground and was not directly visible, it was called a *cryptodome*, in contrast to a true volcanic *dome* exposed at the surface.

In summary, during late March to mid-May 1980, Mount St. Helens was shaken by hundreds of earthquakes, intermittently erupted ash and debris derived by steam blast reaming out of its preexisting summit dome, and experienced extremely large and rapid deformation caused by magma intrusion. The hot intruding magma provided the thermal energy to heat groundwater, which explosively flashed to generate and sustain the observed steam-blast eruptions. For 2 months the volcano was literally being wedged apart, creating a highly unstable and dangerous situation. The eventual collapse of the bulge on the north flank triggered the chain of catastrophic events that took place on May 18, 1980.

View of the "bulge" on the north face of Mount St. Helens, from a measurement site about 2 miles to the northeast *(Photograph by Peter Lipman).* The schematic traces the nearly horizontal movement—about 85 feet in 20 days—of one of the measured points on the "bulge."



The Climactic Eruption of May 18, 1980

May 18, a Sunday, dawned bright and clear. At 7 a.m. Pacific Daylight Time (PDT), USGS volcanologist David A. Johnston, who had Saturday-night duty at an observation post about 6 miles north of the volcano, radioed in the results of some laser-beam measurements he had made moments earlier that morning. Even considering these measurements, the status of Mount St. Helens' activity that day showed no change from the pattern of the preceding month. Volcano-monitoring data—seismic, rate of bulge movement, sulfur-dioxide gas emission, and ground temperature—revealed no unusual changes that could be taken as warning signals for the catastrophe that would strike about an hour and a half later. About 20 seconds after 8:32 a.m. PDT, apparently in response to a magnitude 5.1 earthquake about 1 mile beneath the volcano, the bulged, unstable north flank of Mount St. Helens suddenly began to collapse, triggering a rapid and tragic train of events that resulted in widespread devastation and the loss of 60 people, including volcanologist Johnston.

(Left) The climactic eruption in full fury in the late morning of May 18, 1980 *(Photograph by Joseph Rosenbaum).*

(Right) Aerial views of the volcano at the moment the summit collapse (see text) triggered the debris avalanche and associated catastrophic eruption *(Photographs selected from the copyrighted sequence taken by Keith and Dorothy Stoffel).* The tail of the plane can be seen in the upper right-hand corner of the lower picture, as the Stoffels took a final backward look while escaping.

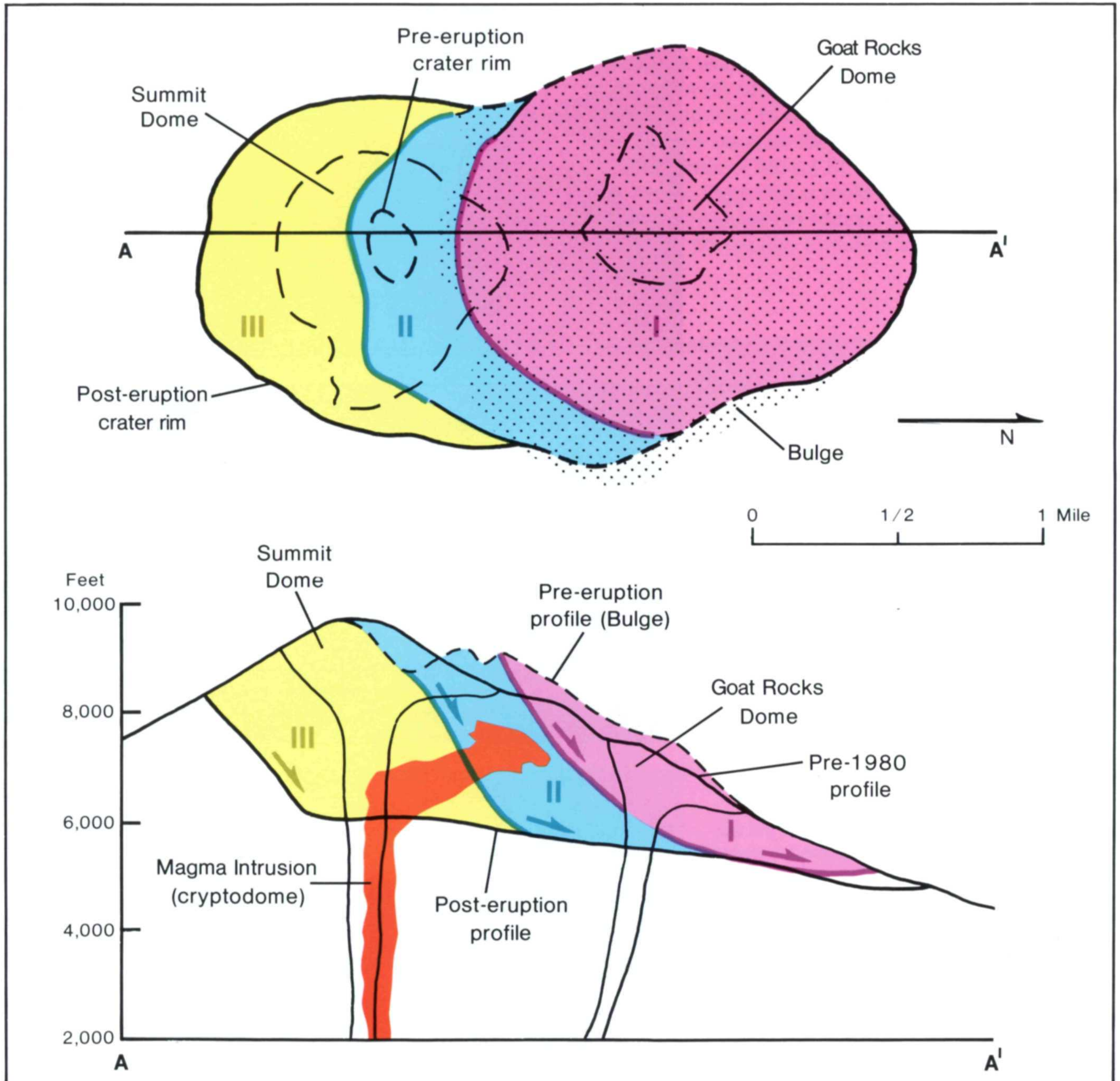
Debris avalanche

Although the triggering earthquake was of slightly greater magnitude than any of the shocks recorded earlier at the volcano, it was not unusual in any other way. What happened within the next few seconds was described by geologists Keith and Dorothy Stoffel, who at the time were in a small plane over the volcano's summit. Among the events they witnessed, they

> noticed landsliding of rock and ice debris inward into the crater...the south-facing wall of the north side of the main crater was especially active. Within a matter of seconds, perhaps 15 seconds, the whole north side of the summit crater began to move instantaneously. ...The nature of movement was eerie.... The entire mass began to ripple and churn up, without moving laterally. Then the entire north side of the summit began sliding to the north along a deep-seated slide plane. I [Keith Stoffel] was amazed and excited with the realization that we were watching this landslide of unbelievable proportions.... We took pictures of this slide sequence occurring, but before we could snap off more than a few pictures, a huge explosion blasted out of the detachment plane. We neither felt nor heard a thing, even though we were just east of the summit at this time.

Realizing their dangerous situation, the pilot put the plane into a steep dive to gain speed, and thus was able to outrun the rapidly mushrooming eruption cloud that threatened to engulf them. The Stoffels were fortunate to escape, and other scientists were fortunate to have their eyewitness account to help unscramble the sequence and timing of the quick succession of events that initiated the May 18 eruption.

Highly generalized drawing showing the cryptodome of magma that produced the bulge and the three major blocks that collapsed to form the debris avalanche. Block I was the first to slide, followed in turn by Blocks II and III.



The collapse of the north flank produced the largest landslide-debris avalanche recorded in historic time. Detailed analysis of photographs and other data shows that an estimated 7-20 seconds (about 10 seconds seems most reasonable) elapsed between the triggering earthquake and the onset of the flank collapse. During the next 15 seconds, first one large block slid away, then another large block began to move, only to be followed by still another block. The series of slide blocks merged downslope into a gigantic debris avalanche, which moved northward at speeds of 110 to 155 miles an hour. Part of the avalanche surged into and across Spirit Lake, but most of it flowed westward into the upper reaches of the North Fork of the Toutle River. At one location, about 4 miles north of the summit, the advancing front of the avalanche still had sufficient momentum to flow over a ridge more than 1,150 feet high. The resulting hummocky avalanche deposit consisted of intermixed volcanic debris, glacial ice, and, possibly, water displaced from Spirit Lake. Covering an area of about 24 square miles, the debris avalanche advanced more than 13 miles down the North Fork of the Toutle River and filled the valley to an average depth of about 150 feet; the total volume of the deposit was about 0.7 cubic mile. The dumping of avalanche debris into Spirit Lake raised its bottom by about 295 feet and its water level by about 200 feet.

View up the North Fork Toutle River toward Mount St. Helens (upper right) showing the valley choked with the hummocky deposits of the debris avalanche *(Photograph by Austin Post).*

Lateral "blast"

Within a few seconds after the onset and mobilization of the debris avalanche, the climactic eruptions of May 18 began as the sudden unloading of much of the volcano's north flank abruptly released the pent-up pressure of the volcanic system. The sudden removal of the upper part of the volcano by the landslides triggered the almost instantaneous expansion (explosion) of high temperature-high pressure steam present in cracks and voids in the volcano and of gases dissolved in the magma that caused the bulge of the cryptodome. The abrupt pressure release, or "uncorking," of the volcano by the debris avalanche can be compared in some ways to the sudden removal of the cap or a thumb from a vigorously shaken bottle of soda pop, or to punching a hole in a boiler tank under high pressure.

At Mount St. Helens, the "uncorking" unleashed a tremendous, northward-directed lateral blast of rock, ash, and hot gases that devastated an area of about 230 square miles in a fan-shaped sector north of the volcano. To the south, the devastated area was much less, extending only a small distance downslope from the summit. Along with older volcanic debris, the blast also included the first magmatic material erupted by Mount St. Helens, indicating that the landslides and the ensuing blast had exposed the cryptodome magma.

What appear to be blades of mown grass are actually large trees, some over 100 feet tall, flattened by the tremendous force of the lateral blast, even out to distances as far as 19 miles from the volcano *(Photograph by Daniel Dzurisin)*.

Although the lateral blast began some seconds later than the debris avalanche, the blast's velocity was much greater, so that it soon overtook the avalanche. Calculations have shown that the blast's initial velocity of about 220 miles an hour quickly increased to about 670 miles an hour. The average velocity did not surpass the speed of sound in the atmosphere (about 735 miles an hour). This observation is consistent with the lack of reports of loud atmospheric shocks or "sonic booms" from nearby observers such as Keith and Dorothy Stoffel in the light plane or survivors on the ground. In some areas near the blast front, however, the velocity may have approached, or even exceeded, the supersonic rate for a few moments.

The splintered and charred remains of a tree removed in the *direct blast zone*. In this picture, the direction of the blast was from right to left. Tree trunk was originally about 2 feet in diameter *(Photograph by Robert Smith)*.

The blast was widely heard hundreds of miles away in the Pacific Northwest, including parts of British Columbia, Montana, Idaho, and northern California. Yet, in many areas much closer to Mount St. Helens—for example, Portland, Oregon, only 50 miles away—the blast was not heard. Subsequent studies by the Oregon Museum of Science and Industry demonstrated a so-called "quiet zone" around Mount St. Helens, extending radially a few tens of miles, in which the eruption was not heard. The creation of the "quiet zone" and the degree to which the eruption was heard elsewhere depended on the complex response of the eruption sound waves to differences in temperature and air motion of the atmospheric layers and, to a lesser extent, local topography.

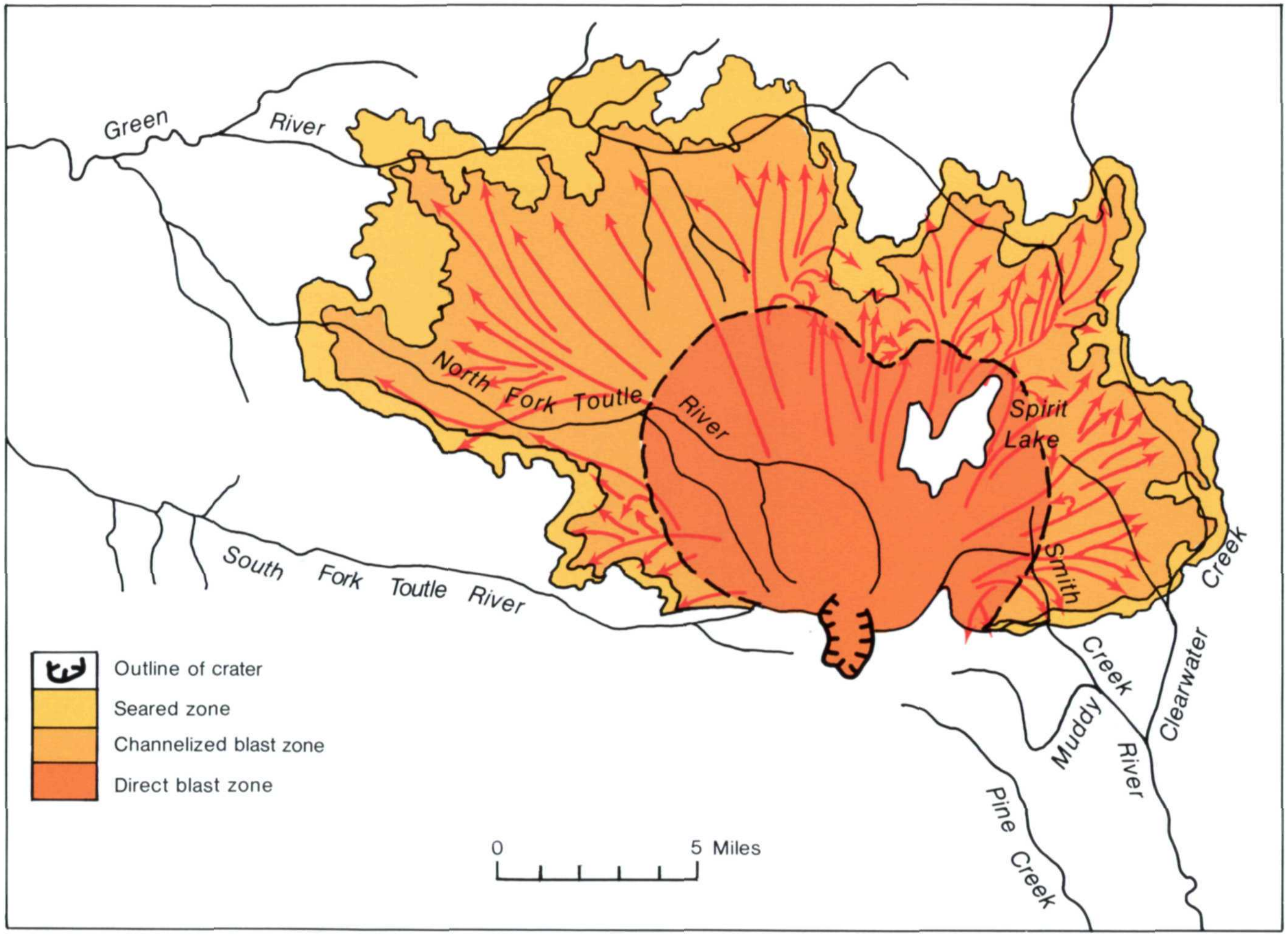
The near-supersonic lateral blast, loaded with volcanic debris, caused widespread devastation as far as 19 miles from the volcano. The area affected by the blast can be subdivided into three roughly concentric zones:

(l) *Direct blast zone,* the innermost zone, averaged about 8 miles in radius, an area in which virtually everything, natural or manmade, was obliterated or carried away. For this reason, this zone also has been called the "tree-removal zone." The flow of the material carried by the blast was not deflected by topographic features in this zone.

(2) *Channelized blast zone,* an intermediate zone, extended out to distances as far as 19 miles from the volcano, an area in which the flow flattened everything in its path and was channeled to some extent by topography. In this zone, the force and direction of the blast are strikingly demonstrated by the parallel alignment of toppled large trees, broken off at the base of the trunk as if they were blades of grass mown by a scythe. This zone was also known as the "tree-down zone."

(3) *Seared zone,* the outermost fringe of the impacted area, a zone in which trees remained standing, but singed brown by the hot gases of the blast.

A similar, but narrower and northeast-trending, strong laterally directed explosion occurred at Mount St. Helens about 1,100 years ago. The blast of May 18, 1980, however, traveled at least three times as far as the 1,100-year-old blast. Thus, the occurrence of a lateral blast such as that of May 18 was not the first in Mount St. Helens' history, but its power and resulting destruction were unprecedented. The lateral blast, debris avalanche, and associated mudflows and floods caused most of the casualties and destruction on May 18; the adverse impact of volcanic ash fallout downwind was minor by comparison.



Generalized map showing the lateral-blast zones.

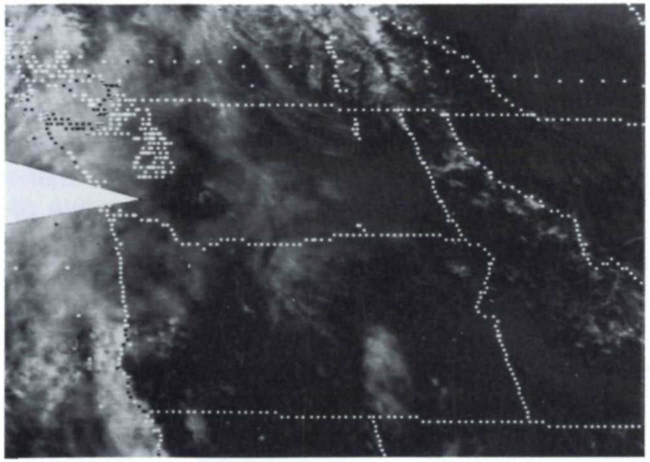
The early form of the May 18 eruption plume, which was not photographed, probably resembled the mushroom-shaped ash cloud of the July 22, 1980, eruption shown here *(Photograph by James Vallance).*

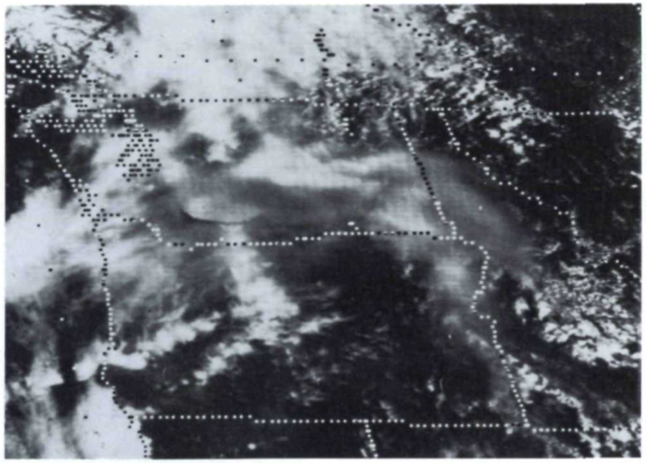
Ash eruption and fallout

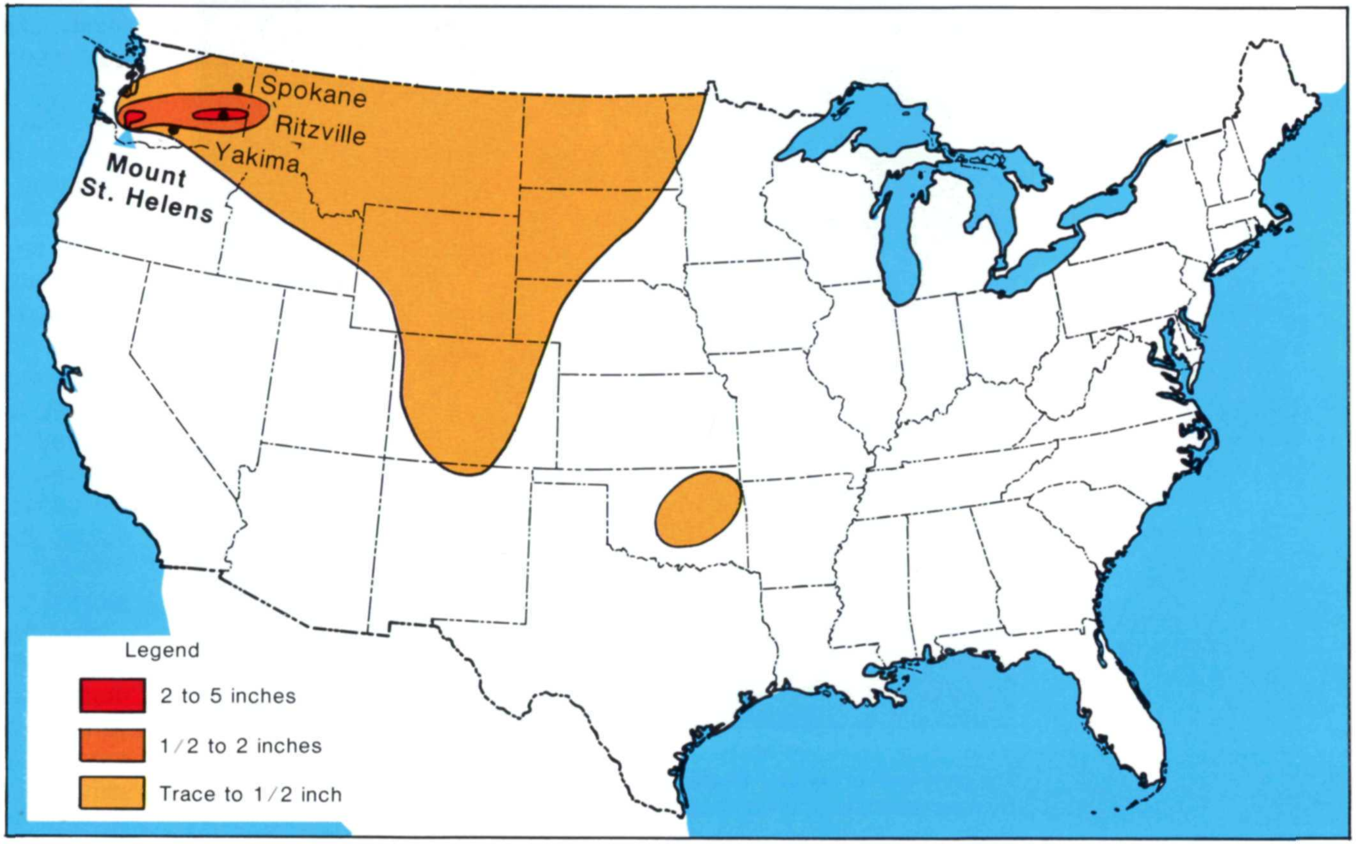
A strong, vertically directed explosion of ash and steam began very shortly after the lateral blast. The resulting eruptive column rose very quickly. In less than 10 minutes, the ash column reached an altitude of more than 12 miles and began to expand into a characteristic mushroom-shaped ash cloud. Near the volcano, the swirling ash particles in the atmosphere generated lightning, which in turn started many forest fires. As the eruption roared on, the major part of the ash cloud drifted downwind in an east-northeasterly direction, although ash that rose above the high-speed (jet-stream) winds followed other paths determined by complex wind directions.

Clear skies permitted tracking the advance of the drifting cloud by satellite imagery. Moving at an average speed of about 60 miles an hour, the cloud reached Yakima, Washington, by 9:45 a.m. PDT and Spokane, Washington, by 11:45 a.m. The ash cloud was dense enough to screen out nearly all sunlight, activating darkness-sensitive switches on street lights in Yakima and Spokane. Street lights remained on for the rest of the darkened day, as the eruption continued vigorously for more than 9 hours, pumping ash into the atmosphere and feeding the drifting ash cloud.

The eruptive column fluctuated in height through the day, but the eruption subsided by late afternoon on May 18. By early May 19, the eruption had stopped. By that time, the ash cloud had spread to the central United States. Two days later, even though the ash cloud had become more diffuse, fine ash was detected by systems used to monitor air pollution in several cities of the northeastern United States. Some of the ash drifted around the globe within about 2 weeks. After circling many more times, most of the ash settled to the Earth's surface, but some of the smallest fragments and aerosols are likely to remain suspended in the upper atmosphere for years.







Weather-satellite imagery *(courtesy of NOAA)* tracked the movement of the eruption plume: left (8:45 PDT)—the expanding plume shortly after the beginning of the May 18 eruption; right (12:15 PDT)—the plume had reached Idaho, and a new pulse of ash can be seen at the volcano.

The generalized map shows the distribution of ash fallout from the May 18 eruption.

(Top) The advancing ash cloud from Mount St. Helens, as seen from the ground in eastern Washington.
(Bottom) Eastern Washington resident sweeping the ash from the roof of his house *(Photograph by Kurt Smith)*.

Prevailing winds distributed the fallout from the ash cloud over a wide region. Light ash falls were reported in most of the Rocky Mountain States, including northern New Mexico, and fine ash dusted a few scattered areas farther east and northeast of the main path. The heaviest ash deposition occurred in a 60-mile-long swath immediately downwind of the volcano. Another area of thick ash deposition, however, occurred near Ritzville in eastern Washington, about 195 miles from Mount St. Helens, where nearly 2 inches of ash blanketed the ground, more than twice as much as at Yakima, which is only about half as far from the volcano. Scientists believe that this unexpected variation in ash thickness may reflect differences in wind velocity and direction with altitude, fluctuations in the height of the ash column during the 9 hours of activity, and the effect of localized clumping of fine ash particles leading to preferential fallout of the large particle clumps.

During the 9 hours of vigorous eruptive activity, about 540 million tons of ash fell over an area of more than 22,000 square miles. The total volume of the ash before its compaction by rainfall was about 0.3 cubic mile, equivalent to an area the size of a football field piled about 150 miles high with fluffy ash. The volume of the uncompacted ash is equivalent to about 0.05 cubic mile of solid rock, or only about 7 percent of the amount of material that slid off in the debris avalanche. The eruption of ash also further enlarged the depression formed initally by the debris avalanche and lateral blast, and helped to create a great amphitheater-shaped crater open to the north. This new crater was about 1 mile by 2 miles wide and about 2,100 feet deep from its rim to its lowest point. The area of this crater roughly encompassed that of the former bulge on the north flank of the volcano and the former summit dome. After the eruption, the highest point on the volcano was about 8,364 feet, or 1,313 feet lower than the former summit elevation.

Pyroclastic flows

The term "pyroclastic"—derived from the Greek words *pyro* (fire) and *klastos* (broken)—describes materials formed by the fragmentation of magma and rock by explosive volcanic activity. Most volcanic *ash* is basically fine-grained pyroclastic material composed of tiny particles of explosively disintegrated old volcanic rock or new magma. Larger sized pyroclastic fragments are called *lapilli, blocks,* or *bombs.* Pyroclastic flows—sometimes called *nuées ardentes* (French for "glowing clouds")—are hot, often incandescent mixtures of volcanic fragments and gases that sweep along close to the ground. Depending on the volume of material, proportion of solids to gas, temperature, and slope gradient, the flows can travel at velocities as great as 450 miles an hour. Pyroclastic flows can be extremely destructive and deadly because of their high temperature and mobility. During the 1902 eruption of Mont Pelée (Martinique, West Indies), for example, a nuée ardente demolished the coastal city of St. Pierre, killing nearly 30,000 inhabitants.

Pyroclastic flows commonly are produced either by the fallback and downslope movement of fragments from an eruption column or by the direct frothing over at the vent of magma undergoing rapid gas loss. Volcanic froth so formed is called *pumice.* Pyroclastic flows originated in both ways at Mount St. Helens on May 18, but flows of mappable volume were of the latter type. The flows were entirely restricted to a small fan-shaped zone that flares northward from the summit crater.

Pyroclastic flows and pits were formed by "secondary" eruptions when the hot volcanic debris came into contact with water or moist ground. This picture also shows an eruption in progress (lower center) *(Photograph by Daniel Dzurisin).*

Pyroclastic flows were first directly observed at 12:17 p.m. PDT, although they probably began to form shortly after the lateral blast. They continued to occur intermittently during the next 5 hours of strong eruptive activity. Eyewitness accounts indicated that the more voluminous pyroclastic flows originated by the upwelling of volcanic ejecta to heights below the rim of the crater, followed by lateral flow northward through the breach of the crater. One scientist likened this process to a "pot of oatmeal boiling over." Most of the rock in these flows was pumice. A few smaller pyroclastic flows were observed to form by gravitational collapse of parts of the high eruption column. The successive outpourings of pyroclastic material consisted mainly of new magmatic debris rather than fragments of preexisting volcanic rocks. The resulting deposits formed a fan-like pattern of overlapping sheets, tongues, and lobes. At least 17 separate pyroclastic flows occurred during the May 18 eruption, and their aggregate volume was about 0.05 cubic mile.

When temperature measurements could safely be made in the pyroclastic flows 2 weeks after they were erupted, the deposits ranged in temperature from about 570° to 785°F. As might be expected, when the hot material of the debris avalanche and the even hotter pyroclastic flows encountered bodies of water or moist ground, the water flashed explosively to steam; the resulting *phreatic* (steam-blast) explosions sent plumes of ash and steam as high as 1.2 miles above the ground. These "secondary" or "rootless" steam-blast eruptions formed many explosion pits on the northern margin of the pyroclastic flow deposits, at the south shore of Spirit Lake, and along the upper part of the North Fork of the Toutle River. These steam-blast explosions continued sporadically for weeks or months after the emplacement of pyroclastic flows, and at least one occurred about a year later, on May 16, 1981.

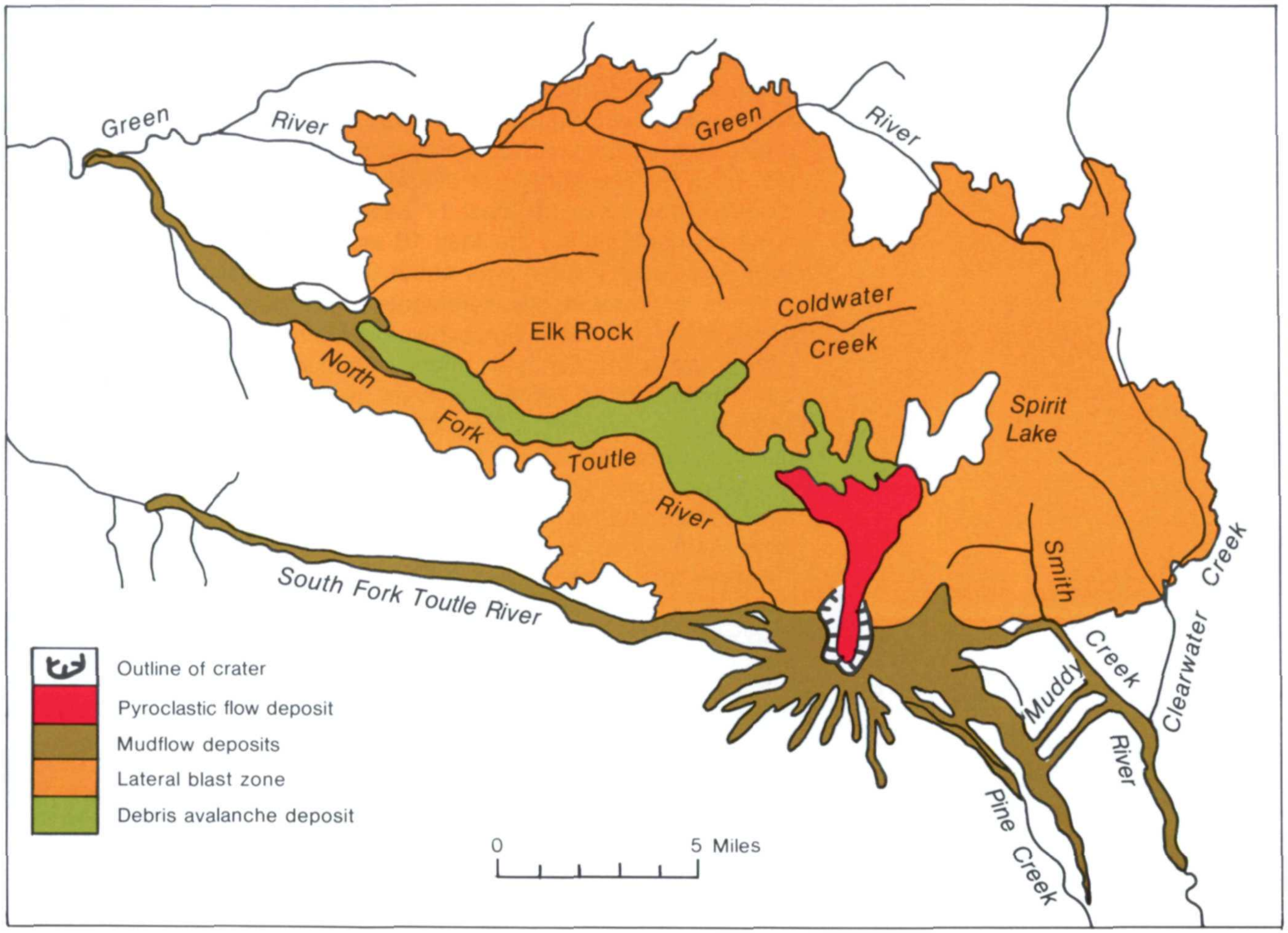
Mudflows and floods

Mudflows—mobile mixtures of volcanic debris and water—often accompany pyroclastic eruptions, if water is available to erode and transport the loose pyroclastic deposits on the steep slopes of stratovolcanoes. Destructive mudflows and debris flows began within minutes of the onset of the May 18 eruption, as the hot pyroclastic materials in the debris avalanche, lateral blast, and ash falls melted snow and glacial ice on the upper slopes of Mount St. Helens. Such flows are also called *lahars,* a term borrowed from Indonesia, where volcanic eruptions have produced many such deposits.

Mudflows were observed as early as 8:50 a.m. PDT in the upper reaches of the South Fork of the Toutle River. The largest and most destructive mudflows, however, were those that developed several hours later in the North Fork of the Toutle River, when the water-saturated parts of the massive debris avalanche deposits began to slump and flow. The mudflows in the Toutle River drainage area ultimately dumped more than 65 million cubic yards of sediment along the lower Cowlitz and Columbia Rivers. The water-carrying capacity of the Cowlitz River was reduced by 85 percent, and the depth of the Columbia River navigational channel was decreased from 39 feet to less than 13 feet, disrupting river traffic and choking off ocean shipping. Mudflows also swept down the southeast flank of the volcano—along the Swift Creek, Pine Creek, and Muddy River drainages—and emptied nearly 18 million cubic yards of water, mud, and debris into the Swift Reservoir. The water level of the reservoir had been purposely kept low as a precaution to minimize the possibility that the reservoir could be overtopped by the additional water-mud-debris load to cause flooding of the valley downstream.

Fortunately, the volume of the additional load was insufficient to cause overtopping even if the reservoir had been full.

On the upper steep slopes of the volcano, the mudflows traveled as fast as 90 miles an hour; the velocity then progressively slowed to about 3 miles an hour as the flows encountered the flatter and wider parts of the Toutle River drainage. Even after traveling many tens of miles from the volcano and mixing with cold waters, the mudflows maintained temperatures in the range of about 84° to 91°F.; they undoubtedly had higher temperatures closer to the eruption source. Shortly before 3 p.m., the mud- and debris-choked Toutle River crested about 21 feet above normal at a point just south of the confluence of the North and South Forks. Another stream



Generalized geologic map showing the impact and deposits of the climactic eruption in the vicinity of the volcano.

gage at Castle Rock, about 3 miles downstream from where the Toutle joins the Cowlitz, indicated a high-water (and mud) mark also about 20 feet above normal at midnight of May 18. Locally the mudflows surged up the valley walls as much as 360 feet and over hills as high as 250 feet. From the evidence left by the "bathtub-ring" mudlines, the larger mudflows at their peak averaged from 33 to 66 feet deep. The actual deposits left behind after the passage of the mudflow crests, however, were considerably thinner, commonly less than 10 percent of their depth during peak flow. For example, the mudflow deposits along much of the Toutle River averaged less than 3 feet thick.

Mudflow-damaged house along the Toutle River. The height of the mudflow is shown by the "bathtub-ring" mudlines seen on the tree trunks and the house itself *(Photograph by Dwight Crandell)*.

The catastrophic first minute

During the initial hours of the May 18 activity, people were obviously confused about the nature and sequence of the phenomena taking place. Did the eruption trigger the 5.1 magnitude earthquake or did the earthquake trigger the eruption? Or were both associated with some other, but unknown, cause or causes? At first, these questions and others could not be answered because of the rapidity of developments and the initial lack of firsthand observations by people who were close to the mountain and who survived the catastrophe. It was not until many hours, indeed days, later that scientists were able to reconstruct clearly the sequence of events. The reconstruction was aided by eyewitness accounts. Geologists Keith and Dorothy Stoffel, flying over the volcano in a small plane when the earthquake struck, observed "minor landsliding of rock and ice debris" into the crater. Within the next 15 seconds, the north flank of the volcano "began to ripple and churn up, without moving laterally." At the same time the Stoffels were witnessing from the air the developing debris avalanche, a remarkable series of ground-based photographs was being taken by Keith Ronnholm and Gary Rosenquist from Bear Meadows, a camping area located about 11 miles northeast of Mount St. Helens. Seconds after the earthquake, William Dilly, a member of the Rosenquist party, noticed through binoculars that the north flank was becoming "fuzzy, like there was dust being thrown down the side" and shouted that the "mountain was going." Within seconds Rosenquist began taking photographs in rapid succession.

Frame-by-frame analysis of the Rosenquist photographs, taken within a span of about 40 seconds, together with seismic and other evidence, established the following sequence of events during the first minute of the climactic eruption. The times indicated are in hours, minutes, and seconds (Pacific Daylight Time).

08:27 (approximate) Pre-earthquake view of the bulge on the volcano's north flank produced by the growing cryptodome of magma intruded since March 20. About 5 minutes later (08:32:11.4 PDT), a 5.1 magnitude earthquake struck beneath the mountain at shallow depth.

08:32:47.0 Estimate of the time of the first photograph in Rosenquist's sequence that shows movement of the mountain. By this time, the first slide block had already dropped about 2,300 feet and a second block behind it had slid 330 feet. The beginning of the north flank's collapse and downward movement to initiate the debris avalanche was estimated to be 26 seconds earlier (08:32:21.0 PDT).

08:32:49.2 A little more than 2 seconds later, as the slide blocks continued to move, the initial explosions of the vertical eruption column as well as the lateral blast, although obscure, had already begun.

08:32:53.3 The first slide block now had dropped sufficiently to expose more of the cryptodome magma, accelerating the explosive expansion of gases in the magma and the eruption of the first magmatic material of the 1980 eruptions.

08:33:03.7 The continuing movement of the slide blocks and explosions had now thoroughly "uncorked" the magmatic system of the cryptodome, and old and new (magmatic) debris were blasted outward by increasingly more powerful explosions. The high-velocity lateral blast cloud, with its clearly visible trajectory trails of large blocks, was overtaking the slower moving debris avalanche.

08:33:18.8 Less than a minute after the start of the debris avalanche, the eruption of Mount St. Helens was in full fury, further enlarging the crater as smaller slide blocks fell into the vent and were blasted away. The leading front of the lateral blast now had completely overtaken the debris avalanche.

These photographs were selected from the sequence taken by Gary Rosenquist *(Copyrighted by Earth Images, Bainbridge Island, Washington).*

The lateral blast at the vent probably lasted no more than about 30 seconds, but the northward radiating and expanding blast cloud continued for about another minute, extending to areas more than 16 miles from the volcano. Shortly after the blast shot out laterally, the vertically directed ash column rose to an altitude of about 16 miles in less than 15 minutes and the vigorous emission of ash continued for the next 9 hours. The eruption column began to decline at about 5:30 p.m. and diminished to a very low level by early morning of May 19.

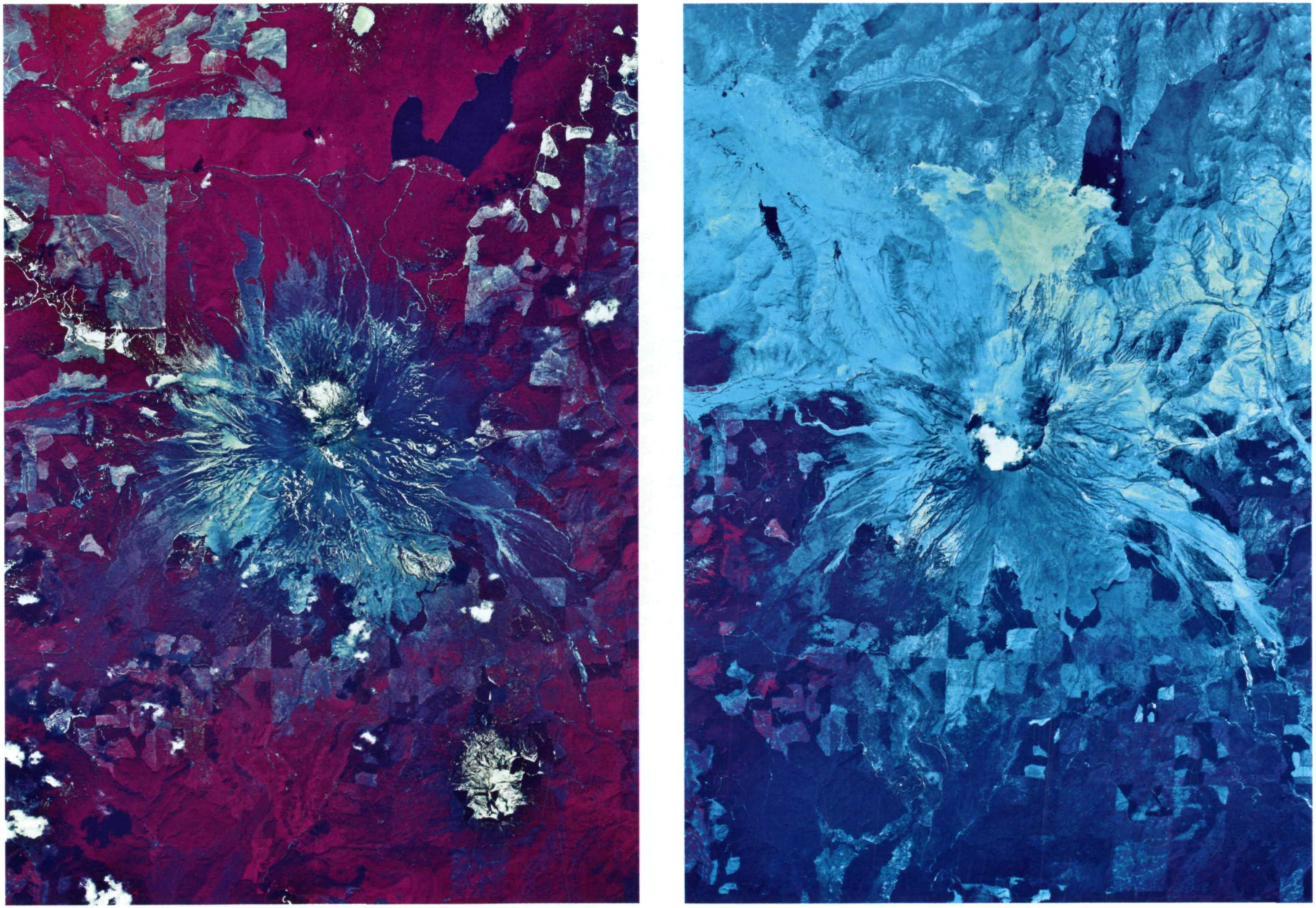
The extraordinary photographic documentation of the first minute enabled scientists to reconstruct accurately what had happened. The 5.1 magnitude earthquake caused the gravitational collapse of Mount St. Helens' north flank, which produced the debris avalanche and triggered the ensuing violent lateral and vertical eruptions. From a scientific perspective, it was fortunate that the initial May 18 events occurred during daylight hours under cloudless conditions; otherwise, the sequence of events during that crucial first minute following the earthquake would have been difficult to reconstruct precisely.

Impact and aftermath

The May 18, 1980, eruption was the most destructive in the history of the United States. Novarupta (Katmai) Volcano, Alaska, erupted considerably more material in 1912, but owing to the isolation and sparse population of the region affected, there were no human deaths and little property damage. In contrast, Mount St. Helens' eruption in a matter of hours caused loss of lives and widespread destruction of valuable property, primarily by the debris avalanche, the lateral blast, and the mudflows.

Landscape changes caused by the May 18 eruption were readily seen on high-altitude photographs. Such images, however, cannot reveal the impacts of the devastation on people and their works. The May 18 eruption resulted in scores of injuries and the loss of about 60 lives (35 known deaths and 25 missing persons). Within the United States before May 18, 1980, only two known casualties had been attributed to volcanic activity—a photographer was struck by falling rocks during the explosive eruption of Kilauea Volcano, Hawaii, in 1924; and an Army sergeant who disappeared during the 1944 eruption of Cleveland Volcano, Chuginadak Island, Aleutians. Autopsies indicated that most of Mount St. Helens' vicitims died by asphyxiation from inhaling hot volcanic ash, and some by thermal and other injuries.

The lateral blast, debris avalanche, mudflows, and flooding caused extensive damage to land and civil works. All buildings and related manmade structures in the vicinity of Spirit Lake were buried. More than 200 houses and cabins were destroyed and many more were damaged in Skamania and Cowlitz Counties, leaving many people homeless. Many tens of thousands of acres of prime forest, as well as recreational sites, bridges, roads, and trails, were destroyed or heavily damaged. More than 185 miles of highways and roads and 15 miles of railways were destroyed or extensively damaged.



High-altitude color-infrared photographs of the Mount St. Helens region "before" and "after" the eruption of May 18, 1980. Green vegetation unaffected by the eruption appears as red *(Photographs courtesy of NASA)*.

Stand of timber north of Mount St. Helens devastated by the lateral blast. The downed trees were salvaged as quickly as possible before the wood began to rot. Note the two people (circled) in lower right *(Photograph by Lyn Topinka).*

Trees amounting to more than 4 billion board feet of salable timber were damaged or destroyed, primarily by the lateral blast. At least 25 percent of the destroyed timber has been salvaged since September 1980. Hundreds of loggers have been involved in the timber-salvage operations, and, during peak summer months, more than 600 truckloads of salvaged timber were retrieved each day.

Wildlife in the Mount St. Helens area also suffered heavily. The Washington State Department of Game estimated that nearly 7,000 big game animals (deer, elk, and bear) perished in the area most affected by the eruption, as well as all birds and most small mammals. A few small animals, chiefly burrowing rodents, frogs, salamanders, and crawfish, managed to survive because they were below ground level

or water surface when the disaster struck. The Washington Department of Fisheries estimated that 12 million Chinook and Coho salmon fingerlings were killed when hatcheries were destroyed; these might have developed into about 360,000 adult salmon. Another estimated 40,000 young salmon were lost when they were forced to swim through the turbine blades of hydroelectric generators because the levels of the reservoirs along the Lewis River south of Mount St. Helens were kept low to accommodate possible mudflows and flooding.

Downwind of the volcano, in areas of thick ash accumulation, many agricultural crops, such as wheat, apples, potatoes, and alfalfa, were destroyed. Many crops survived, however, in areas blanketed by only a thin covering of ash. In fact, the apple and wheat production in 1980 was higher than normal due to greater-than-average summer precipitation. The crusting of ash also helped to retain soil moisture through the summer. Moreover, in the long term, the ash may provide beneficial chemical nutrients to the soils of eastern Washington, which themselves were formed of older glacial deposits that contain a significant ash component. Effects of the ash fall on the water quality of streams, lakes, and rivers were short-lived and minor.

The ash fall, however, did pose some temporary major problems for transportation operations and for sewage-disposal and water-treatment systems. Because visibility was greatly decreased during the ash fall, many highways and roads were closed to traffic, some only for a few hours, but others for weeks. Interstate 90 from Seattle to Spokane, Washington, was closed for a week. Air transportation was disrupted for a few days to 2 weeks as several airports in eastern Washington shut down due to ash accumulation and attendant poor visibility. Over a thousand commercial flights were canceled following airport closures.

The fine-grained, gritty ash caused substantial problems for internal-combustion engines and other mechanical and electrical equipment. The ash contaminated oil systems, clogged air filters, and scratched moving surfaces. Fine ash caused short circuits in electrical transformers, which in turn caused power blackouts. The sewage-disposal systems of several municipalities that received about half an inch or more of ash, such as Moses Lake and Yakima, Washington, were plagued by ash clogging and damage to pumps, filters, and other equipment. Fortunately, as these same cities used deep wells and closed storage, their water-supply systems were only minimally affected.

The removal and disposal of ash from highways, roads, buildings, and airport runways were monumental tasks for some eastern Washington communities. State and Federal agencies estimated that over 2.4 million cubic yards of ash—equivalent to about 900,000 tons in weight—were removed from highways and airports in Washington State. Ash removal cost $2.2 million and took 10 weeks in Yakima. The need to remove ash quickly from transportation routes and civil works dictated the selection of some disposal sites. Some cities used old quarries and existing sanitary landfills; others created dumpsites wherever expedient. To minimize wind reworking of ash dumps, the surfaces of some disposal sites have been covered with topsoil and seeded with grass. About 250,000 cubic yards of ash have been stockpiled at five sites and can be retrieved easily for constructional or industrial use at some future date if economic factors are favorable.

Front-end loader removing ash from Mount St. Helens as part of the massive cleanup effort in eastern Washington *(Copyrighted photograph by Daryl Gusey).*

What was the cost of the destruction and damage caused by the May 18 eruption? Accurate cost figures remain difficult to determine. Early estimates were too high and ranged from $2 to $3 billion, primarily reflecting the timber, civil works, and agricultural losses. A refined estimate of $1.1 billion was determined in a study by the International Trade Commission at the request of Congress. A supplemental appropriation of $951 million for disaster relief was voted by Congress, of which the largest share went to the Small Business Administration, U.S. Army Corps of Engineers, and the Federal Emergency Management Agency.

There were indirect and intangible costs of the eruption as well. Unemployment in the immediate region of Mount St. Helens rose tenfold in the weeks immediately following the eruption and then nearly returned to normal once timber salvaging and ash-cleanup operations were underway. Only a small percentage of residents left the region because of lost jobs owing to the eruption. Several months after May 18, a few residents reported suffering stress and emotional problems, even though they had coped successfully during the crisis. The counties in the region requested funding for mental health programs to assist such people.

Initial public reaction to the May 18 eruption nearly dealt a crippling blow to tourism, an important industry in Washington. Not only was tourism down in the Mount St. Helens-Gifford Pinchot National Forest area, but conventions, meetings, and social gatherings also were canceled or postponed at cities and resorts elsewhere in Washington and neighboring Oregon not affected by the eruption. The negative impact on tourism and conventioneering, however, proved only temporary. Mount St. Helens, perhaps *because* of its eruptive activity, has regained its appeal for tourists. The U.S. Forest Service (USFS) and State of Washington opened visitor centers and provided access for people to view firsthand the volcano's awesome devastation.

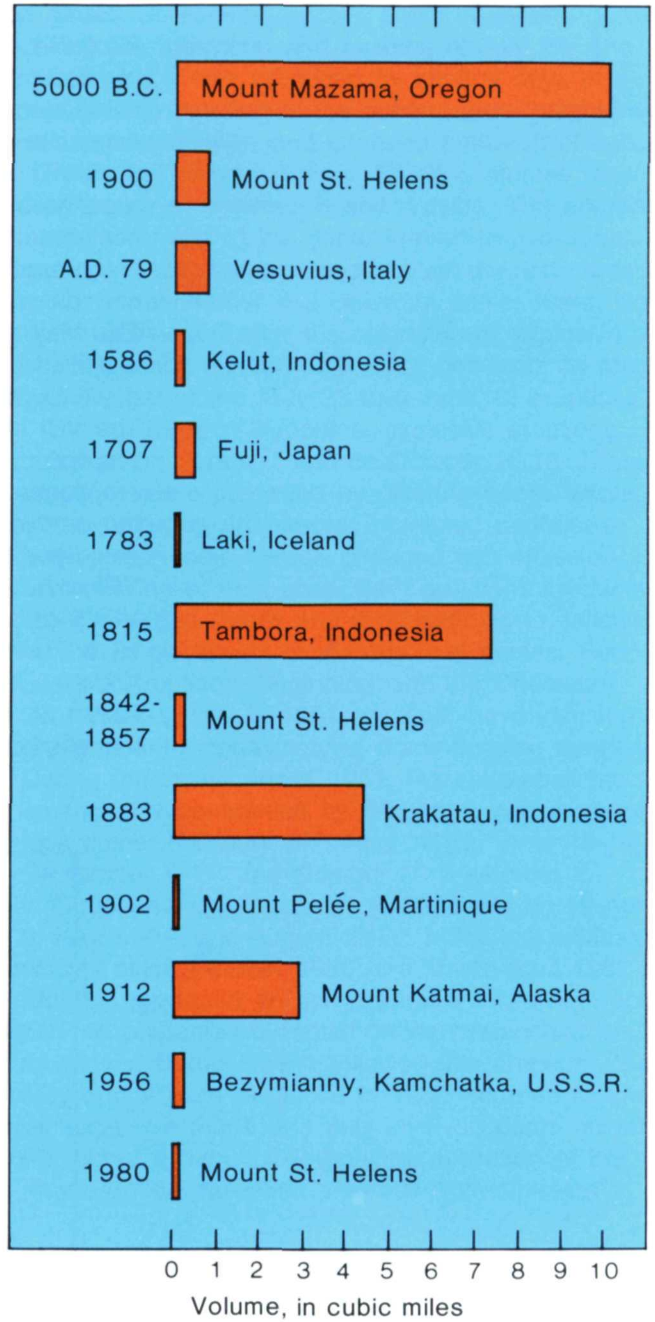
The spectacular eruption impressed upon the people in the Pacific Northwest that they share their lands with both active and potentially active volcanoes. With the passage of time, the damaged forests, streams, and fields will heal, and the memory of the 1980 eruption and its impacts will fade in future generations. The Mount St. Helens experience has been so thoroughly documented, however, that it likely will be a reminder for decades in the future of the possibility of renewed volcanic activity and destruction.

Comparisons With Other Eruptions

The May 18, 1980, eruption of Mount St. Helens was exceeded in "size" by many other eruptions, both in historic times and in the recent geologic past.

For the study of earthquakes, two standard measures of the "size" of the seismic event are commonly used: the *Richter Magnitude Scale* (based on energy released as measured by seismometers) and the *Modified Mercalli Intensity Scale* (based on damage caused as assessed by people). Although some attempts have been made to develop a scale to compare the relative sizes of volcanic eruptions, none has yet been adopted for general use. Volcanologists have proposed and used various schemes to rank eruptions, and these generally included one or more of the following factors—height of eruption column, volume of material erupted, distance and height of hurled blocks and fragments, amount of aerosols injected into the upper atmosphere, and duration of eruption. All these factors relate directly or indirectly to the total amount of energy released during the eruption. Perhaps the two most commonly used and directly measurable factors are eruption volume and height of the eruption column.

The volcano ejected about 0.3 cubic mile of uncompacted ash, not counting an unknown but probably much smaller amount that was deposited in the atmosphere or too diffuse to form measurable deposits. This volume of ash is less than those of several earlier eruptions of Mount St. Helens and considerably less than the ejecta volumes of some historic eruptions elsewhere. The 1815 eruption of Tambora (Sumbawa, Indonesia) ejected about 30 to 80 times more ash than did Mount St. Helens in 1980. The 1815 Tambora eruption ranks as the largest known explosive eruption in historic times. But even the Tambora eruption pales by comparison with the gigantic pyroclastic eruptions from volcanic systems—such as Long Valley Caldera (California), Valles Caldera (New Mexico), and Yellowstone Caldera (Wyoming)—which, within about the last million years, produced ejecta volumes as much as 100 times greater.



Some scientists recently proposed the *Volcanic Explosivity Index (VEI)* to attempt to standardize the assignment of the size of an explosive eruption, using ejecta volume as well as the other criteria mentioned earlier. The VEI scale ranges from 0 to 8. A VEI of 0 denotes a nonexplosive eruption, regardless of volume of erupted products. Eruptions designated a VEI of 5 or higher are considered "very large" explosive events, which occur worldwide only on an average of about once every 2 decades. The May 1980 eruption of Mount St. Helens rated a VEI of 5, but just barely; its lateral blast was powerful, but its output of magma was rather small. The VEI has been determined for more than 5,000 eruptions in the last 10,000 years. None of these eruptions rates the maximum VEI of 8. For example, the eruption of Vesuvius Volcano in A.D. 79, which destroyed Pompeii and Herculaneum, only rates a VEI of 5. Since A.D. 1500, only 21 eruptions with VEI 5 or greater have occurred: one VEI 7 (the 1815 Tambora eruption), four of VEI 6 (including Krakatau in 1883), and sixteen of VEI 5 (counting Mount St. Helens). Considered barely "very large," the eruption of Mount St. Helens in May 1980 was smaller than most other "very large" eruptions within the past 10,000 years and much smaller than the enormous caldera-forming eruptions—which would rate VEI's of 8—that took place earlier than 10,000 years ago.

The number of casualties and extent of destruction also have been used to compare the "bigness" of volcanic eruptions. For obvious reasons, such comparisons are limited at best and misleading at worst. Some of the most destructive eruptions have not been in other terms "very large." As the table below clearly shows, of the six greatest volcanic disasters in terms of casualties since A.D. 1500, only two of them (Tambora and Krakatau) qualify as "very large" eruptions (VEI's greater than 5) in terms of their explosive force.

The May 1980 eruption of Mount St. Helens has a higher VEI (5) than four of the deadliest eruptions in the history of mankind, but it resulted in the loss of far fewer lives (60). Loss of life would have been much greater if a hazard warning had not been issued and a zone of restricted access had not been established.

Volcanic Explosivity Index

Eruption	*Year*	*VEI*	*Casualties*
Kelut, Indonesia	1586	4	10,000
Laki, Iceland	1783	4	10,000
Unzen, Japan	1792	3	10,000
Tambora, Indonesia	1815	7	*50,000
Krakatau, Indonesia	1883	6	36,000
Mont Pelée, Martinique	1902	4	30,000

*Also estimated as high as 92,000

Subsequent Eruptions

Since May 18, 1980, Mount St. Helens has remained intermittently active, and at least 15 eruptions have occurred following the catastrophic activity. The first of these smaller but significant eruptions began early Sunday morning, May 25, 1980, when Mount St. Helens explosively erupted ash and formed an eruption column that rose to a maximum altitude of 9 miles. At least one pyroclastic flow accompanied the vertical ash emission. Although this eruption was considerably less energetic and voluminous than that of May 18, it nonetheless caused much concern because of memories of the events of the previous Sunday. Variable winds dispersed ash over southwestern Washington and neighboring Oregon, producing small to moderate ash falls in communities that had been spared the ash fall of May 18.

For the next 2 weeks, Mount St. Helens remained relatively quiet at its vent, puffing steam and gas but little ash. Meanwhile, rootless steam-blast eruptions continued in the northern periphery of the apron of the pyroclastic flows in the valley of the North Fork of the Toutle River. On clear nights, aerial observers reported seeing glows in the vent crater, interpreted to reflect the presence of near-surface magma even though no lava was extruded. On June 12, the volcano again erupted, generating ash falls to the south-southwest and pyroclastic flows down the north flank. The June 12 eruption was similar to that on May 25 in style and volume, and both eruptions were preceded by harmonic tremor a few hours in advance of the events.

Probably within hours following the explosive activity on June 12, but hidden by poor visibility, pasty magma began to ascend in the vent to form a bulbous dome of lava on the crater's floor. Such lava domes commonly form at stratovolcanoes following major explosive eruptions. The formation of the first of Mount St. Helens' many lava domes during the current activity was confirmed by observers on June 15 when visibility over the volcano improved.

Mount St. Helens erupted again in several pulses during the afternoon and evening of July 22. The July eruption was preceded by several days of measurable swelling of the summit area, heightened earthquake activity, and changed emission of sulfur dioxide and carbon dioxide. Eruption plumes rose to altitudes of between 6 and 11 miles. The eruption destroyed most of the dome formed in mid-June, and pyroclastic flows poured through the north breach of the amphitheater and overrode earlier flows. No dome developed after the cessation of explosive activity, which ejected only about one-tenth as much ash as that of the May 25 and June 12 eruptions.

During the next 3 months, explosive eruptions occurred on August 7 and on October 16-18. These eruptions were preceded by differing combinations of the following precursors: increased earthquake activity, harmonic tremor, changed gas emission, and swelling of vent area. Both eruptions produced ash-steam-gas clouds and pyroclastic flows, followed by the emplacement of viscous lava domes. Subsequent eruptions, beginning with the December 27, 1980-January 3, 1981 eruption, have involved predominantly nonexplosive, dome-building activity. During the remainder of 1981, five dome-building eruptions, accompanied by little or no ash emission, took place: February 5-7, April 10-12, June 18-19, September 6-11, and October 30-November 2.

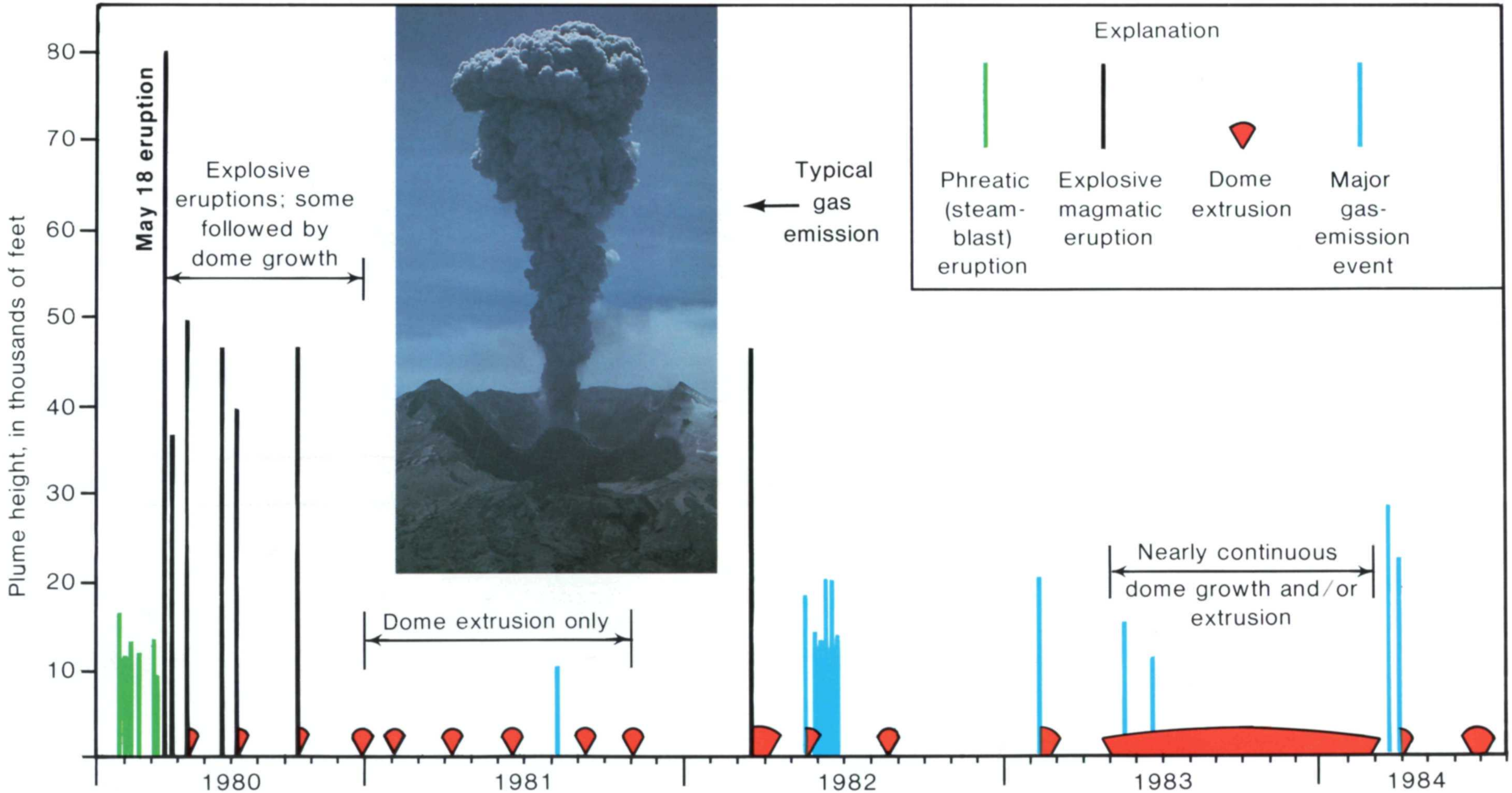
Three eruptions occurred in 1982: March 19-April 9, May 14-18, and August 18-23. In the first explosive activity since October 1980, the March-April 1982 eruption produced an ash column 9 miles high and was accompanied by small debris avalanches and mudflows. Dome growth followed this eruption. The May and August eruptions in 1982 returned to the nonexplosive mode and only involved dome growth. For about a month following the cessation of the May eruption, however, vigorous "gas-emission"

events produced spectacular vertical plumes of steam, gas, and rock debris many thousands of feet high that were visible from Portland, Oregon (50 miles distant) and, on occasion, even from Seattle, Washington (100 miles distant). Scientists believed these emission were caused by steam-blast processes triggered when cold infiltrating rain and ground water came in contact with the subsurface hottest parts of the dome. Gas-emission activity ceased abruptly by late June.

Several eruptions occurred in 1983: one during February 7-28 and another that began at the end of April. The February eruption was preceded by several gas explosions on February 2-4, the largest of which produced plumes of steam and ash 2 to 4 miles high. These explosions ripped open a gash on the dome's summit through which lava extruded about February 7. The February dome-building eruption culminated in the formation of a spine-like protrusion of lava that rose about 200 feet above the

(Left) View of the first lava dome (mid-June) that formed in the bottom of the crater created by the May 18, 1980, eruption. Helicopter (circled) gives scale. This dome was destroyed during the eruption of July 22, 1980 *(Photograph by Robert Tilling).*

A spine-like protrusion of lava rose about 200 feet above the summit of the dome during February 1983 *(Photograph by Thomas Casadevall).*



Summary of the eruptive activity at Mount St. Helens through mid-1984. Beginning in 1981, the eruption sequence has been characterized mainly by intermittent dome-building activity, punctuated by occasional smaller explosive bursts of steam and ash. The inset shows a typical "gas-emission" plume, some of which have risen to 20,000 feet *(Photograph by Jim Zollweg)*.

dome's summit. The spine lasted for about 2 weeks and then collapsed into a heap of rubble. The eruption that began at the end of April was preceded by 3 to 4 weeks of increased seismicity as well as by internal growth of the dome at rates as great as 3 feet per day. Slow extrusion of lava probably began between April 29 and May 4 and has continued intermittently through February of 1984, adding several small lobes to the dome.

Following about 3 weeks of inactivity, the end of March 1984 was marked by increased earthquakes, rapid swelling of the dome, and frequent rockfalls, indicating the onset of renewed dome growth. Extrusion of a new lava lobe was confirmed by aerial observation on March 29. This dome-building event, in contrast to the preceding year-long (February 1983-February 1984) period of virtually nonstop extrusive-intrusive activity, ended by April 6.

Scientists making measurements inside Mount St. Helens' crater to monitor the growth of the "composite dome" *(Photograph by Lyn Topinka).*

Scientists studying Mount St. Helens have called the resultant dome structure rising in the bottom of the crater a "composite dome," because during each eruption, material is extruded onto the surface to add another lobe, cap, or spine to the irregular mound of viscous lava. The composite dome also can increase in size and change shape between eruptions when material added does not break through to the dome's surface. Usually, scientists consider an "eruption" to occur only when the activity involves the visible expulsion of material from the vent. In this regard, the starting and ending dates assigned to the 1983 "eruptions" are somewhat arbitrary because of the virtually continuous, measurable internal growth of the composite dome, punctuated by occasional outbreaks of lava through the dome's surface, which only can be seen under clear weather conditions. Since April 1984, Mount St. Helens appeared to be conforming to its pre-1983 pattern of brief dome-building eruptions, lasting only a few days, separated by relatively calm intervals lasting several weeks or months.

The dome-building eruptive process at Mount St. Helens may be pictured as a periodic squeezing of an upward-pointing tube of toothpaste or caulking compound. It is a dynamic process involving the squeezing up of new material, cracking and pushing aside of old material, sloughing off of material from steep surfaces of the dome, and occasional, small violent eruptions to blast out pieces of the dome.

As of summer 1984, the composite dome measured about 2,880 feet long, 2,720 feet wide, and 810 feet high, comprising an aggregate volume of over 60 million cubic yards. Thus, though growing, the composite dome still occupies only about 2 percent of the volume of the volcano (about 3.5 billion cubic yards) removed during the May 18, 1980, eruption. At the present average rate of dome construction (35 million cubic yards per year), it would take nearly a century to fill in the summit crater and to rebuild Mount St. Helens to its pre-1980 size.

Possible Future Behavior

Bezymianny Volcano, Kamchatka, U.S.S.R., erupted violently in March 1956 and has been intermittently active since then. This photograph, taken in 1977, shows the growing composite dome of Bezymianny rising above the crater rim. Mount St. Helens could similarly remain active for several decades, and continuing dome growth ultimately may fill the crater to form a new conical summit *(Photograph courtesy of the Kamchatka Volcanological Station).*

For a few intensively monitored volcanoes, scientists in recent years have greatly improved their capability to forecast when and sometimes even where an eruption might take place with lead times on the order of several days or less. For example, the current ability to forecast eruptive events at Mount St. Helens represents a major advance; since May 1980, all eruptions have been successfully forecasted days, or even several weeks, in advance. Even for accurately forecasted eruptions, however, there is no way to predict their size or duration. Moreover, scientists are not yet able to forecast accurately the long-term future behavior of volcanoes. For example, for Mount St. Helens scientists cannot answer now with any certainty the following questions. How long will the present intermittent eruptive activity last? Will another large explosive eruption comparable to that of May 18, 1980, take place within the next decade or century? Will lava flows accompany future eruptions?

Most earth-science studies are concerned with past events, and the axiom that "the present is the key to the past" is fundamental to these studies. In recent years, as earth scientists have been asked repeatedly to look forward in time, the axiom that "the past *and* present are keys to the future" has become increasingly significant. Clues to the possible future behavior of Mount St. Helens are gleaned from its past eruptive history. During the past 4,500 years, Mount St. Helens has evolved through nine "eruptive periods," not counting the activity that began in 1980. The most recent and best known of these periods began with a major explosive eruption about 1800. For the next half century, this event was followed by intermittent relatively small explosive eruptions, lava flows, and extrusions of lava domes. Such activity ceased by 1857. *Assuming* that Mount St. Helens behaves as it has in the mid-19th century, the present activity seems likely to continue intermittently for years, possibly decades. Such activity could include the outpourings of lava flows, not observed to date, as well as continued dome growth and small-to-moderate explosive events. The probability of another catastrophic landslide and blast comparable to that of May 18, 1980, is exceedingly low. The past history of the volcano suggests, however, that one or more additional explosive eruptions—with heavy ash emission comparable to that of the May 18, 1980, eruption—may occur before Mount St. Helens returns to a dormant state. This history of intermittent activity is one of the most important reasons why scientists monitor the mountain—to detect the intensive, sustained seismic activity and ground deformation that can be expected to accompany any massive infusion of new magma required to feed an eruption of major proportions.

Continuing Volcanic and Hydrologic Hazards

The present intermittent eruptive activity at Mount St. Helens poses volcanic and hydrologic hazards for the foreseeable future. Specific hazards—ash fall, pyroclastic flows, mudflows, and floods—were described by scientists years before they became stark realities on May 18, 1980. Since then, as the volcano settled into a pattern of episodic, moderate and generally nonexplosive activity, the severity and regional impact of ash fall, lateral blasts, and pyroclastic flows have diminished. Given Mount St. Helens' alternations between explosive and nonexplosive activity in its past, however, the possibility of violent eruptions and attendant hazards in the future should not be discounted.

Considerable hazards still exist in the immediate vicinity of the volcano's present summit—the amphitheater-like crater, with its growing and ever-changing composite lava dome. As the composite dome enlarges, chances increase for collapses of its steep, irregular sides. Such collapses, in turn, could hurl rock fragments onto the crater floor and possibly trigger small pyroclastic flows through the crater breach and down the north flank of the mountain toward Spirit Lake. Rockfalls from the unstable steep walls of the crater have been common since the formation of the huge crater, posing a local but significant hazard to scientists working within it. Pyroclastic flows could also pose a serious threat in the Spirit Lake and other areas directly downslope from the breached summit crater.

As an example of continuing hazards, mudflows triggered by the eruption of March 1982 poured down the north flank of Mount St. Helens and reached the valley of the North Fork Toutle River *(Photograph by Thomas Casadevall)*.

Scientists and other people working close to or within the volcano's crater—within the "restricted zone" established by the USFS—must remember these hazards and take safety precautions. Accordingly all work parties are required to maintain radio contact with their headquarters so that they can be notified of any increased seismicity and other precursory indicators of possible impending activity. Scientists working in or near the crater must use helicopters for access; thus, they are always near a helicopter should a quick evacuation be necessary.

Lava flows from Mount St. Helens pose little direct hazard to people or property because such flows are likely to be very sluggish and, therefore, should not move very fast or far from the vent. Anyone in good health should be able to outwalk or outrun the flows, and no major civil works are near enough to the volcano to be overrun by lava flows. Such flows, however, like other high-temperature eruptive products, melt snow and ice and thus could cause mudflows and floods.

Given the current, relatively quiet, eruptive behavior of Mount St. Helens, mudflows and floods at present constitute the greatest hazards related to volcanic activity. The potential for mudflows and floods has been increased by the existence of new ponds and lakes formed when the debris avalanche of May 1980 blocked parts of the preexisting drainage to serve as natural dams. As these natural dams are composed of loose, easily erodible volcanic debris, they are structurally weak and could fail, which would trigger mudflows and floods.

Devastating mudflows or floods or both could be triggered by any or all of the following: heavy rainfall during storms, melting of snow and ice by hot eruptive products (especially pyroclastic flows), or by sudden failure of one of the lakes impounded by the debris avalanche deposits. During winter—the time of peak precipitation and maximum snowpack—the risks of mudflows and floods increase significantly. Normal precipitation in the Mount St. Helens area is heavy, especially on the volcano's upper slopes, where the average annual rainfall totals 140 inches. In a normal winter, the snowpack on the volcano's higher slopes can be about 16 feet thick. Thus, scientists and civil authorities are rightly concerned about the high potential for mudflows and floods posed by the combination of abundant raw materials (rock debris and water) and continuing eruptive activity.

As an example of the flood hazards in the Mount St. Helens region, in August 1980 the failure of a natural debris dam, after a heavy rainstorm, caused the rapid draining of a 250-acre-foot lake in the Toutle River Valley near Elk Rock. The ensuing flood damaged heavy channel-maintenance equipment in the North Fork of the Toutle River, but, fortunately, caused no injuries or deaths. For the remainder of 1980 and into the spring of 1981, there were no major hydrologic disasters, largely because the winter and spring of 1980-1981 were exceptionally dry. Similarly, there also were no damaging mudflows or floods the following year because of lower than normal precipitation. The levels of the lakes impounded by natural dams, however, gradually rose due to rainfall and runoff.

By the summer of 1982, the debris dams for three of the largest lakes—at Spirit Lake, Coldwater Creek, and South Fork Castle Creek—were becoming substantially eroded, thereby increasing the risk of catastrophic flooding should the dams fail or be overtopped. The Army Corps of Engineers, in the fall of 1982, began to control the rise of the level of Spirit Lake by pumping and discharge into outlet channels, and the USGS and the National Weather Service installed flood-warning systems in the Toutle and Cowlitz River Valleys. By March 1983, Spirit Lake had 360,000 acre-feet of water, the lake at Coldwater Creek had 67,000 acre-feet, and that at South Fork Castle Creek had 19,000 acre-feet. Scientists and engineers estimate that a breach of the natural dam at South Fork Castle Creek, the smallest of the three lakes, could unleash mudflows and floods comparable to those triggered by the May 18, 1980,

Scene at the shore of Spirit Lake showing the Army Corps of Engineers' project to control the rise of the lake level. A pump barge is at the upper left *(Photograph by Lyn Topinka).*

eruption of Mount St. Helens. The Army Corps of Engineers, the Soil Conservation Service, and other Federal, State, and county agencies have a variety of projects underway to mitigate the growing hydrologic hazards. These mitigation projects require many people and much equipment to work in the hazardous zones close to the volcano. To ensure the safety of the mitigation operations, scientists must redouble their monitoring efforts not only of the volcano itself, but also of the debris-clogged drainage systems.

Mudflow and flooding hazards should exist for many years, until such time as the slopes and areas around Mount St. Helens, by revegetation and normal erosion, return to or approach their pre-eruption forest cover, stream gradients, rates of flow, discharge, and channel dimensions. In early 1984, the Army Corps of Engineers announced a long-term plan to cope with the continuing hydrologic hazards. This plan included drilling a diversionary tunnel to lower the water level of Spirit Lake. In the meantime, scientists must maintain the vigil and continually assess the volcanic and hydrologic hazards in order to provide sound recommendations and timely warnings to public officials to lessen the impact of the hazards. Human efforts to control the floods and sedimentation are designed not only to gain time to avert hydrologic disasters until natural "healing" is complete, but also to try to guide, if possible, the healing process.

Scientists' Challenge and Opportunity

The eruptions of Mount St. Helens have provided a good test for scientists who faced the challenge of obtaining, relaying, and explaining in easily understandable terms the information needed by the Federal, State, and local officials charged with land management and public safety. It should be reemphasized, however, that a quick response at Mount St. Helens was possible only because decades of systematic research before 1980 had contributed to a good understanding of the volcano's eruptive behavior and potential hazards. Additionally, the Mount St. Helens eruptions also have provided scientists a unique opportunity to learn much about the dynamics of an active composite volcano. The results of studies in progress should improve the understanding of eruptive mechanisms and should refine a forecasting capability, not only for Mount St. Helens, but also for similar volcanoes in the United States and elsewhere.

Scientists of the David A. Johnston Cascades Volcano Observatory (CVO) collecting gas samples in Mount St. Helens as part of the geochemical monitoring program *(Photograph by Lyn Topinka).*

When the 4.0 magnitude earthquake occurred on March 20, 1980, seismologists of the University of Washington and the USGS began a round-the-clock effort to expand the monitoring and to evaluate the seismic activity. As the number of earthquakes increased over the next few days, USGS and other scientists discussed with officials of the Gifford Pinchot National Forest the significance of the seismic activity, the safety of USFS facilities near the volcano, and the need to close its upper slopes because of snow avalanche and other hazards. USGS scientist Donal Mullineaux arrived on the scene the evening of March 25, and an emergency coordination center was set up at the USFS headquarters in Vancouver. The next day, Mullineaux—one of the foremost experts on Mount St. Helens—described the possible types of eruptions and associated volcanic hazards at a meeting of representatives from government and industry. Following the meeting, the USFS, State, and county officials decided to extend the area of closure beyond the immediate flanks of the volcano. The same day (March 26), the general nature of potential eruptive activity and volcanic hazards was discussed again at a joint USFS-USGS press conference. An offical announcement of a Hazard Watch for Mount St. Helens was issued by the USGS at 8 a.m. PST on March 27. By 12:36 p.m. that day, the first eruption of Mount St. Helens in over a century had begun.

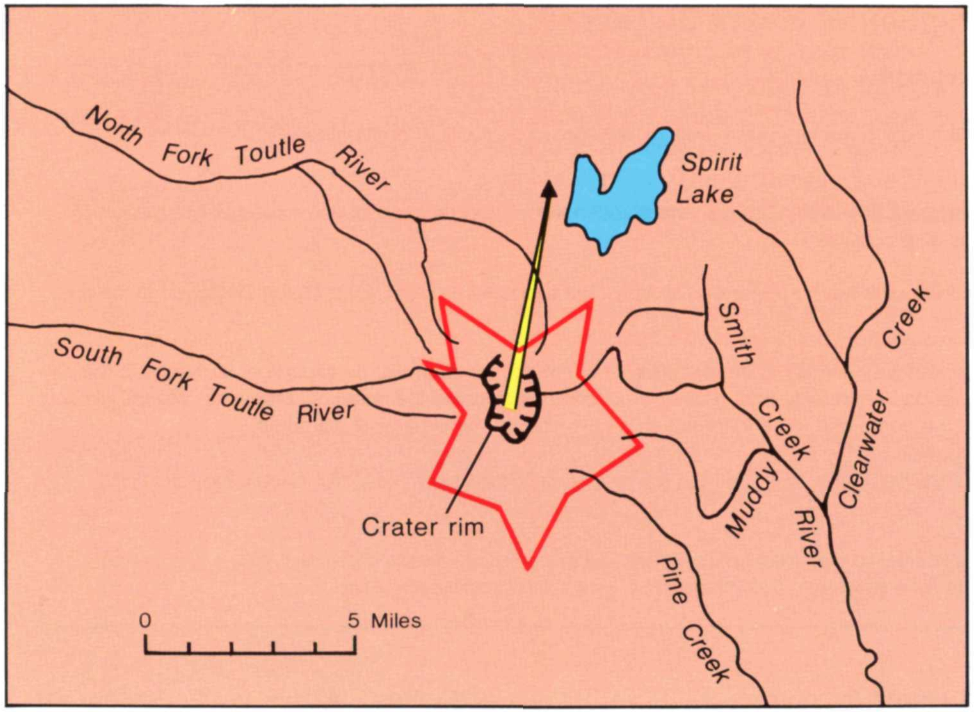
By the time the eruptive activity was into its second week, 25 to 30 scientists were on hand carrying out a wide variety of monitoring and volcanic-hazard-assessment studies. These scientists participated in daily meetings and briefings with USFS and other officials and provided advice on the locations of hazardous zones for use, such as the selection of sites for roadblocks to control access around the volcano. All decisions regarding access and restricted areas, however, were the sole responsibility of the USFS, State of Washington, and other land managers for the Mount St. Helens region. Ironically, in 1980 the section of land containing the summit crater was owned by the Burlington Northern Railroad; it has since been acquired by USFS by land exchanges. On March 31, an onsite, comprehensive, volcanic-hazards assessment was presented at another meeting of agencies responsible for public safety. On April 1, a large-scale volcanic hazards map was prepared for use by these agencies. A news release was issued by the USGS on what might be expected should the activity develop into a "major eruptive phase." Scientists contributed geotechnical and volcanic-hazards information essential for preparing the "Mount St. Helens Contingency Plan" issued by the USFS on April 9. Although the possibility that the collapse of the rapidly deforming "bulge" on the north flank could trigger a magmatic eruption was considered and discussed with officials at various meetings in late April, scientists could not be sure that such an event would actually occur, let alone estimate its timing or size.

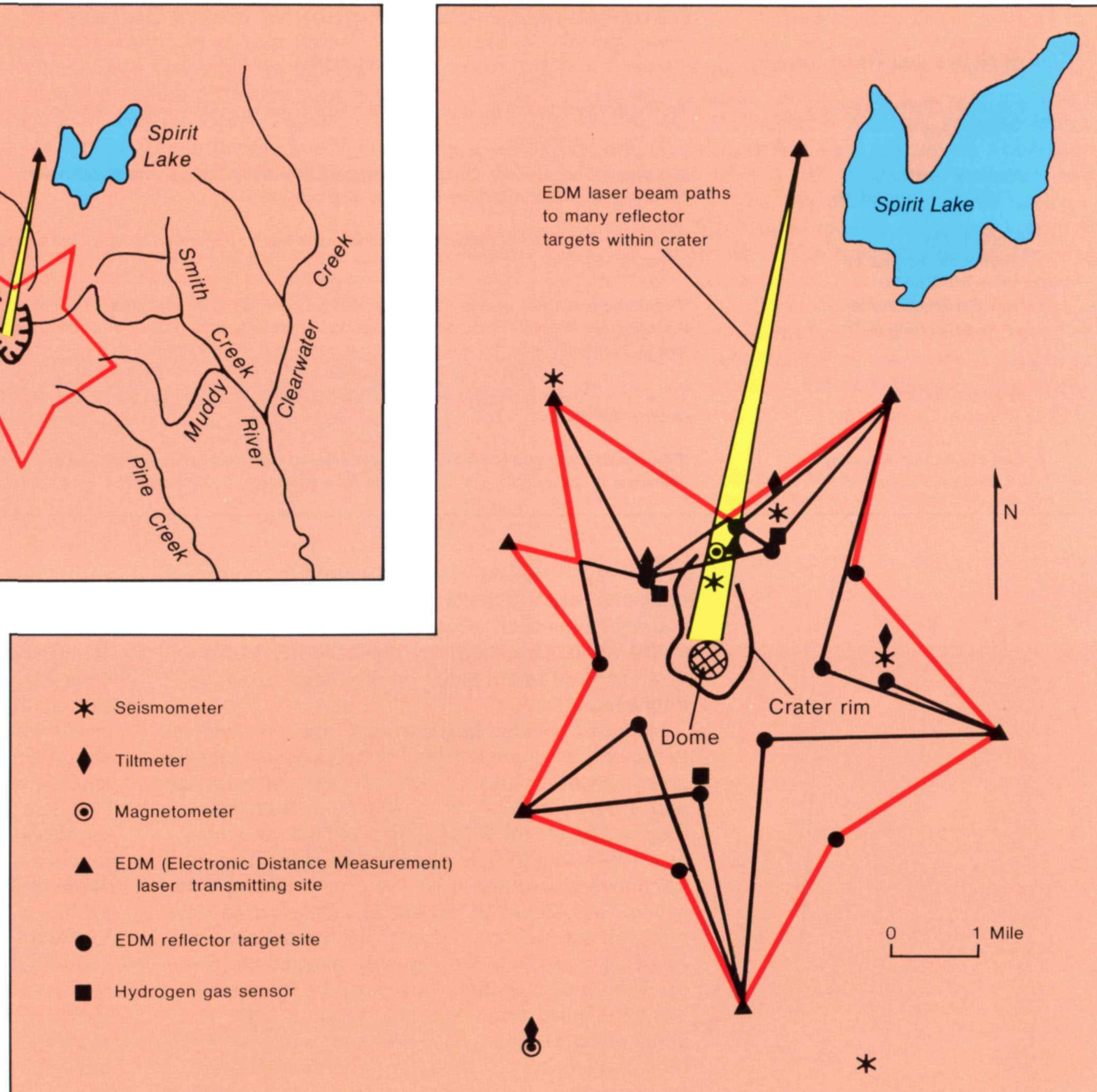
The early recognition of the potential hazards of the bulge on Mount St. Helens' north slope and the systematic measurement of its extremely rapid growth led scientists to advise the USFS that hazards were increasing. Accordingly, the USFS, State, and county officials enforced closure zones. Had these access-control measures not been taken, the catastrophic events of May 18 would have resulted in considerably more human deaths and injury. An element of luck also saved many lives. The catastrophe began hours before the scheduled departure of a caravan of landowners permitted by officials to enter the controlled access area to inspect their properties and cabins. Also, had the eruption occurred on any other day than Sunday, many more people authorized to enter the restricted areas (such as loggers, USFS personnel, and government officials) would have been at work and exposed to the danger.

CVO scientist making a ground-deformation measurement in April 1983 as a small "gas-and-ash emission" event takes place. This photograph shows the laser-beam transmitter positioned atop a heavy 12-foot-high steel tower centered over a benchmark used as the measurement reference point. Such towers allow measurements to be made at Mount St.Helens during the winter despite deep snow *(Photograph by Lyn Topinka).*

Legislation passed by Congress in 1974 made the Geological Survey the lead Federal agency responsible for providing reliable and timely warnings of volcanic hazards to State and local authorities. Under this mandate, and recognizing the need to maintain systematic surveillance of Mount St. Helens' continuing activity, the USGS established a permanent regional office at Vancouver, Washington, after the May 18, 1980, eruption. On May 18, 1982, the office at Vancouver was formally designated the David A. Johnston Cascades Volcano Observatory (CVO), in memory of the Survey volcanologist killed 2 years earlier. Staffed by about 70 permanent and part-time employees—geologists, geophysicists, hydrologists, geochemists, technicians, and supporting personnel—the CVO not only maintains a close watch on Mount St. Helens, but also serves as the headquarters for monitoring other volcanoes of the Cascade Range in Washington, Oregon, and northern California. The Cascades Volcano Observatory is a sister observatory to the USGS' Hawaiian Volcano Observatory (HVO), which was founded in 1912 and has pioneered or refined most of the modern volcano-monitoring methods used in the world today.

As the crater of Mount St. Helens continues to fill with new lava from successive dome-building events, the ability of scientists at CVO and the University of Washington to provide warnings for such eruptions has been exceptional. Indeed, for all eruptions since May 1980, scientists—using data from seismic, ground deformation, and volcanic gas monitoring—have provided reliable forecasts from several hours to several days, even weeks, in advance of these events. The table (p. 44) gives a typical example of the timely information for one 1982 eruption given to government officials charged with emergency management and to the general public via news releases.





Sketch map showing the close-in monitoring network at Mount St. Helens. The seismic network, jointly operated by the USGS and the University of Washington, covers an area much larger than that shown in the diagram—encompassing the entire State of Washington.

August 18-23, 1982, Eruption of Mount St. Helens

Type of Notice and When Issued	Excerpt
Extended Outlook Advisory 1 p.m., July 30	"an eruption will probably begin within the next 3 weeks. ... the eruption will consist primarily of dome growth."
Advisory Update 11:30 a.m., August 16	"eruption will begin within the next 4 days, possibly within 2 days...the eruption will consist primarily of dome growth, but as with all dome growth, minor explosive activity is also possible."
Eruption Alert 6:55 a.m., August 17	"Seismicity and rates of deformation in the crater have accelerated sharply...the expected eruption will probably begin within the next 24 hours."
Updated Eruption Alert 7:45 a.m., August 18	"The dome is already growing internally, but we have not seen any discrete event yet, for example, an explosion, a change in the character of seismicity or deformation...or gas emissions, that in other eruptions has signaled the onset of...eruptions. We still expect lava to eventually work its way through the dome and to be extruded as a new lobe on the surface of the dome."
Eruption Update 7:15 p.m., August 18	"Lava finally broke through to the top of the dome this morning, and a new lobe is flowing slowly onto the western and southern sides of the dome."
End-of-eruption Advisory 8:45 p.m., August 23	"Deformation and gas emissions have returned to their background levels, so this eruption is essentially over. Minor sagging and spreading of the new lobe may continue for a few days, accompanied by occasional rockfalls and dust plumes."

At Mount St. Helens, the track record for predicting eruptions, especially dome-building ones, is better than any previously accomplished for any volcano in the world. Our improving predictive ability, however, has not been tested by any large explosive eruptions.

Mount St. Helens has provided, and will continue to provide, an unprecedented opportunity for scientific research on volcanism. Relatively easy accessibility and a dense network of monitoring instruments have made Mount St. Helens a natural laboratory at which scientists can study processes typical of volcanoes elsewhere along the circum-Pacific "Ring of Fire." As Mount St. Helens is monitored continuously before, during, and after each eruption, and its eruptive products are regularly sampled for chemical and other laboratory analyses, the information being compiled and interpreted yields a better understanding of Mount St. Helens in particular, and other composite volcanoes in general. Moreover, the monitoring techniques now being used at Mount St. Helens and other Cascade volcanoes are the same as, or variations of, those used to monitor the active Hawaiian volcanoes. Thus, in the rather young science of volcanology, a rare opportunity to compare the effectiveness of these techniques on two contrasting kinds of volcanoes—the Hawaiian shield volcanoes, which typically erupt nonexplosively, and the Cascade composite volcanoes, which typically erupt explosively. Scientists have learned that data from *all* types of monitoring are helpful regardless of the type of volcano. From such comparative studies, they will be able to determine which techniques are the most effective and reliable for monitoring each type of volcano. With such tools and broadened knowledge, scientists may be entering a new epoch in volcanology, in which significant advances in understanding volcanic phenomena will be achieved, accompanied by a sharpened ability to forecast and mitigate volcanic hazards.

Mount St. Helens National Volcanic Monument

Despite the troubled economy in the early 1980's, many thousands of tourists flocked to Mount St. Helens. Tens of thousands of people, especially during the summer months, have toured the USFS Mount St. Helens Visitor Center in Toledo, Washington. These people see firsthand the awesome evidence of a volcano's destruction and the remarkable but gradual healing of the land as revegetation proceeds and wildlife returns. On August 27, 1982, President Reagan signed into law a measure setting aside 110,000 acres around the volcano as the *Mount St. Helens National Volcanic Monument,* the Nation's first such monument. At dedication ceremonies on May 18, 1983, Max Peterson, head of the USFS, said "we can take pride in having preserved the unique episode of natural history for future generations." The National Volcanic Monument preserves some of the best examples and sites affected by volcanic events for scientific studies, education, and recreation. Intensive monitoring of the volcano will now be all the more important to ensure the safety of the scientists and the monument's visitors.

This small tree, protected by a snowbank, survived the devastation in the lateral-blast zone and remains among the vegetation beginning to grow on the scarred land *(Photograph by Peter Lipman).*

People view exhibits about Mount St. Helens at the U.S. Forest Service Visitor Center in Toledo, Washington *(Photograph courtesy of the USFS).*

Selected Readings

Brantley, Steven, and Topinka, Lyn, 1984, Volcanic studies at the U.S. Geological Survey's David A. Johnston Cascades Volcano Observatory, Vancouver, Washington: Earthquake Information Bulletin, v. 16, no. 2, p. 41-120. (A well-illustrated report of the activities at the observatory.)

Crandell, D. R., and Mullineaux, D. R., 1978, Potential hazards from future eruptions of Mount St. Helens, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p. (Description of the types of eruptions and associated volcanic hazards from Mount St. Helens—which proved to be remarkably close to what actually took place 2 years later.)

Crandell, D. R., Mullineaux, D. R. , and Rubin, Meyer, 1975, Mount St. Helens Volcano: Recent and future behavior: Science, v. 187, no. 4175, p. 438-441. (First publication to forecast that Mount St. Helens could erupt ". . . before the end of the century.")

Foxworthy, B. L., and Hill, Mary, 1982, Volcanic eruptions of 1980 at Mount St. Helens: The first 100 days: U.S. Geological Survey Professional Paper 1249, 125 p. (A description of the events during the first 100 days of eruptive activity, in nontechnical language, that serves as a backdrop for the scientific articles in USGS Professional Paper 1250.)

Hamilton, Warren, 1976, Plate tectonics and man, *in* U.S. Geological Survey Annual Report, Fiscal Year 1976, p. 39-53. (A general summary of plate tectonics theory and its relationship to earthquakes, volcanoes, and natural resources. Also available as a separate reprint in the USGS series of general interest publications.)

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———, 1982, Volcanoes, U.S. Geological Survey series of general interest publications, 46 p. (A general summary of the nature, types, workings, products, and hazards of volcanoes.)

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View of Mount St. Helens from the north in April 1981, with Spirit Lake in the middle ground *(Photograph by Lyn Topinka).*

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.