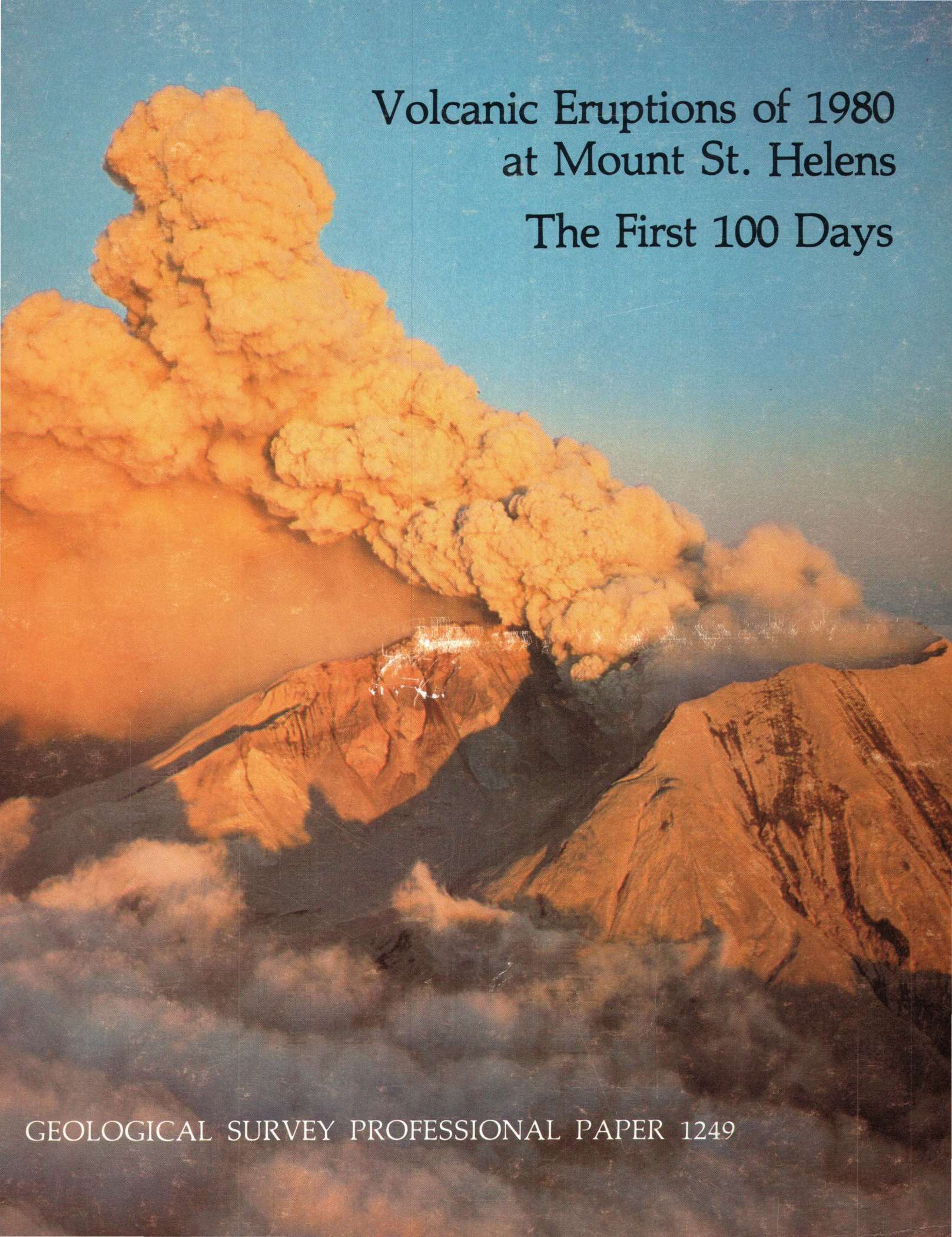
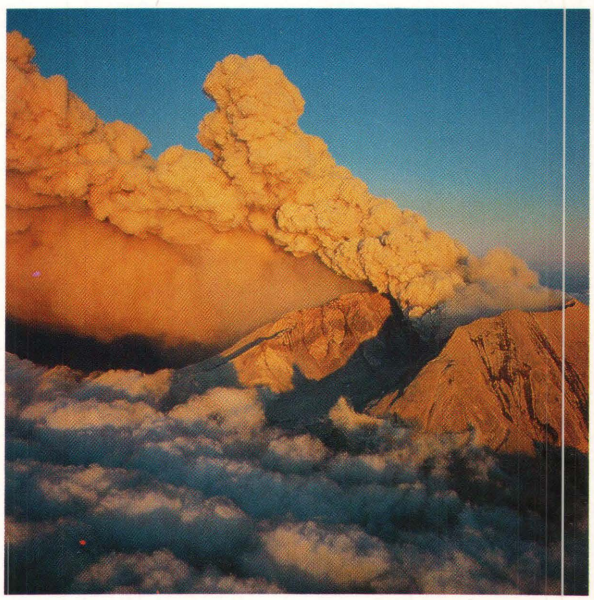


Volcanic Eruptions of 1980 at Mount St. Helens

The First 100 Days

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1249



Volcanic Eruptions of 1980 at Mount St. Helens

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Photographs of Mount St. Helens after (top) and before (bottom) the May 18, 1980, eruption, taken from exactly the same spot at Coldwater II observation station, 5.7 miles north-northwest of the peak. Haze in the top view is mostly airborne volcanic ash, which is present near the volcano during all but the calmest (or rainy) days. These photographs were taken by Harry Glicken on May 17 and September 10, 1980.

Volcanic Eruptions of 1980 at Mount St. Helens

The First 100 Days

By BRUCE L. FOXWORTHY *and* MARY HILL

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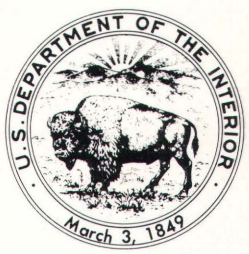

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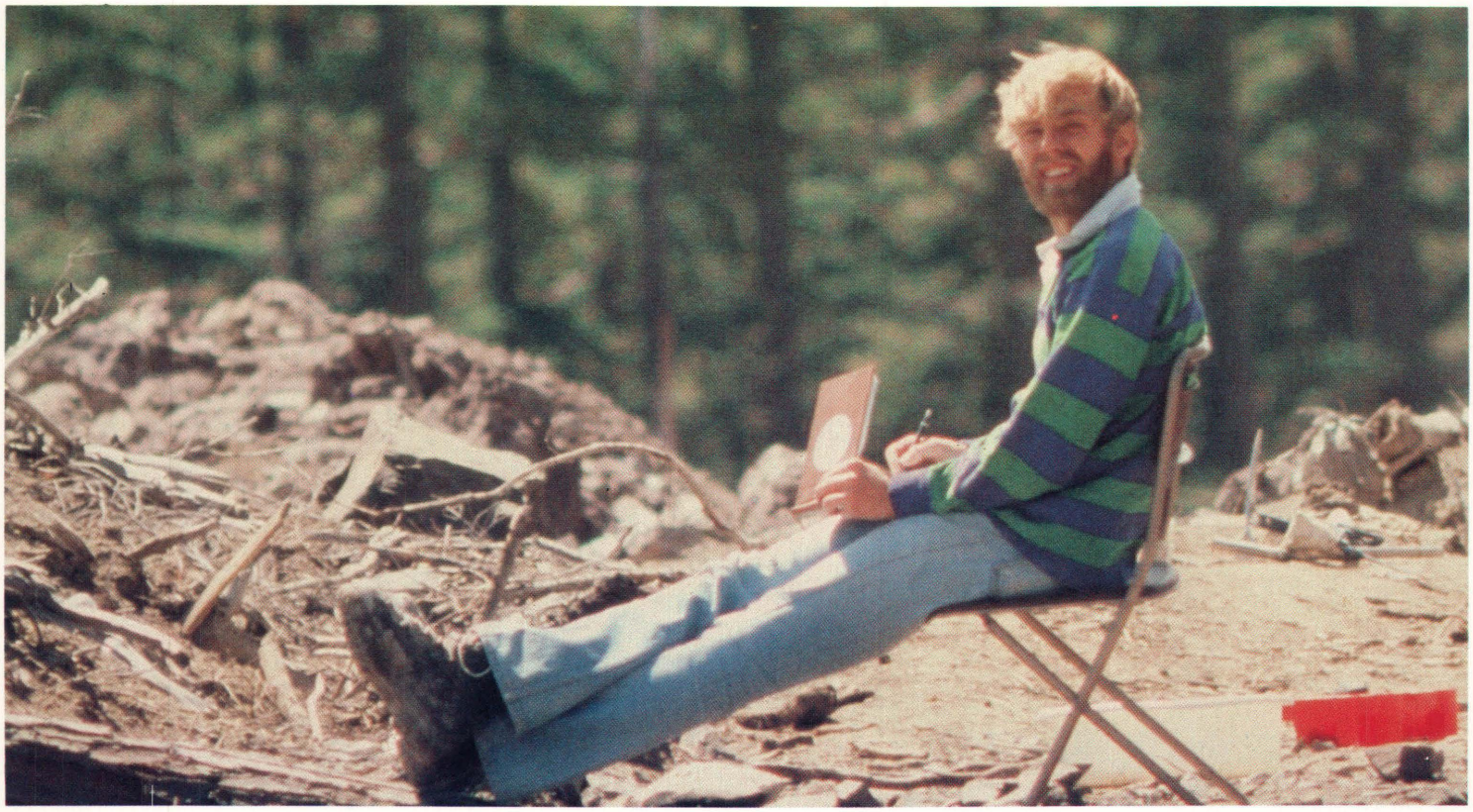
IN DEDICATION

DAVID A. JOHNSTON
DECEMBER 1949–MAY 1980



Volcanologist David A. Johnston writing field notes at Coldwater II observation station May 17, 1980, the evening before he was killed by the lateral blast of the Mount St. Helens eruption. Earlier in the day, Johnston had collected volcanic gas samples from a fumarole high on the unstable northern side of the volcano (see fig. 20.). This photograph was taken by Harry Glicken, who was relieved of his observer duties at Coldwater II by Johnston and who brought this film out of the area the night before the fatal eruption.

Among those who lost their lives in the May 18, 1980, eruption of Mount St. Helens was an exceptional colleague, volcanologist David Johnston.

David was special not only because he was the first member of the U.S. Geological Survey to die in a volcanic eruption but also because of his capabilities and his dedication to his science. He knew well the personal risks involved in studying active volcanoes. Yet, his belief in the need to better understand volcano behavior led him to vigorous service in the "front lines" at Mount St. Helens. Through it all, he displayed a rare combination of inventiveness and originality in his scientific observations and interpretations.

On the morning of May 18, David was alone at the Coldwater II observation station, 5.7 miles from the mountain's summit, measuring the volcano's bulging northern side. He was among the first to see the beginning of the eruption and tried to send a warning to the control center. "Vancouver, Vancouver, this is it!," he shouted into his radio. Then, as the black, billowing front of the lateral blast raced toward him, he tried a second message, which was garbled by atmospheric disturbance from the eruption. Then—nothing.

The lateral blast obliterated Coldwater II observation station. Ironically, the location was (and is again) considered to be much safer than some of the sites on the mountain itself that David and his colleagues visited regularly.

We dedicate this report to David Johnston, an untimely loss to his science as well as to his friends.

PREFACE

This report is unusual for the U.S. Geological Survey's Professional Paper series. Not only does it attempt to describe volcanic events that are unprecedented in United States history, it also tries to describe those events in ways that the nontechnical reader will understand and in a context of human concerns to which he can relate. This account will serve as a backdrop for more technically written scientific reports on the volcanic activity at Mount St. Helens and the geologic and hydrologic effects of its eruptions.

Because this report is intended for a broad audience consisting mainly of nonscientists, we have avoided technical language wherever it was possible. Discussions of the volcanic processes and related hazards, however, touch upon many scientific specialties and involve some terms and concepts for which nontechnical counterparts simply do not exist. Some of these technical terms are explained when they are used in the main body of the report, and some are defined in a glossary at the back of the report (p. 121). A term that is explained in the glossary appears in bold italicized type the first time that it is used in the text.

Similarly, we have used mostly English units of measurement (inches, feet, miles, and so forth) rather than metric units for presenting quantitative information. Exceptions include altitudes and contour intervals (given in meters) on one of the general maps (fig. 7) and ash thicknesses (given in millimeters) on the ash-distribution maps (figs. 35, 43, and 48). Temperatures are given in both Fahrenheit and Celsius units. A table for converting other units to the metric system is provided at the back of the report (p. 125).

Although the words in this report are largely ours, most of the information comes from the work of many others. These information sources range from scientific publications prepared years before the 1980 eruptions to oral accounts, news releases, and data obtained after the major eruptions. It is impossible to present appropriate and balanced credits for all information and materials used; generally we have cited only the more readily indentifiable sources, such as photographers (in photographic credits) and published reports (listed in the reference section).

Among the sources that can be identified are the daily, summary, and hazard reports prepared by the leaders of the U.S. Geological Survey's Mount St. Helens task force—Robert L. Christiansen, Dwight R. Crandell, Robert W. Decker, Donal R. Mullineaux, and Donald W. Petersen—and by the leader of the University of Washington seismology center, Stephen D. Malone. We also have borrowed freely from U.S. Geological Survey press releases prepared by Donovan Kelly, Edna C. King, and Donald R. Finley. With permission, we have quoted the eyewitness account provided by Keith L. Stoffel, first published in Information Circular 71 of the Washington Department of Natural Resources, Division of Geology and Earth Resources (Korosec and others, 1980). Many other eyewitness accounts and observations by both scientists and nonscientists are quoted or paraphrased.

Christiansen provided us with a typescript copy of a paper published in *Nature* (June 19, 1980) (Christiansen, 1980). We made extensive use of it and of monthly reports prepared by many scientists on the U.S. Geological Survey–University of Washington team. We also have quoted from *Potential Hazards from Future Eruptions of Mount St. Helens Volcano, Washington*, published as U.S. Geological Survey Bulletin 1383–C (Crandell and Mullineaux, 1978). The "Glossary of Volcanic and Related Terms" (p. 121) is derived largely from a glossary prepared by Roy A. Bailey.

Although most of the technical information for this report was provided by colleagues in the U.S. Geological Survey, other individuals and agencies also provided valuable information. Malone furnished summary data on seismic events recorded by the University of Washington Geophysics Program. We used information selectively from bulletins prepared by the Mount St. Helens Technical Information Network; other information was taken from daily reports and news releases of the U.S. Forest Service, the U.S. Army Corps of Engineers, and the Federal Emergency Management Agency. For the human side of the volcanic events, we relied on the news media and a few personal interviews.

Photographs used to depict various events or features discussed in the text were selected, insofar as it was practical, to reflect the first occurrence or discussion of the specific event or feature. Better illustrations of several subjects, however, are provided by photographs that were not strictly equivalent in time. Other illustrations are enhanced by paintings by U.S. Geological Survey hydrologist-artist Dee Molenaar.

Technical reviews of part or all of this report were provided by Mullineaux, Peterson, Crandell, Molenaar, David G. Frank, David P. Dethier, Philip J. Carpenter, Edwin H. McGavock, John E. Cummans, Mark L. Holmes, and Jerry C. Stephens of the U.S. Geological Survey; Malone of the University of Washington Geophysics Program; James L. Unterwegner of the U.S. Forest Service; and geologists Vaughn E. Livingston, Jr., J. Eric Schuster, and Michael A. Korosec of the Washington Department of Natural Resources, Division of Geology and Earth Resources. Individual credits for the many other scientists, graphics specialists, and reviewers who contributed to this report are impractical, but the helpful cooperation of all is most gratefully acknowledged.

Finally, we wish to acknowledge the key role played by David A. Rickert, assistant to the Chief Hydrologist of the U.S. Geological Survey, who developed the concept for this report and provided encouragement and many helpful suggestions during its preparation.

Bruce L. Foxworthy

Mary Hill

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The First 100 Days

By BRUCE L. FOXWORTHY *and* MARY HILL

ABSTRACT

On May 18, 1980, after nearly 2 months of local earthquakes and steam eruptions, picturesque Mount St. Helens, a Cascade Range volcano in southwestern Washington, suddenly began a major explosive eruption directed first northward and then upward. The lateral blast, which lasted only the first few minutes of a 9-hour continuous eruption, devastated more than 150 square miles of forest and recreation area, killed countless animals, and left about 60 persons dead or missing. The 9-hour eruption, the huge debris avalanche that immediately preceded it, and intermittent eruptions during the following 3 days removed about 4 billion cubic yards (0.7 cubic mile) of new magmatic material and of the old upper and northern parts of the mountain, including about 170 million cubic yards (0.03 cubic mile) of glacial snow and ice. The eruption caused pyroclastic flows and many mudflows, the largest of which produced deposits so extensive and voluminous that they reached and blocked the shipping channel of the Columbia River about 70 river miles from the volcano. The May 18 eruption blew volcanic ash, consisting of pulverized old rock from the mountain's core as well as solidified new lava, more than 15 miles into the air. Winds carried the ash generally eastward across the United States and, in trace amounts, around the world. The ash, which fell in troublesome amounts as far east as western Montana, severely disrupted travel, caused widespread economic loss, and resulted in other problems that persisted to the end of the first 100 days of the volcano's activity (June 27, 1980). During that time, two other major eruptions (May 25 and June 12) also produced troublesome ashfalls in western Oregon and Washington.

Mount St. Helens had been labeled in a 1975 U.S. Geological Survey report as the Cascade volcano most likely to erupt. When frequent earthquakes began beneath the mountain on March 20, 1980, the potential for volcanic activity was recognized quickly by University of Washington seismologists and soon was accepted by most other knowledgeable scientists. Officials of emergency-services agencies and other appropriate organizations at all governmental levels were alerted to the possibility of an imminent eruption. Scientists quickly stepped up the collection and interpretation of pertinent geologic, geophysical, hydrologic, and atmospheric data. As events progressed toward the climactic eruption of May 18, scientists, law-enforcement officers, and other responsible officials teamed up in round-the-clock efforts to evaluate the increasing hazards and to protect tourists and local residents (often against their will) while also attempting to minimize panic and hardships among the citizenry. Officials of the State of Washington and the U.S. Forest Service established restricted-entry zones around the volcano. Most people respected these restrictions, but the spectacular eruptions of steam and ash from the mountaintop were an irresistible attraction to some, who entered the danger zone by way of logging roads too numerous to blockade. An information center established at Vancouver, Wash., coordinated the release of warnings and other information, including thousands of news releases and responses to telephone inquiries, daily briefings by scientists, and explanatory meetings with officials and local citizens.

From mid-April to May 17, eruptions and seismic activity diminished to such a degree that some residents and loggers were clamoring for entry into the restricted area near the volcano. (Limited entry was, in fact, granted on May 17 and scheduled also for the morning of the cataclysmic eruption.) The scientific data, however, showed that the mountain was bulging on its upper northern side and undergoing other ominous changes and, therefore, that the hazards were increasing rather than decreasing. Although opposition to official restrictions was widespread before the May 18 eruption, the human responses to the far-reaching effects of that eruption included acts of exceptional heroism, and selfless cooperation was commonplace.

The May 18 eruption differed from what was generally expected by the scientific team mainly in the character and destructiveness of the lateral blast and the lack of prior seismic warning. With these notable exceptions, the scientists' evaluation provided an ample hazard warning and unquestionably saved hundreds of lives. That evaluation was based not only on the many-faceted project for monitoring restless Mount St. Helens but also on information obtained by earlier geologic investigations of this volcano, of other Cascade volcanoes, and of other volcanoes throughout the world.

Hazards that continued after the first 100 days of activity at Mount St. Helens in 1980 included possible ashfall and ash clouds, pyroclastic flows, lateral blasts, lava flows, floods, mudflows, and fires. The main flood hazard existed along the channels of the Toutle and lower Cowlitz Rivers, which were so choked with mudflow deposits from the May 18 eruption that normal wet-season runoff could have caused severe overbank flooding. Dredging undertaken on an emergency basis to open the channels probably will be continued in subsequent years.

The volcanic activity at Mount St. Helens during the 100-day period ending June 27, 1980, is not exceptional in recorded history or in the evolution of the Cascade Range. Mount St. Helens was only one of perhaps 50 volcanoes worldwide that were active during 1980, although its May 18 eruption was by far the most powerful during the year and, perhaps, during the last decade. At the end of the 100-day period, the mountain remained dangerous to those nearby, but the near-term likelihood of another eruption as destructive as that of May 18 was considered to be small. So far as is known, the 1980 eruptions of Mount St. Helens do not increase the probability that other Cascade Range volcanoes will erupt. The eruptions should, however, serve as a reminder that other Cascade volcanoes will erupt in the future as surely as they have in the past and that they are likely to produce effects that no amount of farsightedness or good intentions will be able to prevent.

The outlook for the future of Mount St. Helens and the areas that it affected can be discerned only partially. Salvage of blowndown timber was begun in June 1980, but proposals have been made to incorporate part of the devastated forest area into a park. Tourists are expected to be attracted in great numbers. Future uses of land near the volcano probably will resume largely as they were—forestry, farming, recreation, and hydropower generation—but will depend ultimately on the behavior of the volcano. The volcano might go through a period of dome building (as it was on June 27, 1980) interspersed with occasional explosive eruptions; it might extrude enough lava to overflow the crater that was left open to the north; or the volcanic activity might simply stop indefinitely at any stage.

In the meantime, the ash gradually will be assimilated into the soil. The streams and lakes that persist on the mountain flanks and in the devastated area will adjust to the new conditions of runoff and sediment load. Glaciers and snowfields will adapt to the different shape and lower altitude of the cone. Animals and vegetation, already returning to the devastated areas at the end of June 1980, will become abundant again. The restorative phase of the cycle, repeated many times before at this volcano and others in the Cascades, has begun once more.

INTRODUCTION

On May 18, 1980, Mount St. Helens in southwestern Washington exploded in a volcanic eruption more violent than any in the conterminous United States during the 20th century. An immense ***avalanche*** from the volcano's northern side was followed immediately by an explosive eruption directed first northward and then upward. The sustained lateral blast spewed hot gas and rock particles from the volcano at hurricane speeds, its devastation reaching nearly 16 miles outward from the volcano's center. Nearer the mountain, massive deposits of rock and ice from the avalanche were followed by intensely hot ***pyroclastic flows*** and by countless ***mudflows.*** In a wide swath northward from the mountain, survivors of the blast—plant, animal, or human—were rare.

Some of the consequent, more distant effects of the May 18 eruption, which were themselves considered to be major disasters, included smothering layers of volcanic ***ash*** that fell on much of Washington and parts of other States. Others were the extensive floods and mudflows that poured down stream courses leading from the mountain and left huge deposits of sediment that choked the channels of major rivers in southwestern Washington—even a part of the mighty Columbia River.

The eruption of May 18, 1980, so far has been the main event in a sequence of volcanic activity that began on March 20 of that year and persisted for 100 days (to June 27) and beyond. The eruptive events at Mount St. Helens during the spring of 1980 were probably the most intensively observed, photographed, documented, and reported series of geologic events in history. The broad coverage of the events, particularly by the news media, resulted in many different accounts, from many different viewpoints, on many different aspects of the volcanic activity and its impacts. Unfortunately, these accounts do not all agree or reflect the facts as they are now known.

The U.S. Geological Survey (USGS) has played a major role in the observation, interpretation, and documentation of this sequence since it began. As the Federal agency responsible for geologic and hydrologic investigations and geologic hazard warnings (see p. 121), the USGS has an obligation to report to the Nation on these events. This paper is intended to provide a scientifically sound, general description of the events and their effects—to supply answers for the general reader, from the perspective of earth scientists, to the questions, "What happened?" and "What does it all mean?"

Another major purpose of this report is to provide an accurate summary of the events before, during, and shortly after the devastating eruption of May 18, 1980, and the two lesser eruptions of May 25 and June 12. A chronological summary is preceded by a brief general discussion of Cascade Range volcanoes, the geologic processes involved in a volcanic sequence, the conditions at and near Mount St. Helens before the volcanic activity began, and the perception of and warning about the volcanic hazards. The chronology is followed by a short discussion of the continuing hazards, the outlook for future volcanic activity, and some implications for the future use and management of affected land and water resources.

CASCADE RANGE VOLCANOES

Mount St. Helens is one of a group of high volcanic peaks that dominate the Cascade Range between northern California and southern British Columbia, Canada (fig 1.) The distribution of these volcanic peaks in a band that roughly parallels the coastline is typical of the so-called "Ring of Fire," a roughly circular array of volcanoes located on islands, peninsulas, and the margins of continents that rim the Pacific Ocean (Anderson, 1980).

Even before it began erupting in 1980, Mount St. Helens and at least six other volcanoes in the Cascade Range were known to be ***active***—that is, to have erupted at least once during historical time. Few major Cascade volcanoes are known to have been inactive long enough to be considered ***extinct*** or incapable of further eruption. Most display some evidence of residual volcanic heat, such as ***fumaroles,*** hot springs, or hot ground where snow melt is unusually rapid. Information about the previous eruptions of some major Cascade volcanoes is presented in table 1.

Dramatic eruptive activity in the Cascades has been rare so far in the 20th century. Until the recent eruptions at Mount St. Helens, the only Cascade volcano that had a major eruption during this century was Lassen Peak in California. A series of intermittent eruptions of steam and volcanic ash beginning in May 1914 and lasting until 1921 climaxed, during the 4 days from May 19 to 22, 1915, in a series of violent events comprising small ***lava flows,*** massive lava-triggered mudflows, and explosive eruptions of ash. The most destructive of these eruptions included a nearly horizontal (lateral) blast that reached only about one-fifth as far as the recent Mount St. Helens lateral blast (Day and Allen, 1925). From the time when Lassen Peak quieted until March 1980, the only other known increase in activity at a Cascade volcano occurred at Mount Baker (fig. 1), when a sudden increase in emanations of heat, steam, and other gases from a previously steaming old ***crater*** began on March 10, 1975. Although new fumaroles were formed and minor amounts of "volcanic dust" and sulfur were emitted, "the greatest undesirable natural results" that were observed at Mount Baker were "an increase in local atmospheric pollution and a decrease in the quality of some local water resources" (Bortleson and others, 1977, p. B1). Since 1976, however, even those effects have subsided to levels only slightly higher than those that prevailed before 1975.

Eruptions of Cascade volcanoes tend to be much more explosive than those of, for example, the well-known Hawaiian volcanoes. This explosive tendency is related to the chemical composition of the ***magma*** that feeds

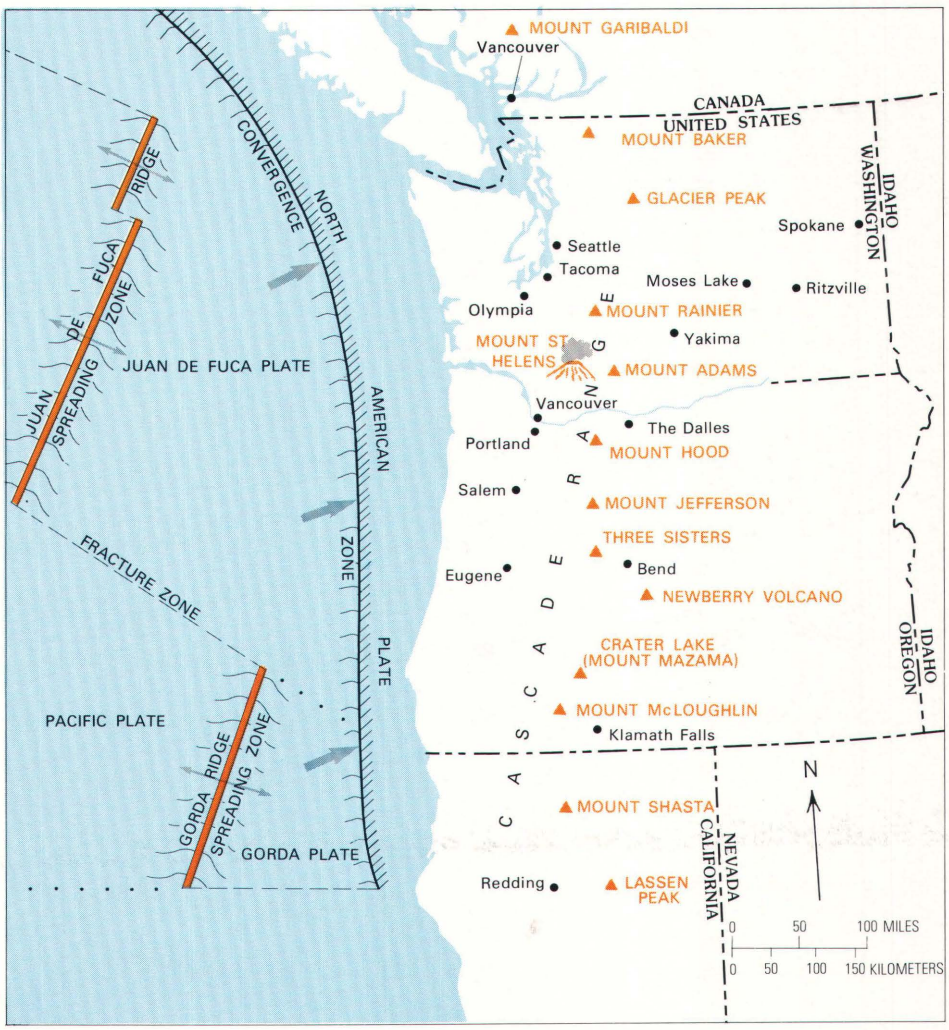


FIGURE 1.—Sketch map of the Pacific Northwest and the western Pacific Ocean showing major Cascade Range volcanoes and other regional features. The position and alinement of the Cascade Range volcanoes result from the slow grinding together (convergence) of huge plates of the Earth's crust as new volcanic rock is added at spreading zones beneath the ocean (after Atwater, 1970). Arrows indicate relative movement of the crustal plates. These processes are further illustrated in figure 2.

TABLE 1.—*Activity of major Cascade Range volcanoes*
[Locations of volcanoes shown in fig. 1]

Volcano	Summit altitude (ft above sea level)	Times of eruptions [1]	Nature or products of eruptions [2]	Present thermal activity	Remarks and references
		British Columbia, Canada			
Mount Garibaldi	8,787	About 10,000(?) years ago.	Lava flows; fragmental pyroclastic deposits.	None; may be extinct.	Volcano's core is solid dacite rocks. Most of cone comprises fragmental material that was deposited on surrounding ice of a continental glacier (Mathews, 1952; Harris, 1980).
		Washington			
Mount Baker	10,775	1820(?); 1843; 1846; 1853–1854; 1858; 1859–1860; 1863; 1870.	Steam, pyroclastic materials, mudflows.	Steaming fumaroles at flank and crater locations.	Heat emission increased markedly in crater area in 1975 and produced warm, acidic meltwater and effusive emissions of steam containing occasional traces of ash and sulfur dust. Activity had diminished somewhat by 1978 (Malone and Frank, 1975).
Glacier Peak	10,451	About 200–300 years ago; 1,000–1,800 years ago; 1,800–2,800 years ago.	Mudflows; pyroclastic flows; widespread ash and pumice.	Two hot springs on the volcano's lower flanks.	Eruptions have characteristically produced large volumes of volcanic ash and airborne pumice that could endanger closest centers of population (Tabor and Crowder, 1969; Beget, 1979).
Mount Rainier	14,410	About 1820(?); 1841–1843(?); 1854(?); 1879; 1882.	Light pumice fall between 1820 and 1854, only steam emission and mudflows thereafter.	Occasional steam explosions on upper slopes; many steam vents and hot rocks in summit craters.	Largest of the Cascade volcanoes. A mudflow caused by steam explosions about 5,700 years ago was one of the largest known in the world. Expected to erupt again within the next few hundred years; hazards consist mainly of mudflows, floods, and fallout of tephra (Crandell and Mullineaux, 1967).

TABLE 1.—*Activity of major Cascade Range volcanoes*—Continued

Volcano	Summit altitude (ft above sea level)	Times of eruptions [1]	Nature or products of eruptions [2]	Present thermal activity	Remarks and references
		Washington—Continued			
Mount St. Helens	8,364 (9,677 before May 18, 1980).	Between 1600 and 1700; about 1800–1802; 1831; 1835; 1842–1844(?); about 1847–1854; 1857; 1980–? (see table 2).	Violent explosions, pyroclastic flows, lava extrusions; lava dome formation; steam and ash; mudflows.	Strong steaming; occasional eruptions of steam and ash; occasional pyroclastic flows, intermittent extrusion of dome-forming lava (as of June 27, 1980).	Had been identified in 1978 as an especially dangerous volcano because of its past behavior and relatively high frequency of eruptions (Crandell and Mullineaux, 1978).
Mount Adams	12,286	No more than 1,000 or 2,000 years ago.	Lava flows	Fumaroles emitting steam and hydrogen sulfide in the crater area.	Appears to consist of a group of several superimposed volcanic cones. Summit crater has extensive sulfur deposits that were formerly mined (Hopkins, 1969; Harris, 1980).
		Oregon			
Mount Hood	11,245	1865; 1859(?)	Incandescent(?) gaseous plumes; small amount of pumice.	Extensive fumaroles emitting steam and other gases; also hot ground on upper southwestern side.	Expected to erupt again, possibly within the next few decades, but time of eruption cannot now be predicted. Portland metropolitan area probably will not be significantly affected (Crandell, 1980; Harris, 1980).
		200–300 years ago; 1,500–1,800 years ago.	Mudflows; pyroclastic flows, dome extrusions.		
Mount Jefferson	10,495	Earlier than about 40,000(?) years ago.	Lava flows	None; may be extinct.	Future eruptions in the vicinity are most likely to be from smaller adjacent volcanoes, last active about 6,400–6,500 years ago (Harris, 1980).
Three Sisters	10,085 (North Sister); 10,047 (Middle Sister); 10,358 (South Sister).	Possibly within the last 1,000 years.	Lava extrusion summit area (South Sister).	None known	A cluster of closely grouped, glacier-clad large volcanoes in an area of many smaller young volcanic cones (Williams, 1944; Harris, 1980).
		Less than 2,500(?) years ago.	Flank eruptions of lava and pyroclastic deposits (South Sister).		

TABLE 1.—*Activity of major Cascade Range volcanoes*—Continued

Volcano	Summit altitude (ft above sea level)	Times of eruptions [1]	Nature or products of eruptions [2]	Present thermal activity	Remarks and references
		Oregon—Continued			
Newberry Volcano	7,985 (Paulina Peak).	About 1,400 years ago.	Lava flows, tephra.	Hot springs in eastern crater lake. Volcano is promising prospect for deep-seated thermal energy.	Actually about 40 miles east of the Cascade Range. A broad shield volcano with a large summit crater occupied by two lakes. One of the region's largest volcanoes before its explosive eruption and collapse (Williams, 1935; Harris, 1980).
Crater Lake (Mount Mazama)	8,156 (Hillman Peak).	At least 800–900 years ago.	Explosive eruptions that built Wizard Island and two other cones (submerged) on present crater floor.	None	From a probable altitude of roughly 12,000 ft, the top of former Mount Mazama was lost to eruption and collapse that left the present huge crater and the deepest lake (1,932 ft) in North America (Williams, 1942; Harris, 1980).
		About 6,600 years ago.	Very explosive eruptions producing region-wide ashfall and extensive pyroclastic flows.		
Mount McLoughlin	9,493	About 1,500–2,000(?) years ago.	Lava flows	None	(Harris, 1980)
		California			
Mount Shasta	14,161	During about the last 200 years.	Pyroclastic flows, hot mudflows, cool mudflows.	Two small fumarole areas on the summit dome; one has a small acidic hot spring.	Has erupted an average of about once every 600 years during the last 4,500 years. Future eruptions very likely from vents at or near the present summit but could also occur at new vents almost anywhere in the vicinity of Mount Shasta (Miller, 1980).
		About 700 years ago.	Pyroclastic flow.		

TABLE 1.—*Activity of major Cascade Range volcanoes*—Continued

Volcano	Summit altitude (ft above sea level)	Times of eruptions [1]	Nature or products of eruptions [2]	Present thermal activity	Remarks and references
		California—Continued			
Lassen Peak	10,457	1914–1921	Violent explosions; pyroclastic flows; lava flow; steam and ash; mudflows; lava dome formation.	Small steaming fumaroles in summit craters; hot ground on northern flank.	One of youngest major Cascade volcanoes. Most of the mountain is a single mass of dacite rock, emplaced in a relatively short time. Only volcano in the 48 conterminous United States, besides Mount St. Helens, to have erupted during the 20th century (Macdonald and Katsura, 1965; Harris, 1980).

[1] Nearly all dates before the mid-1800's are subject to some uncertainty, earlier dates being more uncertain than later ones. Uncertainty is indicated, in accordance with listings in referenced reports, by (?).

[2] Products are those associated with the eruptions listed in the preceding column; other volcanic rocks and related deposits were involved in earlier cone-building phases.

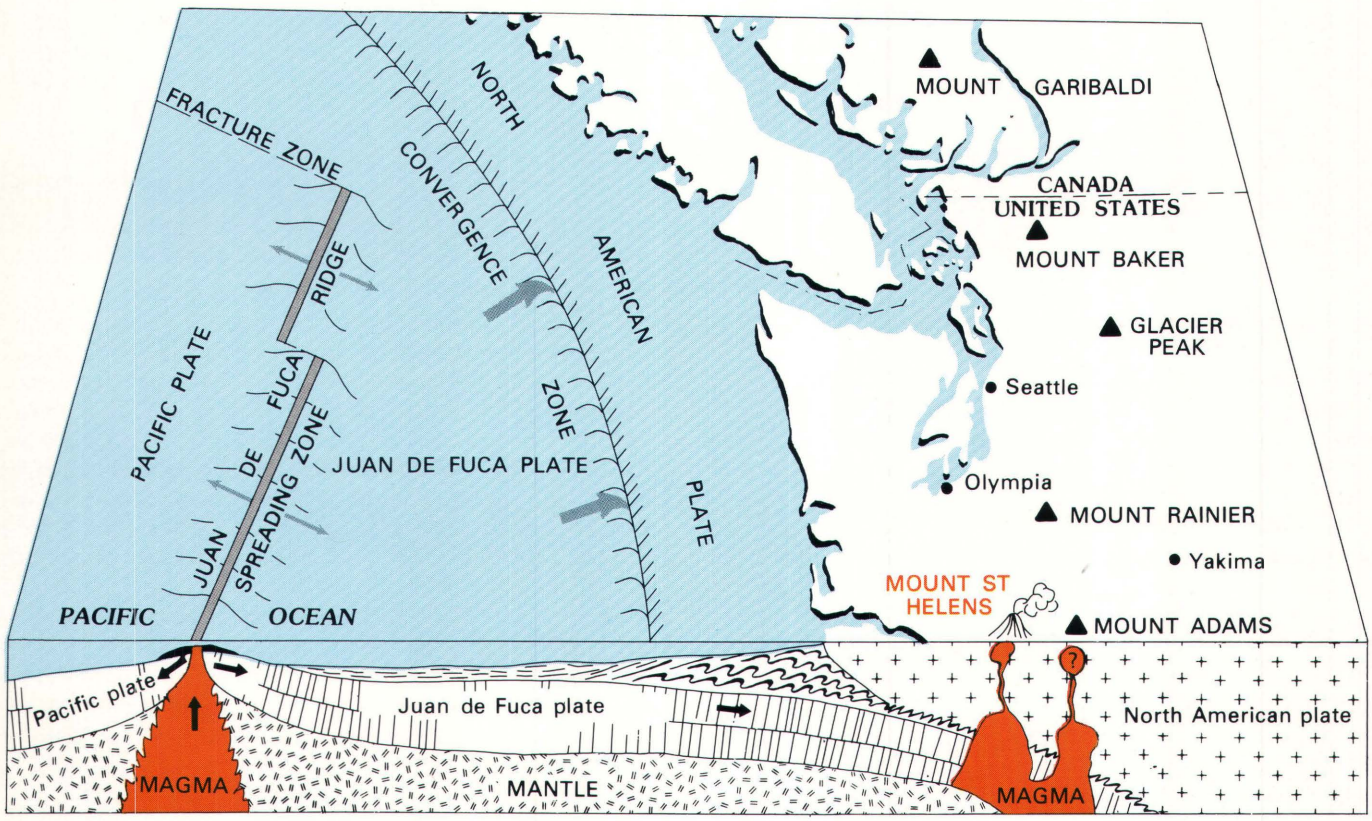


FIGURE 2.—The Juan de Fuca crustal plate is slowly thrusting under the North American plate and into the hotter mantle layer, as this greatly simplified diagram shows. This process results in the formation of magma and probably also causes the zones of weakness in the North American plate through which magma rises to feed Cascade volcanoes. As the Juan de Fuca plate moves northeastward (relative to the mainland) at a rate of perhaps 1 inch a year, new rock material is added by volcanic extrusion in the Juan de Fuca Ridge spreading zone. (Data from Atwater, 1970; Srivastava and others, 1971; Riddihough, 1978.)

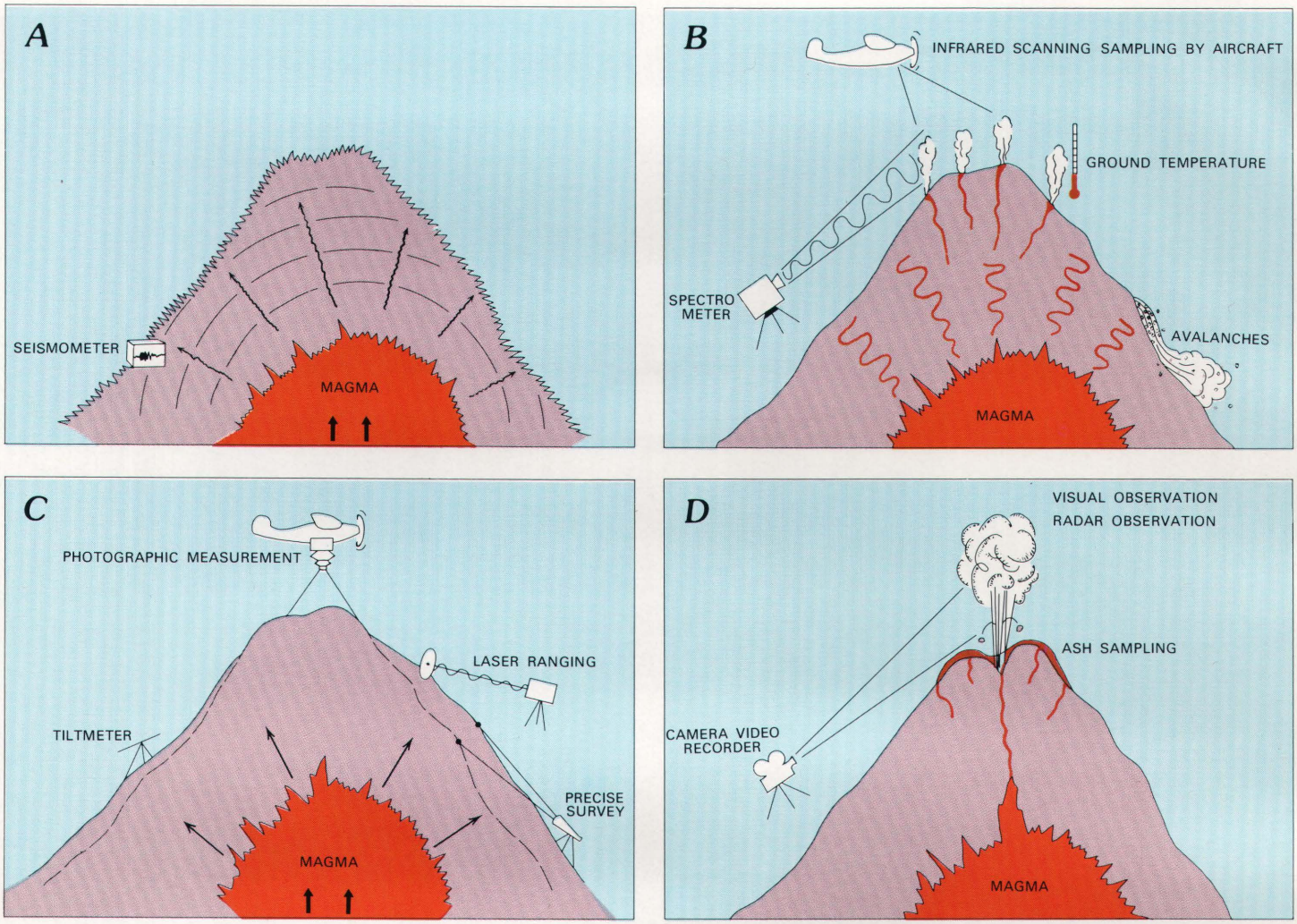


FIGURE 3.—Typical warning signs of possible increase in volcanic activity and some ways in which they can be detected and monitored. In addition to the phenomena shown, slight variations in local gravity or magnetism often are related to changes in volcanic activity. None of these clues tells for sure whether or when a volcano will erupt. *A*, Earthquakes caused by magma intrusion, measured by seismometers; may be felt by people nearby. *B*, Increased heat and gas emission; may be detected from visible fuming, water-quality changes in streams draining from the volcano, or unusual increases in streamflow or avalanches. May be measured with ground-level temperature instruments, by sampling at fumaroles, by spectrometer scanning (to determine gas contents), and by infrared (heat) scanning and gas sampling from aircraft. *C*, Inflation caused by magma intrusion; may be measured by tiltmeters and by sequences of photographs, precise optical surveys, and laser-electronic distance measurements that span the period of inflation. *D*, Steam-driven (phreatic) eruptions of old rock and ash; monitored by visual observation, radar observation, photography and video recording, and by studies of the ejecta.

the volcanoes and to the amount of gas contained in the magma. Magma from the more explosive volcanoes contains relatively large amounts of gas and silicon and produces rocks such as ***andesite***, ***dacite***, or ***rhyolite.*** Magma from the less explosive volcanoes contains smaller concentrations of gas and silicon and produces ***basalt*** as well as andesite. Some Cascade volcanoes, including Mount St. Helens, have had nonexplosive eruptions of andesite and basalt, as well as explosive eruptions, in the past.

The existence, position, and recurrent activity of the Cascade volcanoes are generally thought to be related to the convergence of shifting crustal plates (figs. 1 and 2). The Juan de Fuca plate and the Gorda plate are oceanic crustal plates that apparently are slowly but inexorably thrusting under the North American plate at a rate of perhaps 1 inch a year along a convergent margin that generally parallels the northern Pacific coast. Although the deep structural relationships are complex and not thoroughly understood, the presence of magma bodies beneath the Cascade Range, as well as the zones of structural weakness along which the magma rises to form the Cascade volcanoes, probably is related

to the convergence of these crustal plates. The diagrammatic cross section (fig. 2) shows the relationship between the Juan de Fuca plate and the North American plate and the source of magma for Cascade volcanoes.

Lava eruptions occur when magma, formed many miles beneath the Earth's surface, moves upward through zones of weakness in the crustal rock layers and is ejected from surface vents. Tilling (1977, p. 37) described the processes leading up to a typical eruption: ". . . magma is fed from depths into a [magma] reservoir [analogous to air filling a balloon], the internal pressure increases, and the surface [rock] layers are pushed upward and outward in order to accommodate the swelling, or inflation. The net effects of such inflation include: the steepening of slope of the volcano's surface; increase in horizontal and vertical distances between points on the surface; and, in places, the fracturing of the [rock] layers stretched beyond the breaking point. Such rupturing of materials adjusting to magma-movement pressures results in earthquakes." The earthquakes, inflation, and related phenomena can be monitored by several methods (fig. 3), and such monitoring provides the best available guidance about the state of volcanic activity and associated hazards. Although this concept of internal volcanic processes was developed through years of research on volcanoes in other parts of the world, the foregoing description is generally applicable to the sequence of the Mount St. Helens eruptions.

MOUNT ST. HELENS BEFORE 1980

Mount St. Helens was known as "the Fuji of America" because its symmetrical beauty was similar to that of the famous Japanese volcano (fig. 4*A*). The graceful cone top, whose glistening cap of perennial snow and ice dazzled the viewer, is now largely gone. On May 18, 1980, the missing mountaintop was transformed in a few hours into the extensive volcanic ash that blanketed much of the Northwestern United States and into various other deposits closer to the mountain.

Even before its recent loss of height, Mount St. Helens was not one of the highest peaks in the Cascade Range. Its

FIGURE 4.—*A*, Aerial view of Mount St. Helens from the west in October 1977. The symmetry of the cone and its snow cover gave the volcano its nickname, the "Fuji of America," because of its similarity in appearance to the famous Japanese volcano. Mount Adams is in the background. (Photograph by Dee Molenaar, USGS.) *B*, View of Mount St. Helens from Goat Marsh Lake, 5 miles southwest of the peak, in 1978. (Photograph by Dwight R. Crandell, USGS.)

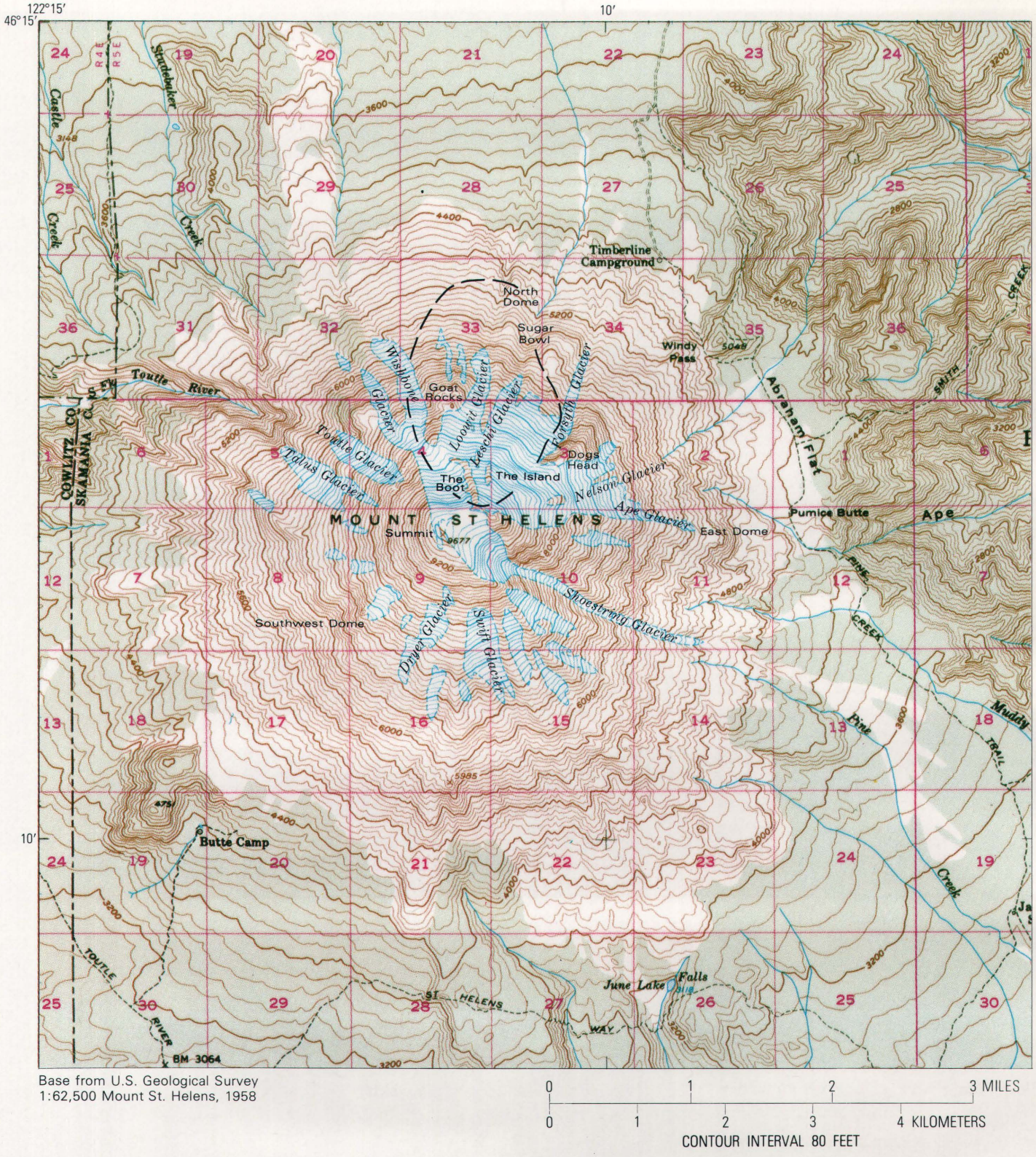


FIGURE 5.—Map of pre-1980 Mount St. Helens showing named features referred to in the text. The shaded area surrounding the peak indicates the approximate extent of timber in 1958, much of which had been logged by 1980. The dashed line encloses the part of the north-side slope that became the unstable bulge area. By 1980, Timberline Campground had been closed and replaced by a public viewpoint about a quarter of a mile to the east (see figs. 7 and 18).

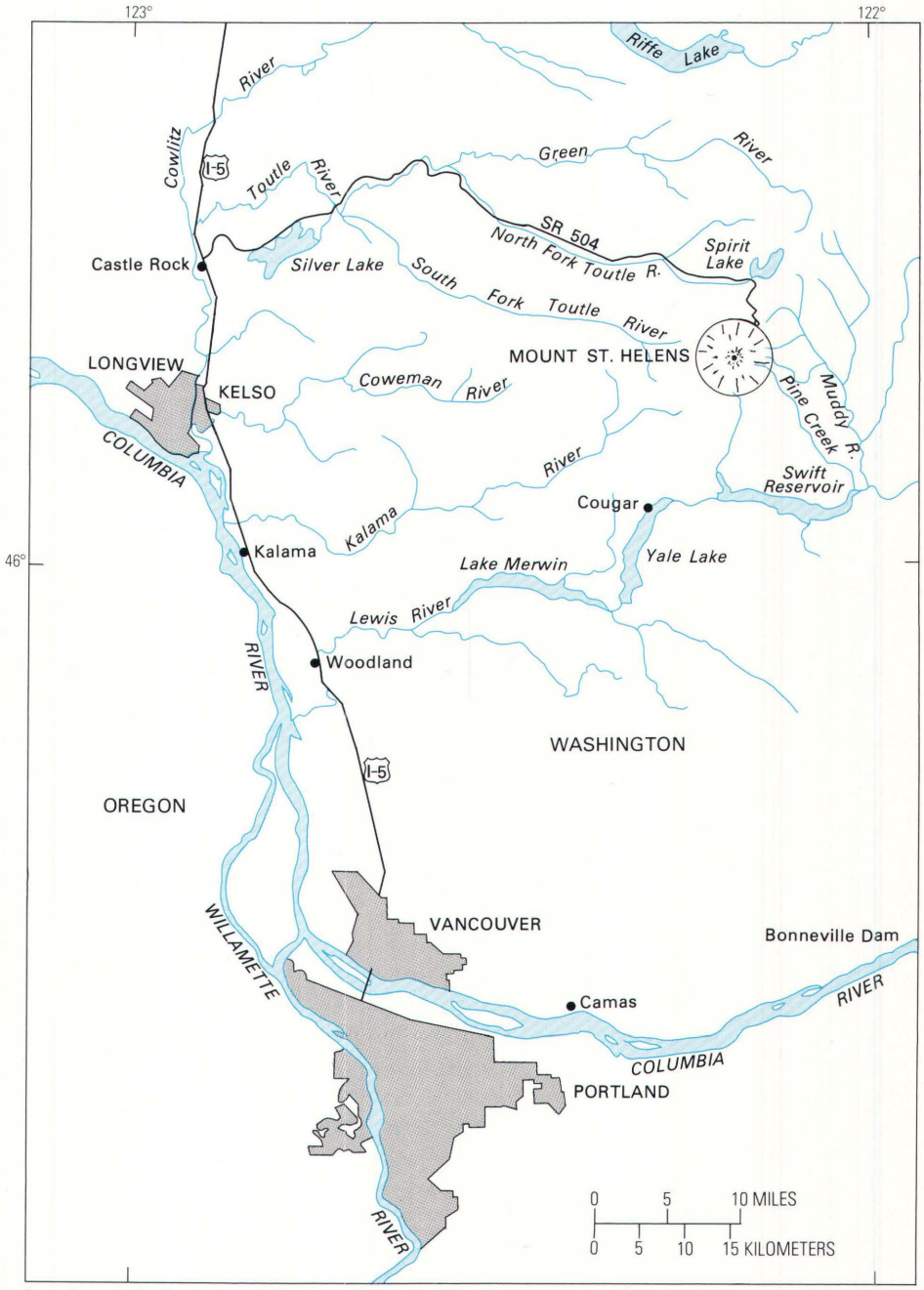
summit altitude of 9,677 feet made it only the fifth highest peak in Washington (table 1). It stood out handsomely, however, from surrounding hills because it rose thousands of feet above them and had a perennial cover of ice and snow (fig. 4*B*). The peak rose more than 5,000 feet above its base, where the lower flanks merge with adjacent ridges. The mountain is about 6 miles across at the base, which is at an altitude of about 4,400 feet on the northeastern side and about 4,000 feet elsewhere. At the preeruption timberline (upper limit of trees), the width of the cone was about 4 miles (fig. 5).

Mount St. Helens is 34 miles almost due west of Mount Adams, which is in the eastern part of the Cascade Range (figs. 1 and 4*A*). These "sister and brother" volcanic mountains are each about 50 miles from Mount Rainier, the giant of Cascade volcanoes. Mount Hood, the nearest major volcanic peak in Oregon, is about 60 miles southeast of Mount St. Helens.

Mount St. Helens was named for British diplomat Alleyne Fitzherbert (1753–1839), whose title was Baron St. Helens. The mountain was named by Commander George Vancouver and the officers of H.M.S. *Discovery* while they were surveying the northern Pacific coast from 1792 to 1794.

Mount St. Helens was recognized as a volcano at least as early as 1835; the first geologist apparently viewed the volcano 6 years later. James Dwight Dana of Yale University, while sailing with the Charles Wilkes U.S. Exploring Expedition, saw the peak (then quiescent) from off the mouth of the Columbia River in 1841. Another member of the expedition later described "cellular basaltic lavas" at the mountain's base.

Although Mount St. Helens is in Skamania County, the best access routes to the mountain run through Cowlitz County on the west. State Route 504 (fig. 6), which formerly ended at Timberline Viewpoint (fig. 7) 2.6 miles from the summit, connects with the heavily traveled Interstate Highway 5 about 34 miles to the west.



Base from U.S. Geological Survey
State base map, 1:500,000 unedited advance print 1981

FIGURE 6.—Sketch map showing selected streams, population centers, and other features in relation to Mount St. Helens.

That major north-south highway skirts the low-lying cities of Castle Rock, Longview, and Kelso along the Cowlitz River (fig. 6) and passes through the Vancouver, Wash.–Portland, Oreg., metropolitan area less than 50 miles to the southwest. The community nearest the volcano is Cougar, which is in the Lewis River valley about 11 miles south-southwest of the peak. Gifford Pinchot National Forest surrounds Mount St. Helens, but some land on the mountain and much of the area adjacent to the national forest are Washington State lands or are privately owned.

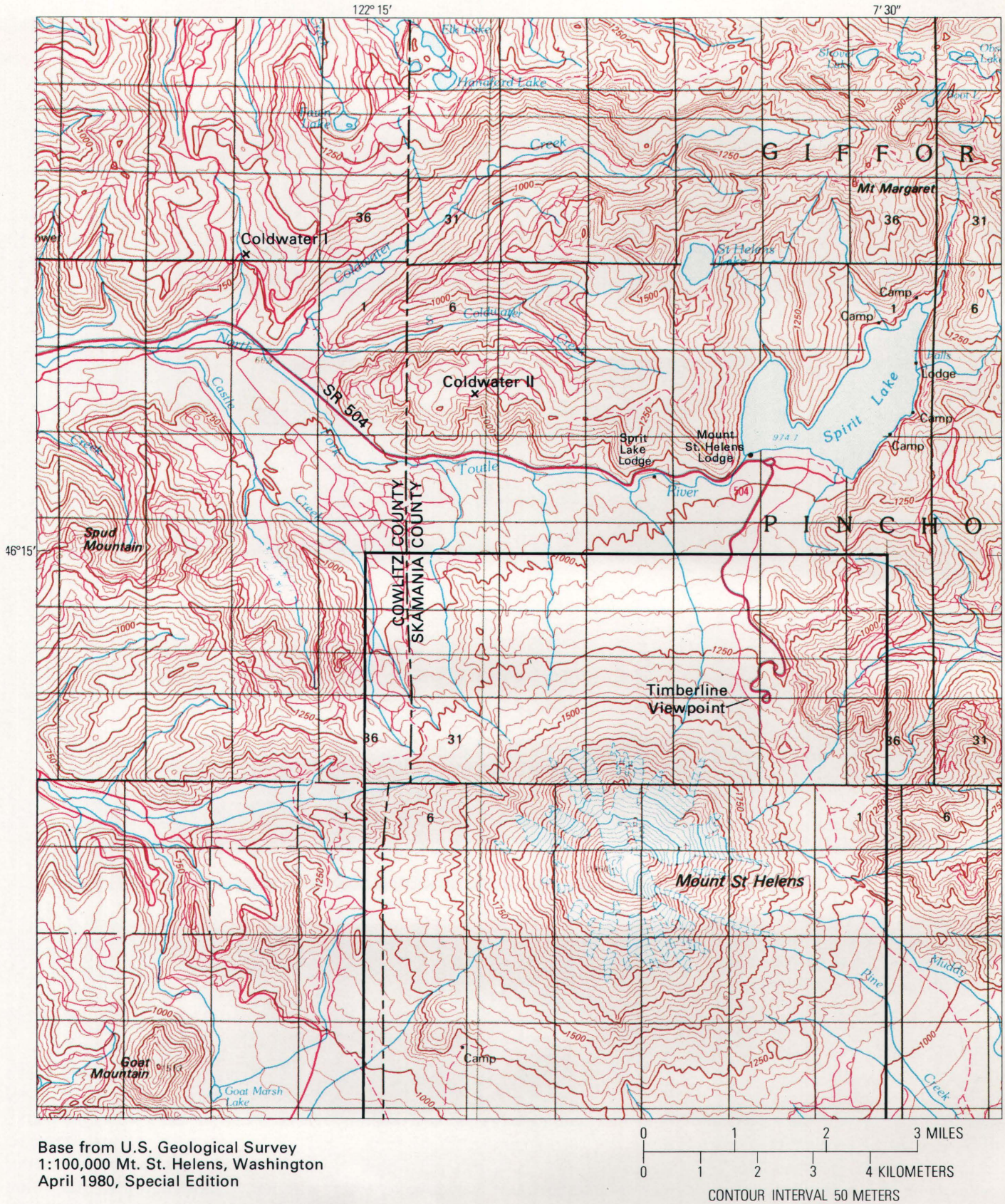


FIGURE 7.—Map showing Mount St. Helens and vicinity before the 1980 eruptions. The heavy line indicates the area shown in figure 5.

Streams that head on the volcano enter three main river systems—the Toutle River on the north and northwest, the Kalama River on the west, and the Lewis River on the south and east (fig. 6). The streams are fed by abundant rain and snow that dump an average of about 140 inches of water on Mount St. Helens a year, according to National Weather Service data. The Lewis River is impounded by three dams for hydropower generation. The southern and eastern sides of the volcano drain into an upstream impoundment, the Swift Reservoir, which is directly south of the volcano. The streams that drain the mountain also are somewhat regulated naturally by the mountain's perennial snowfields and glaciers (blue-contoured white areas on fig. 7; see names on fig. 5). Water is stored as snow and ice during the cool, wet periods and is released as melt water during warmer, drier periods.

Water-related recreation has been one of the major activities in the area. All three reservoirs on the Lewis River (fig. 6) have been used extensively for recreation, as was Spirit Lake (fig. 7) before 1980. Before the eruption, Spirit Lake was impounded in the North Fork Toutle River valley by a natural dam formed chiefly of deposits from one or more ancient mudflows (table 2). The principle resource of the region is timber, and many areas near the volcano had been logged recently and were still being logged at the beginning of the 1980 eruptive activity.

Mount St. Helens, like most other Cascade volcanoes, is a great cone of rubble consisting of lava rock interlayered with ***pyroclastic*** and other deposits. Volcanic cones of this internal structure are called composite cones or stratovolcanoes. Mount St. Helens includes layers of basalt and andesite through which several ***domes*** of dacite lava have erupted. The largest of the dacite domes formed the previous summit; another formed Goat Rocks on the northern flank. Figure 8 is a diagrammatic section through preeruption Mount St. Helens showing the inferred relationship of the former summit dome to the lava layers and the interbedded rubble. Information about previous eruptions is given in table 2.

TABLE 2.—*Summary of volcanic events and deposits formed at Mount St. Helens during the period of about 3,000 years before the 1980 eruptions (after Crandell and Mullineaux, 1978; Hopson and Melson, 1980)*

[Eruption dates in the 1800's generally agree with eyewitness accounts summarized by Harris (1980). All dates A.D. unless indicated otherwise]

Date	Event or type of deposit
1857	Last-reported eruptions before 1980; no resultant deposit has been recognized
About 1847 to 1854	Steam and ash; no recognizable deposits
1842 to 1844(?)	Dacite pumice (extending northeast of volcano); followed by dome of dacite (Goat Rocks), glowing avalanches, hot and cool mudflows, and andesite lava flows (north-northwestern and south-southwestern flanks).
1831 and 1835	Steam and ash; no recognizable deposits
About 1800 to 1802	Dacite pumice
Between 1600 and 1700	Voluminous flows of andesite lava from flank vents on all four sides of the mountain; pyroclastic flows on northern and southwestern sides; mudflows from summit area.
About 1500 to 1600	Thick, extensive dacite pumice; at least three pyroclastic flows down Kalama River valley; andesite lava flows; hot and cool mudflows, some reaching Spirit Lake; growth of Summit Dome (dacite), followed by glowing avalanches on south-eastern, southern, southwestern, and west-northwestern flanks.
800 (±200 years)	Strong flank explosion, laterally directed on the northeast, followed by the growth of a dacite dome (Sugar Bowl).
300 (±200 years)	Pyroclastic flows; extrusion of dacite dome (East Dome); lava flows
50 (±100 years)	Voluminous basalt lava flows on southern and southwestern sides
Between about 700 and 100(?) B.C.	Pyroclastic flows; lava flows; mudflows extending from southeastern and southern sides of mountain.
Between 1200 and 700 B.C.	Sequence of extensive pyroclastic flows and mudflows, some reaching Spirit Lake and into North Fork Toutle River valley; several mudflows reached the present site of Castle Rock; dacite dome formed.

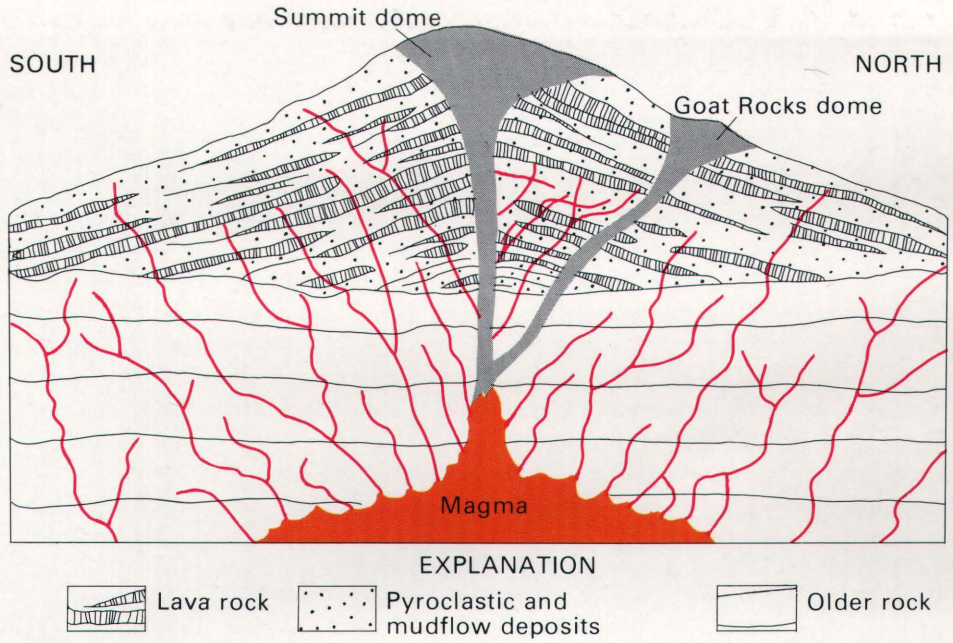


FIGURE 8.—Mount St. Helens is a composite volcano, or stratovolcano, built of alternating layers of lava rock and pyroclastic debris. This cross section of the pre-1980 volcano shows the generalized relationships between the layers of the volcano's cone, the lava dome (emplaced about 1600 A.D.) that formed the summit, and the north-flank dome called Goat Rocks, which formed during the 1840's (table 2). For simplicity, the magma chamber as shown here is much shallower, in relation to the mountain's height, than it actually is thought to be.

PERCEPTION AND WARNING OF THE HAZARDS

The death toll from the May 18 eruption undoubtedly was greatly lessened by the timely dissemination of reliable scientific information about the volcano and the hazards that it presented and by public and private use of that information in response to those hazards. The volcanic hazard information was derived from geologic studies of Mount St. Helens and other Cascade volcanoes and from monitoring the volcano visually and by various geophysical methods. This information was widely spread in written reports and news releases, briefings of public officials and news reporters, replies to thousands of individual telephone inquiries, and the formal announcement of a "Hazards Watch" and subsequent updates by the USGS. Responsible officials reacted to that information by taking steps that significantly reduced public exposure to the risks. These steps included restricting and eventually prohibiting access to lands identified as being within zones of relatively high risk and lowering the water level in Swift Reservoir (fig. 6).

Although historical accounts of eruptions during the 1800's (table 2) suggested the possibility of renewed volcanic activity at Mount St. Helens, the foundation of scientific information that allowed realistic evaluation of the hazards was laid over several decades. Because the volcano has long been a favorite of climbers and naturalists, the two areas of fumaroles and warm ground known before 1980 had been documented as early as 1939 in a report on the flora of the mountain (Lawrence, 1939). The first systematic geologic investigation of Mount St. Helens, begun in the 1930's, was a reconnaissance-type study by Verhoogan (1937). The report was concerned mainly with the character of the rocks that make up the volcanic cone and underlie adjacent areas. Two of Verhoogen's statements were especially pertinent to the recent activity of the volcano. According to Verhoogen (1937, p. 268), "The activity of the volcano seems to have continued without interruption until very recent times. Many [lava] flows cannot be more than a few hundred years old, as evidenced by the vegetation." Further on, he said, "The writer has been told that, until a few years ago, climbers on Mount St. Helens could witness solfataric action [emission of sulfurous gases] and hot springs. Today [1937] the mountain is completely ***dormant***."

Later geologic studies verified the relative youthfulness of volcanic deposits from Mount St. Helens, and geologists most familiar with the Cascade volcanoes gradually became aware of the unusual potential hazards posed by the volcano. The geologic record of past eruptions was sufficiently well documented by 1975 to enable USGS geologists Dwight Crandell and Donal Mullineaux and geochemist Meyer Rubin to warn, in an article in *Science* magazine, that ". . . an eruption [of Mount St. Helens] is likely within the next hundred years, possibly before the end of this century" (Crandell and others, 1975, p. 441).

That judgment was verified in a more comprehensive assessment of the volcanic hazards of Mount St. Helens produced by the USGS in 1978 as part of a broad program for the systematic evaluation of volcanic hazards (see section on "Geologic Hazard Responsibilities"). The results of that assessment were published as USGS Bulletin 1383–C, *Potential Hazards from Future Eruptions of Mount St. Helens Volcano, Washington* (Crandell and Mullineaux, 1978). The report summarized the mountain's volcanic history since the year 2500 B.C. and

showed the extent of the deposits resulting from those events. On the basis of that reconstructed history, as well as prevailing land uses and developments near the volcano, Crandell and Mullineaux described the anticipated effects of future eruptions and included maps showing the hazard zones for various kinds of future eruption results (***ashfalls,*** lava flows, pyroclastic flows, mudflows, and floods). The Crandell-Mullineaux report proved to be remarkably prophetic, differing from the actual eruptive effects of May 18, 1980, mainly in not anticipating such an extensive and devastating lateral blast. Among the accurate forecasts made Crandell and Mullineaux (1978, p. C1) was ". . . we believe [Mount St. Helens] to be an especially dangerous volcano because of its past behavior and relatively high frequency of eruptions during the last 4,500 years." Another (Crandell and Mullineaux, 1978, p. C25) was "If [a typical eruptive] sequence is followed during future eruptions, the greatest potential danger will exist at or soon after the onset of volcanic activity."

Information about the flow and water quality of streams draining the volcano and other streams likely to be affected by eruptions was available from data collected over several decades by the USGS in cooperation with other agencies and utilities. The stream data were collected primarily for water-resource assessment by the USGS and for water management by other cooperating agencies; the data also, however, provided important background information about preeruption stream conditions, including the flood-carrying capacity of the stream channels.

Under the special responsibilities given to the USGS in the Disaster Relief Act of 1974 to warn of geologic hazards (p. 121), the Crandell and Mullineaux (1978) report and a letter discussing its hazard implications were disseminated as a "Notice of Potential Hazard" in December 1978. The report and letter were sent to appropriate Federal and Washington State officials and selected county and local agencies in southwestern Washington. Also, USGS scientists explained the hazard implications of the report during a meeting with key Federal and State officials in Olympia, Wash., on January 8, 1979.

While the assessment of volcanic hazards was being prepared, the volcano was already being monitored to detect early signs of an impending eruption. No one knew what kinds of monitoring techniques would provide the most reliable warning, however, because knowledge about the behavior of Cascade volcanoes in general was limited and because Mount St. Helens had not been active recently. University and USGS studies in the 1970's had monitored Mount St. Helens intermittently by means of three instrumental methods: (1) seismometers that could detect earthquakes caused by the movement of molten rock into a volcano, (2) precise ground-surface measurements that could detect swelling of the volcano, and (3) aerial infrared surveys and surface-temperature measurements of two "hot spots" high on the mountain to detect any changes in heat emission from the volcano (fig. 3). The volcano also was one of many glacier-clad mountains that were photographed routinely from the air to detect changes in snow and ice as part of a USGS glaciology research project. At the beginning of March 1980, the only instrument directly monitoring Mount St. Helens was a seismometer on the western flank of the volcano, from which a record of seismic shaking was automatically transmitted by radio (telemetered) to seismic recorders at the University of Washington in Seattle. That seismometer was one of about 100 seismic instruments deployed in a network throughout western and central Washington by the university's Geophysics Program in cooperation with the USGS.

That seismometer was one of the first instruments to warn, by registering earthquakes on March 20 and thereafter, of impending eruptive activity. When increasing seismic activity suggested the possibility of an impending eruption, University of Washington and USGS scientists at Seattle notified other USGS volcano experts throughout the country and the USGS Hazards Information Coordinator in Reston, Va. Aerial observations were begun as soon as possible. Within a few days, additional geophysical instruments were brought into use, including more seismometers, precision tiltmeters to measure slight changes in the slope of the volcano's flanks, and gravity meters and magnetometers to detect changes in the character of the subsurface rocks. Photographic and heat-monitoring (thermal infrared) surveys from the air were resumed as weather permitted.

After the first eruption on March 27, scientists and technicians intensified their monitoring activities and began sampling and analyzing volcanic gases, volcanic ash, and snow and melt water from and near the volcano. In the following few weeks, they began using laser distance-measuring instruments and other precise surveying equipment to detect small shifts of the volcano's surface. They also expanded an existing network of hydrologic measuring sites to monitor changes in streamflow and water quality on streams draining Mount St. Helens and streams likely to be affected by volcanic ash. These additional stream-monitor sites were intended to help detect (1) any unusual changes in flow, such as sudden increases in melt water that might result from rapid heating of the rocks under ice and snow, and (2) changes in water quality that might be caused by volcanic gases dissolving in the melt water or by materials leached from volcanic ash.

As scientists and information specialists assembled, first in response to the forewarning earthquakes and then because of the early eruptive events, scientists already on the scene at the University of Washington and in Vancouver, Wash., provided

most of the information that was available to local agency officials, the news media, and the general public. In Vancouver, initial information releases were coordinated by the U.S. Forest Service at its administrative headquarters for the Gifford Pinchot National Forest, where an emergency operations center was set up to provide incoming scientists with work space, communications facilities, and other logistical support until such support could be arranged otherwise. This action greatly assisted the newly launched scientific effort and also was instrumental in providing anxious reporters, officials, and the public with the necessary hazard warnings and authoritative information. The USGS also set up its own temporary headquarters in Vancouver under the general guidance of Mullineaux, in close coordination with the Forest Service. Volcanic hazards analysis and interagency coordination were directed by Crandell, and volcanic monitoring and observational investigations were supervised by Robert L. Christiansen.

In the meantime, USGS hydrologists, glaciologists, and technicians operated their stepped-up program of water-related monitoring and data collection from their normal headquarters at Tacoma, Wash., and Portland, Oreg. Studies of Mount St. Helens glaciers were largely directed by Mark F. Meier in Tacoma. Stream surveillance and water-quality monitoring were supervised by Charles R. Collier in Tacoma and by Stanley F. Kapustka in Portland.

After President Carter declared on May 21 that the State of Washington was a disaster area, the Federal Emergency Management Agency assumed responsibility for coordinating the release of information and hazard warnings at a temporary emergency-operations center in Vancouver. Intensive coverage of the volcanic events by the news media, as well as actions by State and local officials based on coordinated information released by scientists, provided most of the warnings and guidance for local residents.

CHRONOLOGY OF THE FIRST 100 DAYS

The following chronology begins with the first telltale earthquake on March 20 and ends during a dome-building phase on June 27. This interval gave rise to countless fascinating stories about the volcanic events and the human responses to those events. This chronology emphasizes the sequence of geologic occurrences and processes as well as the hazard-warning aspects of that historic period, but it also describes other incidents that relate public and agency responses to the volcanic events.

This chronology has been written as if it were an evening journal recounting the events of the day—a method traditionally used by field scientists. Indeed, the major sources for the account that follows were the daily reports of field scientists and other observers who were on the scene as the Mount St. Helens story unfolded.

By far, the most important event of this period was the devastating eruption of May 18, hereafter referred to as "E Day." For the convenience of the reader, all dates in the chronology are referred to that day.

Unusual Earthquakes Begin

Thursday, March 20, 1980
E Day Minus 59

Seismographs at the University of Washington in Seattle registered at 3:37 p.m. today the first sizable earthquake to shake Mount St. Helens since recording devices were installed in 1972. The quake was distinctly felt near the volcano. It measured ***magnitude*** 4.1 on the Richter scale, was followed by many aftershocks, and originated at shallow depth from a point immediately northwest of the summit of Mount St. Helens. That quake and the others that followed were unlike any earthquake sequence ever recorded in the Northwest.

The initial quake differed from other such earthquakes in the Cascade Range because of its unusually shallow origin (how shallow is yet unknown) and its many aftershocks. A telephone call from the University of Washington seismology center notified the USGS regional office in Menlo Park, Calif., of the earthquake and the unusual persistence of its aftershocks.

Only one telemetered seismic station (linked to university recorders by radio) is operating in the area, but the decision was made to install additional seismometers immediately. Coincidentally, four of the instruments already in shipment to Seattle arrived this evening.

Friday, March 21
E Day Minus 58

Evidence of aftershocks persisted this morning in the record being transmitted by the Mount St. Helens seismic station, and telephone advisories between the Forest Service, USGS, and the University of Washington were stepped up. Forest Service officials in Vancouver telephoned a report of yesterday's earthquake to personnel of the USGS Volcanic Hazards Project in Denver, Colo. Scientists at the University of Washington seismology center contacted the Forest Service in Vancouver for assistance in locating additional seismic stations (because of snowy conditions) and were told that the earthquakes had caused large avalanches yesterday on Mount St. Helens. The seismology center staff also notified the USGS Menlo Park office that yesterday's main shock had a very shallow source, which was indicated by the reported avalanches, the character of the recorded shock waves, and the fact that the earthquake was so strongly felt nearby.

Working together, USGS and University of Washington scientists in-

stalled four additional seismic stations near Mount St. Helens. Three of these stations (one each a few miles east, north, and south of the volcano) are designed to begin recording as soon as they detect a shock and to continue operating unattended for 5 days unless they are reset. The other station, about 20 miles to the northeast, will automatically transmit electronic signals of earth movements to the seismology center in Seattle.

Seismologists expect that the additional instruments will help to define the geologic processes that caused the shocks. Those processes, they believe, involve fairly ordinary crustal movement along subsurface faults.

Saturday, March 22
E Day Minus 57

A second earthquake greater than magnitude 4 occurred today, together with many smaller ones similar to those occurring on Thursday. Seismologists decided that this event was not a single large quake with smaller aftershocks but an earthquake swarm consisting of many separate events.

Scientists at the University of Washington advised the Forest Service's avalanche warning center in Seattle (as they advised the Vancouver office yesterday) that the possibility of continuing earthquake-triggered avalanches on Mount St. Helens was high. A field trip has been arranged for tomorrow to collect records from the 5-day recording instruments in the hope of determining a more precise location for today's major quake.

Sunday, March 23
E Day Minus 56

Visits to the seismic stations near Mount St. Helens today were frustrating. All three recording seismographs installed on Friday were not working properly, two because of bad batteries. Thus, no records are available from them to help pinpoint the source of yesterday's large shock.

Meanwhile, seismic data being received at Seattle show a sharp increase in earthquake activity. Five quakes greater than magnitude 3 were recorded today, including (shortly after 8 p.m. tonight) the third one greater than magnitude 4. Seismologists in Seattle have decided that this earthquake sequence may be a forerunner of volcanic activity, and they will alert Denver Volcanic Hazards Project personnel tomorrow morning.

Monday, March 24
E Day Minus 55

Observers flying over the volcano today were unable to detect obvious signs of increased volcanic or new thermal activity, but they did note a number of snow avalanches triggered by the continuing earthquakes.

Seismic activity continues to increase. Ten earthquakes greater than magnitude 3 were recorded from the Mount St. Helens area; 4 were greater than magnitude 4, and the strongest was magnitude 4.7. The University of Washington seismology center is now being staffed 24 hours a day.

Seismologists added another seismic station to the USGS–University of Washington network monitoring the volcano, reinstalled one of the failed recorders, and made plans for future additions. They also advised USGS Volcanic Hazards Project personnel in Denver, as well as the USGS regional headquarters in Menlo Park, Calif., and the Forest Service Vancouver office, that a "tremendous increase in seismicity" has been observed and that the seismic records are indicating a volcanic earthquake sequence. The University of Washington and the Forest Service immediately began asking the public to stay away from Mount St. Helens and Spirit Lake. The USGS Hazards Information Coordinator in Reston, Va., was advised that the earthquakes near Mount St. Helens were showing a "classic preeruption pattern," a behavior seen previously at Japanese volcanoes.

David Johnston, a USGS volcanologist from Menlo Park, Calif., who was vacationing in the Seattle area, visited the seismology center and stayed on to help handle the rapidly accumulating seismic data.

Tuesday, March 25
E Day Minus 54

Seismic activity increased greatly again today, when as many as 5 earthquakes of magnitude 4 or greater were recorded in 1 hour (22 during one 8-hour period). At this rate, recorder traces of earthquakes even as large as magnitude 3.5 are buried in the continuations of traces of previous quakes.

This sharp increase in the number and magnitude of earthquakes has prompted USGS geologist Mullineaux to leave Denver for Forest Service headquarters for the Gifford Pinchot National Forest in Vancouver, where an interagency meeting about Mount St. Helens has been scheduled for tomorrow. Mullineaux will stay on to direct the USGS study of the volcano.

The Forest Service announced that national forest areas on the mountain above the tree line (or timberline; fig 5) have been closed, along with the information center at Spirit Lake, and warned residents near the mountain of the danger of earthquake-induced avalanches. The closed area ranges from less than 2 miles to nearly 4 miles from the summit. The Skamania County Sheriff's office closed the main highway into the north-side area, State Route 504 (fig. 7), at a point even farther away—about 5 miles northwest of the peak. Many national forest roads also were closed.

News reporters and photographers have flocked to the mountain. The Federal Aviation Administration has imposed special flight restrictions near the volcano because of the number of aircraft carrying scientists, reporters, and other observers for a close look.

Bud Kimball, a commercial aerial photographer, reported to USGS scientists in Tacoma that he had photogaphed a large crack in the snow and ice across the top of Mount St. Helens.

Wednesday, March 26
E Day Minus 53

Extensive cloud cover hid the mountain from view all day.

The University of Washington seismology center this evening registered the 100th quake of magnitude 3.5 or larger in the Mount St. Helens area since March 20. Today, 7 earthquakes of magnitude 4.0 or greater occurred—many less than the 25 recorded yesterday. Most of these quakes originated at relatively shallow depths of about 3 miles or less below the land surface.

Additional recording equipment was installed at the seismology center to handle the saturation of seismic data from the telemetered stations. Data processing and attempts to locate earthquakes' origins are now round-the-clock efforts.

A meeting of Federal, State, and county emergency-services officials was held today in Vancouver. USGS scientists explained their interpretations of the seismic events and potential hazards. An emergency coordination center was set up by the Forest Service at its Vancouver headquarters.

In spite of the earthquakes and news reports, some residents do not believe that an eruption is possible. Said one, according to the Associated Press, "It's just . . . cooked up by the Federal forestry service for them environmentalists to delay a big development of the Spirit Lake recreation area. That's my opinion."

Ash Eruptions Begin

Thursday, March 27
E Day Minus 52

USGS officials today issued a formal "Hazards Watch" announcement to more than 300 State and Federal officials, representatives of other agencies, and the local congressional delegation.

At 11:20 a.m., an observer in an Army National Guard reconnaissance airplane reported seeing a hole in the icecap on the mountain near the summit and a gray streak (presumably ash) extending southeast from the hole. No emissions from the hole were reported at that time. Then, at about 12:30 p.m., people near the volcano heard a loud boom. This boom probably marked the first sighted eruption, which took place during cloudy weather. Mike Beard, a reporter from a Portland radio station, was flying over the cloud-shrouded mountain and apparently was the first to report seeing the eruption. He is quoted as saying that he " . . . saw ash and smoke spewing out, a little like smoke out of a chimney. It was not explosive. . . ."

At 2:00 p.m., the University of Washington seismology center recorded a magnitude 4.7 earthquake, the second strongest to date. The quake was one of 57 during the day to register magnitude 3.5 or greater. (Earthquakes have become so common in the Mount St. Helens area that a half dozen quakes greater than magnitude 4 are considered normal for a day.) After this magnitude 4.7 shock, the eruption, as described by airborne observers, was a thick black plume rising about 7,000 feet above the volcano.

Observers flying over the mountain shortly afterward saw a crater about 200 to 250 feet wide near the summit (fig. 9). They also noted that the ice, snow, and rocks around the crater were deformed and that volcanic ash had darkened the snow in a band that extended across the crater and down the cone's southeastern slope. Two crack systems trending east-west were seen extending across the peak. The southernmost crack is about 1 mile long; it turns north on both the eastern and western sides of the summit and reaches short distances down the northeastern and northwestern flanks of the mountain.

Within hours of the initial eruption, hundreds of people were evacuated from logging camps, scattered homes, and public facilities in the area. Emergency-services officials advised residents within a 15-mile radius of the mountain to leave. Forest Service employees and their families left the ranger station at the head of Swift Reservoir. About 300 loggers moved out of three Weyerhaeuser Company logging camps near the volcano, as did 20 people from the State fish hatchery on the North Fork Toutle River, about 30 miles downstream from the volcano. Skamania County Sheriff's deputies moved 45 people, mostly newsmen and scientists, from the Spirit Lake area. Cowlitz County law-enforcement officers evacuated people farther downstream along the Toutle River. Deputies from both counties set up roadblocks on several main routes to keep out the curious. The Washington Department of Emergency Services distributed to residents of the town of Cougar information sheets suggesting that they "pack an overnight bag" and be ready to move quickly.

One longtime resident, Harry Truman, proprietor of the Mount St. Helens Lodge at the southwestern end of Spirit Lake, refused to leave in spite of strong urging to do so.

The evacuations were spurred by two major concerns. One is that the cracks across the summit resulted from a slumping of the ice field on the upper northern flank of the volcano, which may increase the danger of major avalanches. The other is that widespread flooding and mudflows might result if heat from the volcano melts the mountain's mantle of snow and ice. By evening, however, USGS hydrologists reported that none of the streams that drain the volcano's slopes was rising.

More scientists have been arriving at the Vancouver coordination center to study phenomena such as earthquake activity, deformation of the volcano surface, composition of volcanic gas and ash, heat emissions, and changes in the quantity and quality of melt water (fig. 3).

Friday, March 28
E Day Minus 51

Another explosive eruption began about 3:00 a.m. today and lasted near-

FIGURE 9.—On March 27, 1980, observers saw Mount St. Helens erupt for the first time in 123 years. The eruption, which was preceded by a loud "boom," left a single crater, 200 to 250 feet across, in the snow and ice that capped the volcano's cone. The snow around the crater was coated with volcanic ash, a material that was to become all too familiar to many residents of the Northwest. The view here is from the north. (Photograph by Austin Post, USGS, March 27, 1980.)

ly 2 hours. Although observations were hampered by bad weather and darkness, a cloud of ash and steam was seen by airborne observers to rise "more than a mile" above the volcano, and an ***ash cloud*** cascaded slowly down its eastern flank.

By dusk, at least a dozen other eruptions lasting from a few minutes to nearly an hour had occurred. Columns of steam and ash at times reached nearly 10,000 feet above the volcano and drifted eastward. An eruption just before sunset threw out not only ash but also rocks that ranged in size from a few inches to about 3 feet across. A short time later, volcanic ash was falling in a wide swath east of the volcano. It was reported as far away as Trout Lake, about 35 miles to the southeast.

Several mud-darkened avalanches of snow and ice moved down the eastern flank of the mountain; a few extended down to the 6,400-foot level. Because of their dark color, some observers mistook them for lava flows or mudflows, an error that added to concerns about flood hazards in the valleys of streams draining the mountain.

Earthquake activity remains about the same. Eight events of magnitude 4 or greater took place today; the strongest earthquake to date, which occurred shortly after midnight this morning, registered 4.9 in Seattle. Geophysicists report that the earthquakes are centered beneath the volcano at a depth of less than 1 mile.

Scientists from the University of Washington Cloud Physics Research Group flew over the volcano to collect samples of the emanating gases. They found that sulfur dioxide, which is associated with high temperatures, was the main sulfur gas present. This discovery was the first indication that a high-temperature source inside the mountain is releasing gas during eruptions. The presence of sulfur dioxide in the gases is of special interest because its content is usually low in geothermal steam but relatively high in gases emanating from magma.

Despite the bad weather and frequent eruptions, scientists in a helicopter flew to the 4,000-foot level of the volcano to collect ash samples for analysis to determine whether the volcanic ash was coming from new magma or from pulverized old rock.

University of Puget Sound scientists began making gravity measurements at sites near the volcano to detect any changes that might be related to intrusion of magma.

USGS water specialists began collecting water-quality data systematically from sites around Mount St. Helens and in the direction of prevailing winds from the volcano. They also began installing additional water-quality monitors near the volcano.

The Pacific Power and Light Company has been releasing water from its Swift Reservoir to two reservoirs downstream; the water level in the Swift consequently was about 20 feet below capacity today. The objective was to create storage space to accommodate rapid snowmelt runoff or mudflows that might be caused by eruptions. A USGS report (Crandell and Mullineaux, 1978) had pointed out that Swift Reservoir, the closest one to the volcano, was both a danger and a margin of safety—a danger if floods were to overtop it, a margin of safety if it could be used to hold back sudden floods or mudflows.

Sightseers jammed possible evacuation routes with their vehicles and tried to evade roadblocks to get closer views of the volcano. Officials of the Washington Department of Emergency Services have implored curiosity seekers to keep away from potential danger areas.

Yesterday, volcanologist Johnston left his volunteer duties at the University of Washington seismology center in Seattle for Vancouver to join the field studies at the volcano. In an interview today with reporters at Timberline Viewpoint, he likened the mountain to dynamite with a lit fuse; " . . . but you don't know how long the fuse is," he said.

Mountaintop Cracks and Craters Grow

Saturday, March 29
E Day Minus 50

The weather cleared today, and airborne observers noted a second, larger crater west of the first (fig. 10). Sporadic eruptions of steam and ash were now coming mainly from this new crater.

Clouds of erupted ash and steam that swept slowly down the mountain (fig. 11) sometimes were accompanied by lightning flashes, some of them 2 miles long. Scientists speculated that the ground-hugging lightning bolts were caused by rock particles in the ash cloud rubbing together to produce electrostatic discharges, much as static electricity is sometimes generated by walking over a rug.

The first USGS analyses of volcanic ash showed that the ash is composed of pulverized old rock propelled into the air by steam eruptions. There was no evidence of "juvenile" rock material (from the magma) that would indicate the presence of the magma at shallow depth in the volcano.

The explosive eruptions to date are ***phreatic eruptions***, attributed mainly to subsurface water coming into contact with very hot rocks that are being heated by the magma beneath. When the water reaches boiling temperature, it expands suddenly and violently into steam. Rapid expansion of other gases, such as carbon dioxide, also may contribute to these eruptions.

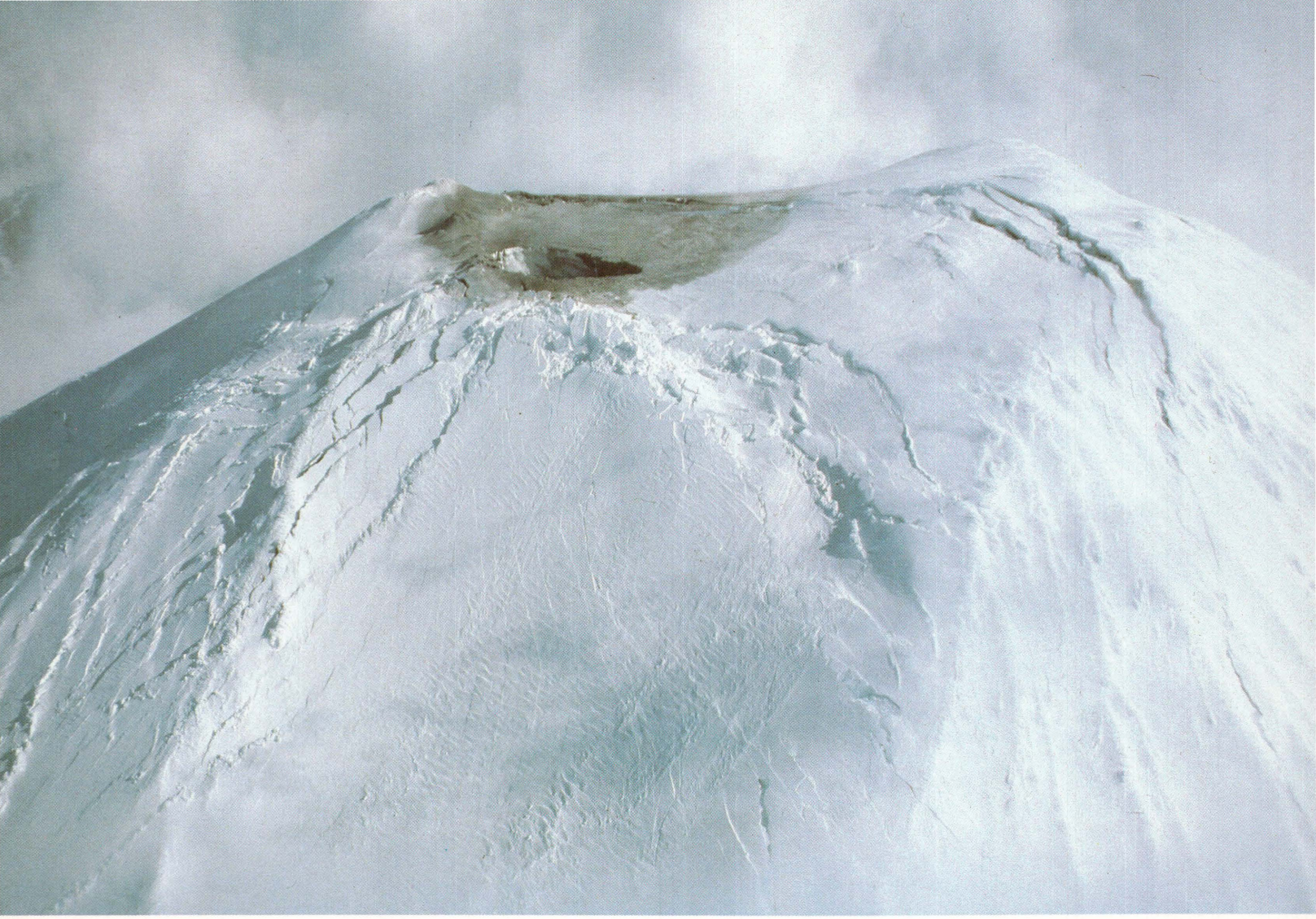
Earthquakes recorded today in the Mount St. Helens area included 39 ranging in magnitude from 3.5 to 4.4, part of a total of 86 that exceeded magnitude 3.

Field crews installed the first tiltmeter station, which will help to measure the surface deformation of the volcano. A tiltmeter network is planned, in conjunction with the use of precise distance-measuring instruments, so that changes in the volcano's shape—particularly swelling that might indicate upward movement of the magma (fig. 3)—can be detected.

USGS hydrologists continue to monitor the streams closely but have detected no unusual increases in streamflow. Stream-water quality also has remained stable, except at sampling sites on two streams southeast of Mount St. Helens, both about 40 miles from the mountain and in the path of ash from yesterday's eruptions. Water acidity, hydrologists have found, increased slightly at those sites; the pH, an index of acidity or alkalinity, went from about 7 (neutral) to 6 (slightly acid). (The pH returned to normal within 2 days.)

FIGURE 10.—The sight of two craters instead of one greeted airborne observers as clouds lifted over Mount St. Helens on March 29, 1980, after more than a day of bad weather and frequent eruptions. At night, blue flames, probably from burning hydrogen sulfide gas, were flickering within the old crater (left) or jumping from crater to crater. The view here is from the north. (Photograph by David Frank, USGS, March 30, 1980.)

FIGURE 11.—Erupted plumes of ash and steam (and minor amounts of other gases) were carried from the crater by winds and sometimes streamed down the flanks of Mount St. Helens for considerable distances. Spectacular displays of lightning occasionally were generated in these ground-hugging plumes by charges of static electricity built up when ash particles rubbed against one another in the turbulent cloud. This photograph was taken from the northwest by David P. Dethier (USGS) on April 8, 1980.



Some tourists admitted to reporters that, despite roadblocks, they had evaded the barriers and gone closer to the mountain but could not see the volcano because of the cloud cover.

Sunday, March 30
E Day Minus 49

The first major eruption of the day was reported at 4:10 a.m. By 7:40 a.m., a huge anvil-shaped cloud of steam and ash had formed; drifting to the southeast, it produced light ashfalls miles away. Fine gray volcanic ash was reported at Stevenson, Wash., about 25 miles south of the volcano, and officials were concerned about the effects of the ash on the quality of the Bull Run River, the main water source for Portland. Five later eruptions sent ash more than 1 mile above the twin craters. Altogether, observers counted 93 eruptions of steam and ash from the volcano today.

Last night, airborne observers could see a flickering blue flame burning within the old crater or jumping from crater to crater. Volcanologist Johnston reasoned that the blue flame meant that a flammable gas was being emitted. Possible gases were hydrogen, hydrogen sulfide, methane, or carbon monoxide, the most likely being hydrogen sulfide. (The flame disappeared on April 2 before scientists could determine the exact composition of the gas.) Burning gas has been observed previously above lava flows and lava lakes in other volcanic regions but not in craters before the appearance of lava.

Seismographs at the University of Washington recorded 58 earthquakes of magnitudes greater than 3.0, including 6 above 4.0.

A group from Dartmouth College in Hanover, N.H., began remote monitoring of sulfur dioxide (SO_2). Early results showing that the volcano is emitting SO_2 at the rate of 0.3 tons a day verify the March 28 identification of the gas, which is typically found in emanations from magma. This measurement also shows that Mount St. Helens at present is not a major source of sulfurous air pollution. (For comparison, some large coal-burning powerplants may emit more than 100 tons of SO_2 a day.)

In the afternoon, as many as 70 aircraft reportedly were flying around the volcano at the same time, and strict air-traffic control was necessary to prevent aerial collisions.

Monday, March 31
E Day Minus 48

Shifting winds sent ash from the volcano's frequent eruptions toward different, more densely populated areas today. By noon, the Kelso-Longview area, about 40 miles west of Mount St. Helens, was lightly dusted by ash. No juvenile rock material has been seen in the ash at month's end.

Airborne observers reported that the twin craters are both growing and have nearly merged.

The frequency of earthquakes near the volcano slackened, although an increase in the number having magnitudes greater than 4.3 suggests that the total energy release remains about the same.

Tourists, who earlier had been disappointed by bad weather and roadblocks around the mountain, have been penetrating the closure boundary during the good weather at the end of March ". . . until it appeared," wrote Bill Stewart in the Vancouver *Columbian*, "that there was a competition to see who could get closest. Some people [in helicopters] actually landed on the crater rim and climbed inside." One group wearing camouflage clothing climbed to the top and filmed scenes intended for a documentary movie—and for beer commercials.

Tuesday, April 1
E Day Minus 47

Clouds shrouded the lower part of the mountain, as they do much of the time, but the top was clear enough for aerial observations. Several eruptions of ash and steam made clouds that reached as high as about 20,000 feet—10,000 feet above the peak. Light ashfall was reported on the outskirts of Vancouver, and the village of Cougar, 11 miles southwest of the volcano, received somewhat larger amounts. Some observers believe that these eruptions are the strongest since the volcano reawoke last month.

USGS scientists reported that a huge wedge (***graben***) of ice-capped rocks, including the crater area, has settled at least 200 feet downward between the systems of major cracks crossing the mountaintop (see fig. 14). This settling has caused a noticeable outward displacement, or bulging, of the rocks and glacier ice north of the crater. Airborne observers noted that the two summit craters are now essentially a single crater more than 600 feet across. At least two new steam vents also were spotted in the crater area.

Last night and early this morning, seismographs recorded three of the strongest quakes to date—two with magnitudes of 4.6 and one of 4.7. This afternoon, another of magnitude 4.6 occurred.

Between 7:25 and 7:30 p.m., the first weak ***harmonic tremor*** was noted on the seismograms at the University of Washington seismology center. It was an undulating ground movement of the kind typically associated with the underground movement of magma (fig. 12). (Although harmonic tremor has preceded and accompanied volcanic eruptions in Hawaii, it may occur without being followed by an eruption.)

Volcano experts are saying that the possibility of eruptions involving magma seems to be increasing. Their evidence includes the stronger earthquakes accompanied by harmonic tremor; the new steam vents and the more vigorous eruptions, which may reflect a general heating up of the volcano; and the presence in the gas samples taken last Friday of sulfur

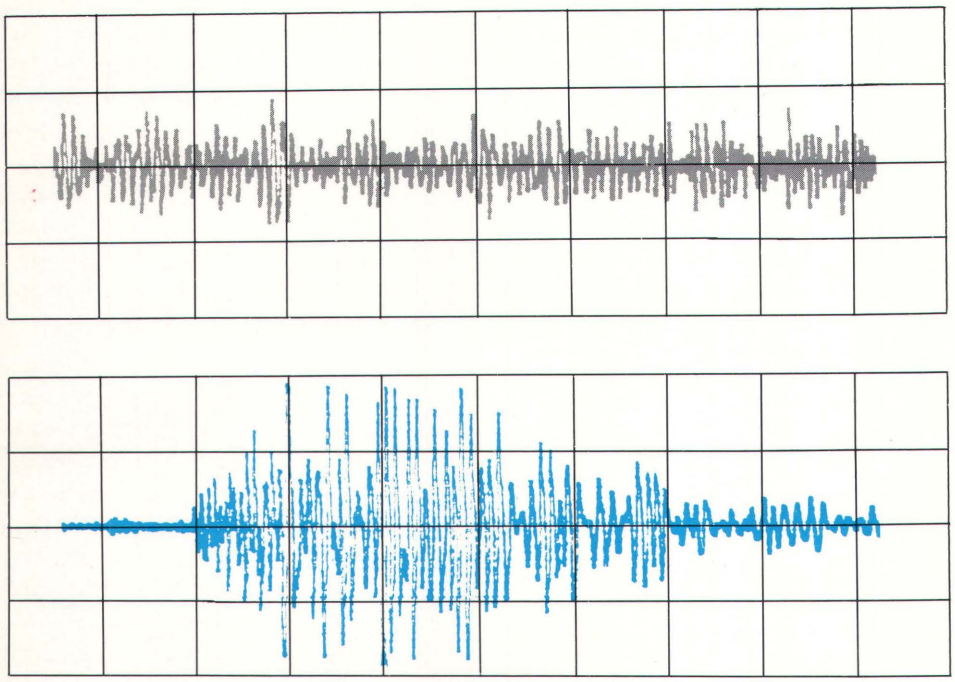


FIGURE 12.—Seismograph traces comparing harmonic tremor (top) to normal earthquake pattern (bottom). (Data from the University of Washington Geophysics Program.)

dioxide, which shows that a high-temperature source for the gas exists within the mountain. A magmatic eruption may not occur soon, however, and its onset cannot yet be predicted.

Scientists are eager to get new aerial photographs looking straight down on the mountain to compare with similar vertical photographs taken in 1979. Comparison of the two sets of photographs will help to determine the physical changes that the mountain has undergone during the last few months. A U-2 reconnaissance plane took high-altitude pictures of the volcano today, but the images were unsatisfactory because clouds obscured too much of the area.

Representatives of the University of Washington Geophysics Program and the USGS field headquarters have decided to install a computer link between the seismology center in Seattle and the Vancouver facility to improve the exchange of scientific data and to speed warnings of earthquake-related hazards.

April 1, which usually marks the start of the mountain-climbing season, finds Mount St. Helens closed to climbing. Spirit Lake, which (by Forest Service records) averages 658,000 "visits" a year, is also closed. Farther from the mountain, however, about 300 loggers have returned to their jobs on and near the lower flanks of Mount St. Helens and at Camp Baker, some 15 miles northwest of the peak (fig. 13).

Officials of Cowlitz and Skamania Counties have decided, because of limited county budgets and small law-enforcement staffs, that they must ask the Washington National Guard to help maintain the roadblocks around the volcano. Sheriffs' deputies from both counties have been manning roadblocks across several main access roads west and south of the mountain around the clock since last Thursday, the day of the first eruption.

The restricted zone (fig. 13) is not difficult to enter because the mountain is crisscrossed by dirt logging roads. One official estimated that, instead of the 6 roadblocks being maintained by Cowlitz County, as many as 29 barriers requiring about 180 officers would be needed to completely block the mountain roads.

Nolan Lewis, Cowlitz County Emergency Services Director, was quoted today in the Tacoma *News Tribune*: "I just can't fathom it," he said. "People are swarming in from all over, putting their lives in danger. . . Sunday, when the weather was clear, the road up to the mountain looked like downtown Seattle at rush hour."

Wednesday, April 2
E Day Minus 46

A stronger burst of harmonic tremor was recorded by many seismographs in the Mount St. Helens area between about 7:35 and 7:50 a.m. This burst confirmed the recognition of the harmonic tremor of yesterday and is the best indication to date that magma is moving beneath the mountain. (Seismologists later determined that short episodes of harmonic tremor also occurred on March 31 and earlier this morning.)

The number of earthquakes greater than magnitude 3.0 increased to 63 today, reversing the decreasing trend of the past 3 days. Five of the quakes were stronger than magnitude 4.0; one was 4.8, among the strongest of the volcanic sequence to date. (Today was to be the most active day, for earthquakes stronger than magnitude 3.0, during the month of April.)

At least a dozen major eruption plumes shot above the mountain, one reaching an altitude of more than 20,000 feet. Large boulders and "blocks of undetermined matter" (rock or ice) were thrown out of the crater during one 30-minute eruption in midafternoon. A light ashfall left small amounts of ash on automobiles in Vancouver and Portland.

The Forest Service's Pine Creek Ranger Station, south of the volcano, was closed permanently today. It had been evacuated on March 27.

Asked about the likelihood of an explosive eruption—one that would hurl rock and lava from the mountain —Mullineaux replied that it was the

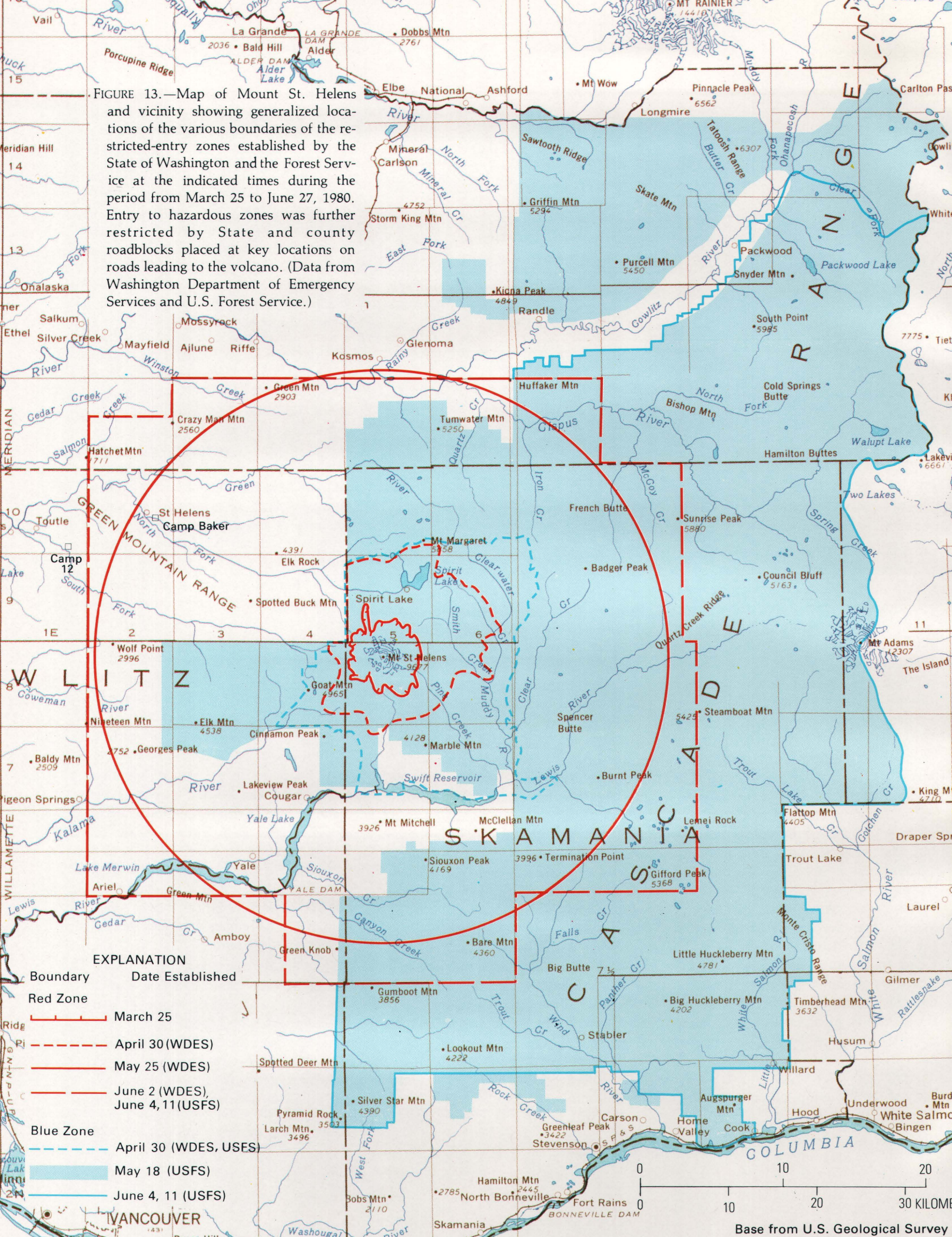


FIGURE 13.—Map of Mount St. Helens and vicinity showing generalized locations of the various boundaries of the restricted-entry zones established by the State of Washington and the Forest Service at the indicated times during the period from March 25 to June 27, 1980. Entry to hazardous zones was further restricted by State and county roadblocks placed at key locations on roads leading to the volcano. (Data from Washington Department of Emergency Services and U.S. Forest Service.)

least likely of the volcano's possible actions. "A series of small eruptions would be more likely than a large, cataclysmic event," he said.

State of Emergency

Thursday, April 3
E Day Minus 45

Washington Governor Dixy Lee Ray today declared a state of emergency and set up a "Mount St. Helens Watch Group." Local officials in both Washington and Oregon issued leaflets prepared by the Federal Emergency Management Agency entitled "What To Do During a Volcano Ashfall." The leaflet gives advice on the dangers of ashfalls, mudflows, and floods.

Seismographs recorded six earthquakes of magnitude 4.0 and greater, the strongest of which was 4.6. Two more bursts of harmonic tremor occurring this evening indicate continued movement of magma beneath the mountain. The total duration of harmonic tremor—33 minutes—is more than double last evening's 15-minute episode.

Airborne observers reported that the crater has enlarged to a diameter of about 1,500 feet and a depth of about 300 feet. Plumes of steam and ash billow from the crater almost hourly. Traces of volcanic ash fell in and near Tacoma, about 70 miles north of the mountain.

Friday, April 4
E Day Minus 44

Two episodes of harmonic tremor 27 and 32 minutes in duration were recorded by seismographs today, as were five earthquakes stronger than magnitude 4.0 and many weaker quakes.

Governor Ray called out the National Guard to share duties at roadblocks around Mount St. Helens. Only property owners and scientists are to be allowed inside the blockaded zone.

In an effort to protect sightseers and to keep them out of the way, Washington State officials moved one roadblock on State Route 504 about 20 miles farther from the mountain and established a major public viewing area near Ridgefield, Wash., about 40 miles from the volcano.

Loggers and truckers are urging county officials to let them resume work in the restricted zone, and they have offered to sign waivers releasing public officials from liability for any volcano-related casualties. An attorney for several logging companies argued that loggers should be able to make their own choice about entering and working in the restricted zone, "since they make their living in the woods and are familiar with the dangers," according to a story in the *Seattle Post-Intelligencer.*

No measurable radioactivity was found in the volcanic ash during radiological testing reported today by the Washington Department of Social and Health Services. According to State health officials, there is no reason to believe that the small amounts of ash that sometimes drift beyond the immediate vicinity of the volcano are dangerous to people in good health.

Most scientists believe that the greatest hazard currently posed by the reawakened volcano is the possibility of flash floods or mudflows, especially those that might enter Swift Reservoir and cause a massive overflow and flood surge into the downstream channel and reservoirs.

USGS hydrologist David Frank set up a time-lapse movie camera to take color pictures of the periodically erupting volcano. The camera, designed to expose one frame of film after each preset time interval, was installed on a logged-off ridge accessible only by logging roads, 8.4 miles northwest of the volcano's summit. The site overlooks the North Fork Toutle River near the mouth of Coldwater Creek and affords an unobstructed view of Mount St. Helens. It also is high enough to be safe from even the largest mudflow that might result if the ice and snow were melted by the volcano's heat. The site was selected a few days ago as a scientific observation post, and a tent was set up to shelter observers. Additional instruments, including another time-lapse camera, will be installed within the next few days. Scientists refer to the observation site as "Coldwater" (later called "Coldwater I"; see fig. 7).

Saturday, April 5
E Day Minus 43

At least three eruptions today sent ash to altitudes of about 15,000 feet, and scientists using airborne measuring devices detected low concentrations of sulfur dioxide in the plume. Only four earthquakes today reached magnitude 4.0 or greater. Harmonic tremor occurred for 16 minutes shortly before noon.

Sixty Washington National Guardsmen took up duties this morning at four roadblocks on major routes to Mount St. Helens. They immediately moved two of the roadblocks farther away from the mountain to allow them better control of side roads leading to the volcano and to place some of the most congested (and therefore potentially most dangerous) viewing spots off limits.

Scientists and technicians have been working long hours in the field under difficult and often risky conditions. When the weather permits, some are flown by helicopter from Vancouver to various places on the mountain or to nearby sites such as Timberline Viewpoint or Spirit Lake (fig. 7), depending on their scientific specialty or work assignment. If expensive helicopter support is not available, investigators must drive to the area, usually by way of State Route 504 through the valley of North Fork Toutle River, from headquarters in Seattle and Tacoma as well as in Vancouver. Ground travel away from the vehicles usually involves

trudging through deep snow. Heavy rain or snowfall, often accompanied by bitter wind, is common in the area. When bad storms hit, fieldworkers use tents and umbrellas to shelter sensitive instruments during the measurements. Fieldwork includes visiting instrument sites to change batteries and calibrate instruments already in place or to install additional instruments; photographing the widening crevasses in the upper glaciers; making measurements of gravity and magnetic field with portable instruments; and sampling and measuring fumarole gases, volcanic ash, and the flow of streams draining from the mountain. Some of the work must be done on avalanche-prone slopes while the upper parts of the mountain are hidden in clouds. At such times, the sudden, strong earthquakes can be startling. During good weather, helicopters ferry scientists from one site to another during the day and return them to Vancouver in the evening. The helicopter flights are made during the daylight hours, but the long drives to and from the area often begin and end in darkness. Workers from Vancouver then conduct evening conferences to review the day's activities. Fourteen-hour working days are common; clockwatching is mainly for timing scientific observations and resetting instruments.

Most scientists, however, prefer the hardships and long hours in the field to remaining at the Vancouver center and being besieged by news reporters, who persist in asking questions that the scientists cannot answer about what the volcano will do next.

Sunday, April 6
E Day Minus 42

Although clouds, rain, snow, and occasional "mud rains" containing ash hampered visibility today, they did keep away much of the expected crowd of sightseers. The Spirit Lake area received 6 inches of new snow. Scientists termed the few eruptions of ash and steam as "insignificant."

Earthquake activity around Mount St. Helens was about the same as it has been in the last few days—hundreds of quakes of magnitude 3 or less, 54 greater than magnitude 3, and 6 of magnitude 4.0 or greater. No harmonic tremor was recorded today, however.

Scientists found the ash to be 3 inches thick on the eastern flank of the mountain at the 5,000-foot level.

In an interview with *Seattle Times* reporter Hill Williams, USGS geologist Crandell explained that scientists really do not know what to expect from the volcano because information about actual eruptions of Cascade Range volcanoes is limited and because the eruptive history of Mount St. Helens is different from that of other Cascade volcanoes. "Mount St. Helens has done so many different things in the past that hardly anything would be a surprise," Crandell said. "The only thing it hasn't done is blow itself apart."

Monday, April 7
E Day Minus 41

For the first time, observers today got a clear view of a vent in the floor of the enlarged crater and saw a single circular "throat" at least 20 feet in diameter in the deepest part of the floor (fig. 14*E*). The crater, which has been enlarging progressively since March 27, is now about 1,700 feet long (east to west), 1,200 feet wide, and 500 feet deep. Airborne observers reported ponds of muddy water, large enough to float chunks of ice, in depressions in the crater floor. The ponds are fed by melt water from the crater walls and a capping of ice 30 feet thick on the crater's rim. The water reportedly disappears with each eruption, but more water accumulates again soon after an eruption subsides. Two of the ponds have short streams draining from them into the crater bottom. This is the first report of substantial ponding in the crater.

Overall seismic activity at Mount St. Helens continues at about the same level. Although the number of earthquakes greater than magnitude 3 declined slightly today, the activity included one event of magnitude 4.7 and one of 4.6. A 15-minute episode of harmonic tremor occurred, the first in 2 days. Most quakes were clustered beneath the volcano at depths ranging from 0.5 to 3 miles. A plot of earthquake epicenters since March 20, completed today by scientists from the University of Washington Geophysics Program, showed a heavy concentration of quake locations under the northern slopes of Mount St. Helens.

Scientists installed a new tiltmeter in the parking lot at Timberline Viewpoint, 2.6 miles northeast of the crater (fig. 7). The snow there, 3 feet deep in places, hampers the work of scientists who are using various kinds of geophysical instruments to detect changes in the shape and subsurface makeup of the mountain. The snow surface is coated with volcanic ash, and pits dug in the snow show alternating layers of ash and snow that have fallen during the last 12 days.

Tuesday, April 8
E Day Minus 40

One long, single eruption, visible for more than 5 hours, was first seen at 8:22 a.m. and continued until at least 2:00 p.m. today.

During the eruption, a hole opened in the ice at the head of Wishbone Glacier (fig. 5), near the northwestern rim of the crater, and melt water from the surrounding ice poured into the hole for several minutes to form a pond. Then the rim cracked, the water disappeared, and a slice of the upper Wishbone Glacier caved into the crater, enlarging the crater's northwestern side by more than 300 feet. For several minutes after the cave-in, airborne observers noted an especially heavy concentration of dark ash in the eruption cloud.

On calm days, the white clouds of steam from the volcano sometimes rise nearly 10,000 feet above the crater rim,

and they often resemble thunderheads. On windy days, the steam is carried out laterally from the crater. At times, winds direct the clouds downslope on the leeside of the cone as a ground-hugging plume that deposits ash as it moves (fig. 11). A pattern of black scallops on the slope of the volcano often marks the lower limit of these downslope plumes.

There is still much uncertainty and speculation about what the volcano will do next. Some news reporters complain that they get a different idea or view from each scientist interviewed, depending on his background and specialty. Most scientists prefer to withhold judgment until they have more data to help them decipher the volcanic events.

Wednesday, April 9
E Day Minus 39

Cloud cover prevented scientists from observing the mountain today, either from the air or the ground, but light ashfalls near Timberline Viewpoint and Spirit Lake and the odor of sulfur marked at least three eruptions.

An apparent decrease in seismic activity, begun yesterday, continued today. Yesterday, only 38 earthquakes greater than magnitude 3 were recorded, 4 of which reached or exceeded magnitude 4. Today's totals were 37 and 6, respectively. No harmonic tremor was recorded either day. (This general level of seismic activity was to continue throughout April. Most days this month saw less than 40 events stronger than magnitude 3 and less than 10 events of magnitude 4 or greater.)

The new tiltmeter installed near Timberline Viewpoint started sending to Vancouver continuous records that are expected to show any deformation of the mountain's northern flank.

The Forest Service officially designated Mount St. Helens as a "Geological Area," an area that is protected from land-use changes because of its geologic importance.

Thursday, April 10
E Day Minus 38

Clouds covered the mountain most of the morning, but they cleared enough for aerial observation by early afternoon. Several major and minor eruptions of steam and ash occurred at irregular intervals, most of them lasting no more than a few minutes.

A fresh snowfall last night, as yet unsullied by ash on the southern side of the peak, gave residents and tourists to the south much the same view of the mountain that has existed for more than a century. Fracturing and slumping on the upper northern side, however, are causing cracks in the ice cap that are much too large to be hidden by the fresh snow.

The progressively enlarging crater now measures about 2,000 by 1,200 feet. Coatings of gray volcanic ash give the northern side of the crater's interior a velvety look, except for some jagged rock outcroppings and scattered huge blocks of fallen rock on the crater floor (fig. 14*E*). The eruptions are confined to a single circular vent, perhaps 30 feet across, in the position of the second (western) crater but now at least 500 feet lower than the opening originally blasted through the volcano's ice-cap on March 27. The position of the first, more easterly crater has been largely obscured by crater growth. To the west of the active vent, however, the presence of a cone-shaped depression in the crater floor, separated from the active vent by a small, sharp ridge, suggests that a third orifice for the eruptions of steam and ash may have been active until recently.

Some of the intermittent eruptions since March 27 have consisted of a single explosion; others have surged upward in pulses. The cloud sometimes consists of three parts: (1) a lower, very dark, ***tephra***-rich finger, (2) an intermediate gray cloud of ash and steam, and (3) an upper cloud of white steam (figs. 14*B, C*). The intermediate part develops from the dark finger and soon roils out in all directions to obscure the finger that feeds it. Blocks of rock and ice occasionally blast through the cloud. As the gray clouds drift downward, thin veils of ash fall from them.

Lobate fingers of several "generations" of ash-darkened snow and ice avalanches reach down to the lower slopes of the mountain. The youngest are darkest and contrast sharply with the stark white of the newly fallen snow.

Harmonic tremor, the first in 3 days, occurred twice today. One episode lasted for 22 minutes, the other for 16.

Gravity has been measured repeatedly at most of the established gravity stations, but, so far, measurements near the mountain have shown little change. Precise instrumental measurements on the mountain often are hampered by rapid, short-term tilting of the ground. Two scientists measuring the gravity at East Dome (fig. 5) felt an earthquake and then watched with fascination as the level bubbles on their gravity instruments moved far offcenter in response to a strong upward tilt of the mountainside above them. This tilt was followed a few minutes later by a puff of steam from the crater, whereupon the bubbles registered a similar tilt in the opposite direction.

Friday, April 11
E Day Minus 37

Good weather returned to the mountain, which continued to erupt intermittently. Airborne observers could see into the crater during a moderate eruption that took place from 6:12 to 6:58 a.m. They saw large blocks of ice being hurled into the air along with ash and steam and also noticed two new steam vents on the northwestern flank of the volcano, just below the crater rim, as well as ponded water on the floor of the crater.

For only the second time since activity began 23 days ago, a magnitude-4.9 earthquake occurred today at 3:51 p.m. This quake and the similar one on

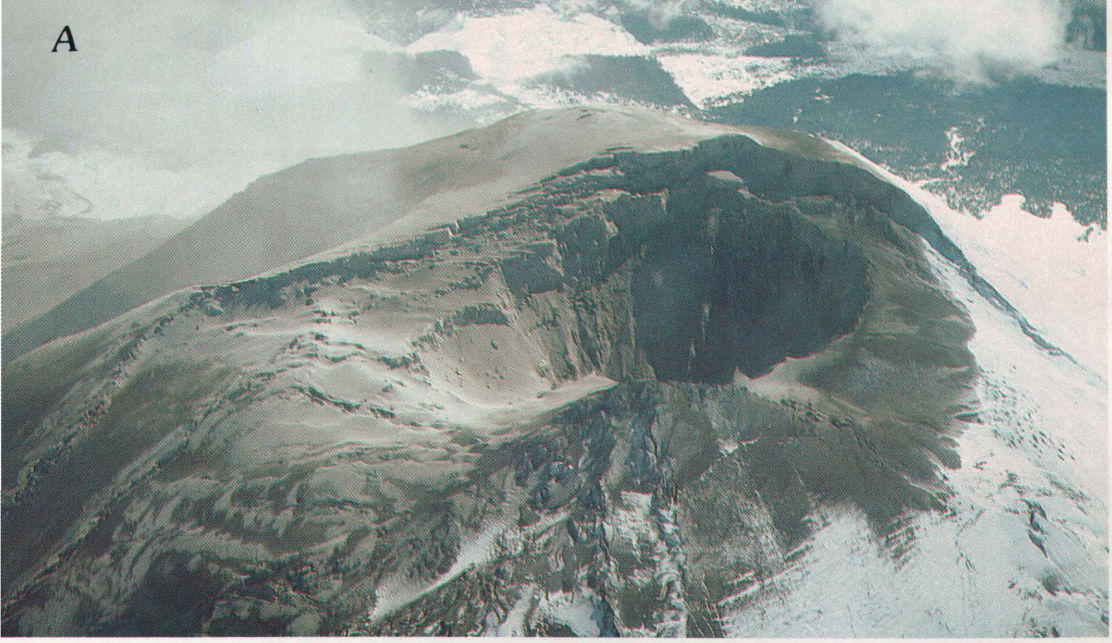


FIGURE 14.—Aerial views of the Mount St. Helens crater and eruptions on April 10, 1980, from the north and northwest. *A*, The oblong crater, enlarged since the merging of two smaller pits, continued to grow with the repeated eruptions and avalanches from the crater walls. The summit graben had slumped noticeably since March 30, as the prominent offset (scarp) along the major crack (fault) on the southern side (back) of the crater shows. (Compare with fig. 10.) (Photograph by John Whetten, USGS.) *B*, The beginning of one of several eruptions observed on April 10. The eruptive cloud often included a lower, very dark, ash-rich finger; an intermediate gray cloud of mixed ash and steam; and an upper, white cloud of steam. (Photograph by Fred Pessl, Jr., USGS.) *C*, These phreatic eruptions seemed to grow in slow motion because of the immensity of the scene. Some were powerful enough to throw out automobile-sized blocks of rock and ice. (Photograph by John Whetten, USGS.) *D*, A moderate-sized eruption cloud obscured the crater as steam and ash drifted eastward. (Photograph by John Whetten, USGS.) *E*, By April 10, eruptions were coming from a single circular vent (shown by an arrow) in the lowest part of the crater and almost directly below the position of the crater first seen on March 29 (fig. 10). Traces of what probably was another, but now-dormant, vent can be seen to the right of the active vent, here steaming weakly. The active vent was about 30 feet across. (Photograph by John Whetten, USGS.)

March 28 have been the strongest of the volcanic earthquakes to date.

The results of tiltmeter measurements on the volcano's northern and eastern flanks are, so far, inconclusive. Although the ground both swells and subsides over periods of minutes or hours, the net change seems to be insignificant.

Signs now have been posted along Interstate Highway 5 notifying motorists of four safe points from which to view Mount St. Helens.

Saturday, April 12
E Day Minus 36

Continued clear weather allowed viewers as far away as Portland to see some of today's many eruptions. Most were small, as activity was less than it has been in the past 2 weeks, but a few larger ash-rich clouds lifted above the crater rim. As the summit crater gradually deepens, eruptive plumes must rise to greater heights in order to be visible above the mountain.

Instruments have detected a slight swelling on the northern flank of the mountain near Goat Rocks (fig. 5), and scientists working on the volcano's flank report fresh, new ground cracks in the swelling area. The clearer weather today made it possible to take aerial photographs so that the shape of the mountain could be compared systematically with its shape as shown on photographs taken last year. Progressive shifting and cracking of the ice on the northern side below the crater are increasing concern that a large mass of ice and rock could break loose and form an avalanche reaching to the valley of the North Fork Toutle River.

A period of harmonic tremor beginning at 2:12 p.m. and lasting until 2:29 p.m. ended with an earthquake of magnitude 4.5. (This harmonic tremor was to be the last recorded for nearly a month.)

USGS Director H. William Menard arrived in Vancouver to observe the volcano and to inspect the scientific instrument installations and data-collection activities.

Officials of Skamania County, in which Mount St. Helens is located, are speculating about how long they can (and can afford to) control access to the mountain. Some question whether it is even appropriate for the county to keep people out against their will.

Sunday, April 13
E Day Minus 35

Between sunrise and sunset today, USGS scientists counted 18 eruptions of steam and ash ranging in duration from a few minutes to 45 minutes.

The recording tiltmeter installed in the parking lot at Timberline Viewpoint showed small but consistent changes, the overall results indicating a slight subsidence of the central part of the volcano relative to the Timberline instrument station. In order to monitor surface tilt more closely, the USGS installed an additional tiltmeter on East Dome at the foot of Ape Glacier.

The number of earthquakes of magnitude 4 or greater increased slightly today; there were nine, the largest number since March 29.

Clear weather brought record-breaking numbers of sightseers to the area from all over the United States and from other countries. This weekend, two television camera crews were airlifted onto the mountain in defiance of closure orders, and unauthorized climbers were also sighted. Forest Service officials warned again that the mountain is not safe and that it is off limits to the press and public above the 4,400-foot level.

Eruptive Activity Decreases

Monday, April 14
E Day Minus 34

Cloudy weather prevented scientists from seeing the volcano, and no new ash fell today. Instruments, however, continue the volcano watch. Seismometers show a continuation of sizable earthquakes but no eruptions. The recording tiltmeter at Timberline Viewpoint showed a shift that may represent additional slight subsidence in the central part of the volcano. The evidence from this one instrument, however, is not conclusive.

Tuesday, April 15
E Day Minus 33

Mount St. Helens became visible by midday for the first time since Sunday, and observers were able to verify that the volcano has slowed its eruptive activity. Only one eruption, near dawn, was seen today. The apparent slight subsidence of the cone has stopped; no change in the ground tilt was recorded by the tiltmeters. Teams are in the field during this lull to collect samples and to try to evaluate the volcano's status.

The Washington Department of Game announced that three popular fishing lakes near Mount St. Helens will remain closed when the regular fishing season opens next Sunday. Officials felt that Merrill Lake, Spirit Lake, and Swift Reservoir, if they were not closed, would add to the temptation to slip around the roadblocks and enter hazardous areas.

Wednesday, April 16
E Day Minus 32

Activity was low again today, although at least nine small steam eruptions and some ashfalls occurred during daylight hours. Seismic activity is lower than it has been at any other time during the month; only 30 earthquakes greater than magnitude 3 occurred today. Three quakes greater than magnitude 4 were recorded during the early morning hours, and two more were recorded this evening. The tiltmeters continued to show no change in ground tilt.

Some erupting volcanoes have shown a marked decrease in activity followed by a dramatic increase in seismic activity just before a major eruption. Scientists have no way of knowing, however, whether Mount St. Helens is experiencing a "lull before the storm" of a magmatic eruption or possibly is in the final part of the eruptive sequence.

A sampling project begun on April 14 ended today as scientists completed taking ash from 30 stations. The samples were taken from accumulated snow so that the ash would not be contaminated by soil.

Thursday, April 17
E Day Minus 31

The summit crater of Mount St. Helens erupted frequently but mildly today; 12 plumes were seen between 7:00 a.m. and 1:30 p.m. Two of them formed vertical columns that extended about 500 feet above the crater rim, but strong winds then carried the plumes away from the summit. In the afternoon, weather conditions prevented observers from seeing clearly into the crater.

Seismic activity remained comparatively low, although two earthquakes of magnitude 4.6 occurred. Scientists took advantage of the relative lull in activity to make a gravity survey around the mountain, to place surveying targets near the summit, and to collect information on the total amount of ash accumulated.

Some fisheries specialists are concerned that accumulating ash washed into the streams by water from the melting snow may harm the valuable fish population in streams near Mount St. Helens. When Mount Baker (fig. 1) suddenly increased its steaming activity in 1975, some of its emanations of gases and "fumarole dust" were acidic. A stream draining the fumarole area of Mount Baker apparently once carried enough acid water into nearby Baker Lake to cause some of the fish there to die. So far, however, none of the Mount St. Helens ash has been found to be strongly acidic.

The greatest hazard other than ash, USGS scientists reported today, is the increasing instability of the northern flank of the volcano. Contributing to this instability are ground shaking, avalanching caused by continuing local earthquakes, subsiding of the summit graben, fracturing of ice and rocks, and accelerated melting of snow and ice caused by the heat of the volcano and possibly by solar heating of the fallen ash. This announcement marks a shift in the emphasis on hazards. The possibility of volcano-related flooding in the Lewis River drainage system is now thought to be less of a threat than the possibility of large avalanches from the volcano's northern slope.

Friday, April 18
E Day Minus 30

Eruptions of steam and ash were rising only about 500 feet above the crater today, and seismic activity stayed at a moderate level. "Because all pertinent factors seem to remain about the same each day," USGS scientists at Vancouver have decided to reduce their information releases from daily to twice weekly.

Scientists are encouraged in their grueling work by the excitement derived from Mount St. Helens' spectacular, historic reawakening and by the opportunity for major scientific achievement. Few of the scientists, if any, had seriously expected to see a Cascade volcano in eruption, much less to be part of an intensive study of the volcanic activity. They are fascinated by what has occurred already, and each hopes for a spectacular event that will advance his or her scientific specialty. They also feel frustrated, however, by the frequent bad weather that obscures the mountain from view and hampers ground travel and fieldwork.

Scientists who lack aircraft support are especially frustrated. Many aspects of the volcano can be seen only from the air, and scientific work on the mountain itself is not practical without helicopter support. For reasons of public safety, teams whose work deals with assessment or warning of the hazards have first call upon aircraft owned or chartered by Federal agencies. Scientists whose work does not relate closely to the hazardous potential of the volcanic activity may have long waits before they can be fitted into the busy flight schedule. Some distinguished scientists and government officials have arrived at Vancouver expecting to be given tours of the volcano, only to find that senior USGS scientists have Federal aircraft completely booked for urgent hazard assessments.

Saturday, April 19
E Day Minus 29

Seismographs today recorded about the same amount of earthquake activity as they have in recent days—37 earthquakes greater than magnitude 3, including 8 greater than magnitude 4. One this afternoon, however, reached magnitude 4.9, equaling the strongest to date. No harmonic tremor has appeared in the past week.

Local scientists who are most familiar with the shape of Mount St. Helens are saying that the upper northern side of the mountain obviously has moved outward (northward), but they are not unanimous about cause and effect. Some believe that the outward displacement is caused by the downward-settling mass of the summit graben. Others believe that intruding magma is inflating the mountain and causing a spreading of the summit that allows the graben to subside (see fig. 3).

Snow surveyors from the U.S. Soil Conservation Service, who periodically measure snow depth and water content in order to predict snow-water resources, have been observing the melting rate of the ash-rich snow near Mount St. Helens. They reported recently that the snow is melting faster where it is covered by the dark ash because it absorbs more heat from the sun than the clean snow does. Whether spring runoff this year will be faster and the danger of flooding greater are still uncertain, because much of the water melted at the snow surface can be held in lower parts of the snowpack. USGS hydrologists report no evidence of unusual runoff at their stream-gaging stations so far.

Sunday, April 20
E Day Minus 28

No eruptions were seen today, but seismic activity increased somewhat. The number of earthquakes stronger than magnitude 3 was 47; 7 were stronger than magnitude 4. This count was the highest in 2 weeks.

Although clouds have covered the peak most of the weekend, tourists continue to be a problem. These first weeks of volcanic activity have been treated as a gigantic carnival by some people in the Northwest, who have come to see Mount St. Helens "performing" on center stage. T-shirts imprinted with various slogans, coffee cups bearing photographs, plastic bags filled with ash, and other souvenirs are being offered for sale. Sightseers line the roads leading to the mountain in spite of the several "Mount St. Helens viewpoints" that the State of Washington has designated near Interstate Highway 5 so that the local roads leading to the mountain would be less congested. The opening of the sport-fishing season this weekend doubtlessly contributed to the crowds in this popular fishing area. Understandably, a great many people want to see the first erupting volcano in the conterminous United States in more than half a century.

Monday, April 21
E Day Minus 27

The lull in eruptive activity continues. Poor visibility kept scientists from observing the volcano closely today, but the instruments continue to watch. The seismographs indicate that earthquake activity today was less than it was yesterday and more like the previous week.

On many of these typical cloudy spring days, airborne observers can fly above the clouds and see the mountain peak even though the lower slopes remain hidden. Mount St. Helens and its neighboring volcanoes then seem to be riding on a billowing sea of clouds. Nearest to Mount St. Helens are Mount Adams, Mount Hood, and Mount Rainier (fig. 1), all easily visible and identifiable. Mount Rainier is the giant of the group. Rising 14,410 feet above sea level, it dominates this part of the Cascade Range. Of these three neighboring volcanoes, only Mount Adams, closest to and due east of Mount St. Helens, has not erupted in historical times (table 1.) Even Mount Adams, however, may not be extinct.

Tuesday, April 22
E Day Minus 26

Improved weather today brought better aerial views of Mount St. Helens, although low clouds still prevented observers on the ground from seeing the volcano clearly. Dawn disclosed a new mantle of snow on the mountain, covered in only one spot with a light dusting of ash. The only eruptions reported during the day were small bursts of steam during the noon hour that barely cleared the crater rim. Steam vents, not directly associated with the eruptions, can be seen on the eastern part of the summit area. The tiltmeters continued to record small changes that have not, as yet, shown a consistent pattern.

In discussing the leveling off of eruptive and seismic activity, USGS volcanologist Johnston reminded reporters that, "Lassen in California went through a year of this kind of activity before it turned into a magmatic eruption in 1915."

Northern Side Bulges Alarmingly

Wednesday, April 23
E Day Minus 25

Good weather allowed scientists to observe the volcano more closely and to note that there were no eruptions large enough to add to the light mantle of ash seen on yesterday's new snow. The volcano's quiet period also permitted researchers to collect gas samples from the steaming areas near the summit itself. (Analyzed later, these samples were found to contain a high concentration of sulfur.) Two new steam vents were seen in the crater today.

Although the slumping of the summit graben and the breaking up of glacier ice on the volcano's northern side have been evident for about 3 weeks, the first real indication of the amount of deformation came today when optical comparisons of aerial photographs taken on August 15, 1979, and on April 12, 1980 (11 days ago), were completed. These comparisons show that some places on the northern flank are about 250 feet higher than they were last year (fig. 15). The full extent of the bulged area is not known. Scientists and technicians flying in by helicopter placed surveying targets on the northern flank of the volcano today to help monitor its changes in slope.

Tiltmeters at Timberline Viewpoint and Spirit Lake indicated a slight tilting of the ground surface downward to the northwest; on the southern side of the mountain, tilting was downward to the southwest. This surface tilting suggests that the volcano may be inflating because of increasing magma pressure beneath it (fig. 3).

The sustained period of relative quiet prompted Forest Service officials to schedule discussions within the next few days on opening some areas around the volcano to restricted use. USGS geologist Crandell, Mount St. Helens Hazard Coordinator, warned, however, that avalanches could begin on the unstable, bulging area of the northern slope and surge into areas downslope. Such avalanches, he said, could also cause floods by suddenly raising the level of Spirit Lake. An avalanche also could dam the North Fork Toutle River temporarily, and the dam could fail later in a washout that would release a torrent to downstream areas.

USGS scientists in Vancouver, in response to demands for more frequent information about the volcano, agreed to resume daily information releases.

Thursday, April 24
E Day Minus 24

Although fumaroles continued to emit steam near the summit crater, no ash eruptions were large enough to throw material outside the crater walls. The number of earthquakes was about the same as it has been in recent days, but the quakes were stronger; eight were of magnitude 4 or greater, and one reached magnitude 4.7.

The USGS Volcanic Hazards Project made public a map showing the possible dangers presented by the bulge area and emphasized the potential for avalanches.

Friday, April 25
E Day Minus 23

Fumaroles continued to steam today, and seismic activity continued at about the level that it has maintained for several days. About 1,560 earthquakes stronger than magnitude 3 have been recorded since activity at the volcano began March 20. More than 200 have been stronger than magnitude 4.

Tiltmeters continue to show slight tilt that, once again, does not have a consistent pattern. In an effort to better define changes in the shape of the volcano, scientists are using electronic distance-measuring devices. They were able today to measure the precise distances to five targets on the upper slopes of the volcano, as well as two additional reference points nearby. These measurements, together with others to be made by using markers installed on the mountain today, will help to define the size, shape, and growth of the bulge on the northern flank in days to come (fig. 16).

Saturday, April 26
E Day Minus 22

The mountain is relatively quiet today. Clear weather allowed observers a good view of the crater, but they saw only fumaroles emitting steam and eruptive bursts too weak to lift ash outside the crater. The seismographs indicate that earthquake activity was about as low as it has been since March 24.

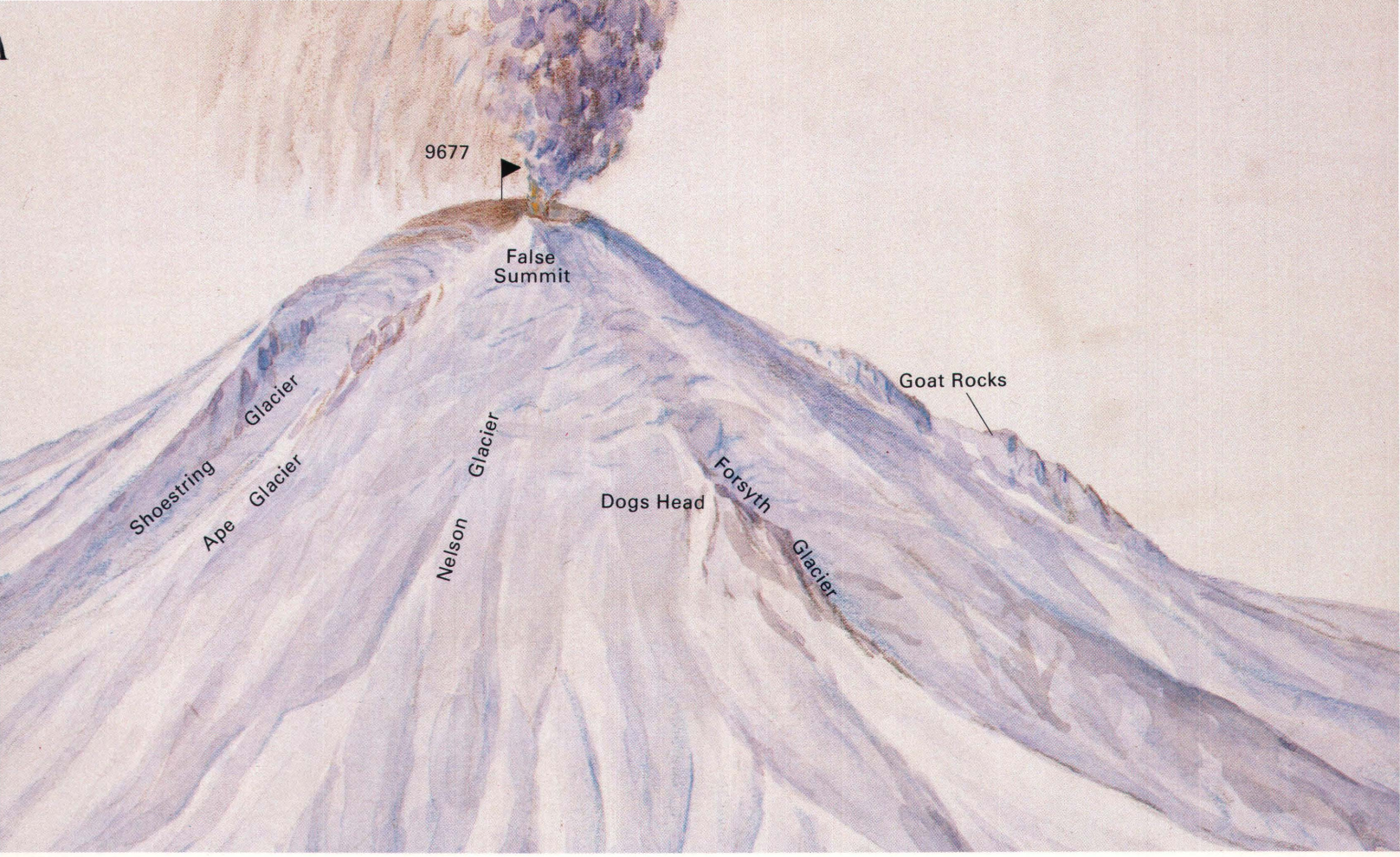
Tiltmeters on the mountain's eastern and southern flanks showed small, unsystematic changes, but the tiltmeter at Timberline Viewpoint recorded downward tilt to the north.

Sunday, April 27
E Day Minus 21

The mountain remains quiet, although fumaroles continue to send up steam. One fumarole on the southeastern crater wall is especially active. Clear weather gave observers a good view today, but they saw no ash eruptions.

On the ground, changes are being detected by the instruments. Ground tilt measured by the tiltmeter at Timberline Viewpoint now shows an increase in tilt, downward toward the northeast. This tilt is interpreted to mean that the volcano is swelling. In addition, surveys of the Goat Rocks

FIGURE 15.—A comparison of the shape of Mount St. Helens (*A*) at the time of the March 27 eruption and (*B*) just before the May 18 eruption shows the large outward displacement of the bulge area. The view here is from the northeast. (Paintings by Dee Molenaar, USGS.)


9677
False
Summit
Goat Rocks
Glacier
Shoestring
Glacier
Ape
Glacier
Nelson
Dogs Head
Forsyth
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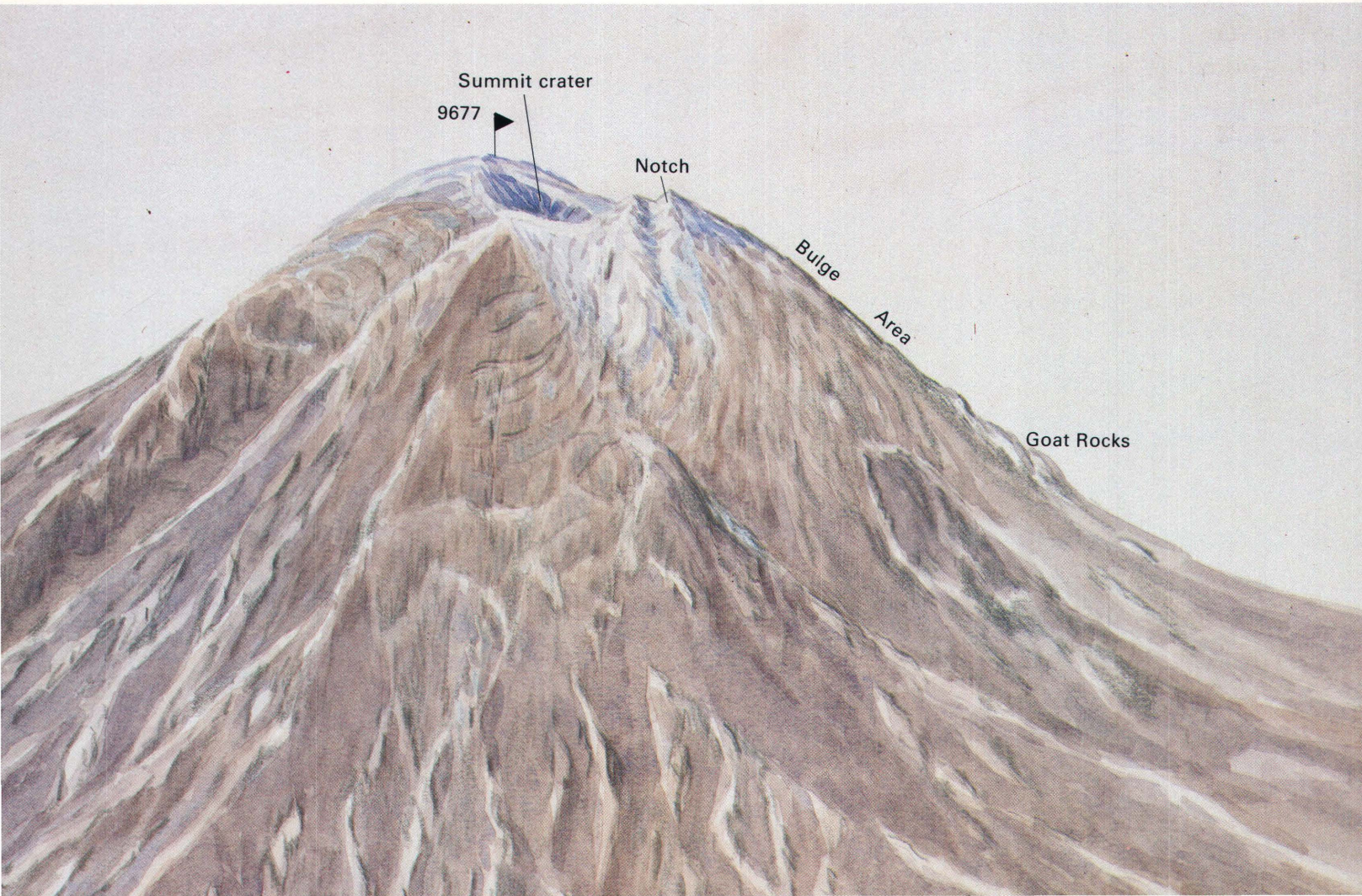

Summit crater
9677
Notch
Bulge
Area
Goat Rocks

FIGURE 16.—At Coldwater II observation station, a scientist (back to camera near rear of vehicle) uses a laser ranging instrument to measure distances to reflector targets on the northern side of Mount St. Helens, including the unstable bulge area (left and center parts of the mountain as viewed here). Dogs Head is on the skyline to the right of the tree, and Goat Rocks, the lava dome that formed during an eruptive period in the 1840's, is directly above the rear of the vehicle. (Photograph by Harry Glicken, May 4, 1980.)

area using instruments on the flank of the volcano indicate that the area has moved outward, away from the main mass of the mountain, at least 15 to 20 feet in the past 4 days. Geologists report seeing new fractures in the bulge; some ground locations on the bulge are now about 300 feet higher than they were in 1979.

Monday, April 28
E Day Minus 20

Although poor visibility hampered aerial observations, there was no indication today that any eruptions of ash were large enough to extend beyond the crater. When the crater was visible, it was emitting clouds of steam punctuated by occasional short bursts of ash.

The northern flank continues to deform, as the tiltmeter at Timberline indicates. Most scientists are unwilling to specify the exact cause of the tilting, but they generally agree that it probably is related to the subterranean movement of magma.

Tuesday, April 29
E Day Minus 19

Continuing studies of aerial photographs show that the bulging area on the northern side of the mountain is now about 1 mile long and 0.5 mile wide and has a northeast-trending axis that extends from the northern side of the summit crater toward Sugar Bowl, on the northeastern flank of the volcano. The outward displacement of the slope has caused ground positions on part of the bulge to be as much as 320 feet higher than they were last year. From this maximum, the bulge decreases toward the east, north, and west. Ground surveys confirm that the deformation is continuing. Between April 27, when the last survey was made, and today, Goat Rocks has shifted about 9 feet toward the north-northwest, and little or no vertical uplift has occurred.

The tiltmeter at Timberline Viewpoint, on the northeastern side of the volcano, indicates tilting downward to the north and confirms that the bulge extends to that site as well.

The mountain itself remains relatively quiet; it has produced only 27 earthquakes stronger than magnitude 3.0 and no sizable eruptions.

The bulge continues to cause scientists concern. They now believe that it represents the most serious potential hazard from the present volcanic activity. They are especially worried about the likelihood of avalanches headed toward the North Fork Toutle River and Spirit Lake. (Spirit Lake itself was formed over a period of time by volcanic mudflows damming the river.) USGS geologist Crandell said, in a prepared statement to be released tomorrow morning, that Forsyth Glacier (fig. 5), upslope from Spirit Lake, "looks so unstable that a sharp earthquake or volcanic explosion could trigger a large avalanche of snow, ice, and possibly rock, without warning. In addition, measurements indicate that the upper part of the volcano from Forsyth Glacier west to Goat Rocks is shifting and may be unstable. An avalanche from this high part of the volcano could result in [millions of] tons of debris dropping a vertical distance of more than 4,000 feet, from an altitude of about 7,600 feet down to about 3,200 feet, the altitude of Spirit Lake. Such an avalanche could move downslope at a high velocity—more than 100 miles per hour—and could move long distances, certainly as far as [State Route] 504, about two and a quarter miles away."

Scientists believe that such an avalanche could extend beyond Timberline Viewpoint as far as Spirit Lake and could cause a large surge wave in the lake. The momentum of such an avalanche might carry parts of it across the valley of the North Fork Toutle River west of Spirit Lake and upslope along the northern wall of that valley, as well as down the valley to the west.

Emergency-services officials are being frustrated in their attempts to make the public aware of potential dangers. One official, quoted in the *Seattle Post-*

Intelligencer, said, "The hardest thing is to warn people of the danger. The mountain looks so serene, so people can't fathom 4,000 vertical feet of earth, rock, and ice plunging into [Spirit Lake] in less than two minutes."

Wednesday, April 30
E Day Minus 18

The crater was not active today, except for steam venting from many fumaroles. Earthquakes continued, although larger ones—those stronger than magnitude 4—numbered only 6, and only 15 stronger than magnitude 3 were recorded. Since March 20, about 240 earthquakes of magnitude 4 or greater have been recorded.

The northern flank of the volcano continues to swell and move outward. In order to compare the large movement at Goat Rocks with possible movement elsewhere on the mountain, scientists commenced ground measurements near Sugar Bowl and Dogs Head, ancient lava domes that are prominences on the northeastern side of the cone near the base and the upper flank of the bulge, respectively (figs.5 and 16).

During the lull in eruptive activity, volcanologist Johnston flew by helicopter to the crater rim and climbed down into the crater to collect samples of water from a small lake that had formed in the crater bottom. Formed by melting ice, the lake had a temperature of 17°C (62°F), and gas bubbled through it. Analyzed later, the sample of lake water was found to have a pH of 5.1 (slightly acid), 120 milligrams of chlorine per liter, and 32 milligrams of sulfur in the form of sulfate per liter. These analyses indicate that the water has a low to moderate concentration of dissolved minerals. The radioactive gas radon was present in the minor amount of 100 picocuries per liter, well within the range found in geothermal waters in other regions.

USGS scientists, concerned over the increasing instability of the bulge area and the possibility that large avalanches of snow, ice, and rock could disrupt State Route 504 south and west of Spirit Lake, today issued an updated Hazards Warning to State and local officials and to the Forest Service.

Governor Ray and the Forest Service's Forest Supervisor Robert Tokarczyk, acting on this and earlier hazard assessments, closed additional areas near the volcano to entry. A "Red Zone" (fig. 13) was established around the peak to distances ranging from about 3 to 8 miles and included the Spirit Lake area. Only scientists, law-enforcement officers and other officials, and search-and-rescue personnel are permitted in this zone. In a "Blue Zone," which extends beyond the Red Zone, logging operations are allowed to continue, and property owners holding special permits may enter, but no overnight stays are allowed. As an added precaution, Governor Ray also declared the entire State an emergency area because, under certain conditions, winds could scatter tephra from volcanic activity over hundreds of miles.

Toutle Lake School, located about 25 miles from the mountaintop, held a "volcano drill," the first of its kind in the United States.

Despite the ominous bulging on its northern side, the mountain remains quiet as the month closes. The eruptions of March and April spread ash for at least 30 miles in every direction and as far as 60 miles to the south-southeast and 70 miles to the north. So far, the ash has been derived from pulverized old rocks. Although 35 days have passed since the first eruption, no new lava has been seen or found in the ejected ash.

The installation and use of instruments to measure and monitor the volcano have continued throughout the month. As April closes, the instruments being used to measure at various sites include:

- Six 5-day seismic recorders operating within 10 miles of the summit of Mount St. Helens and 10 telemetered seismometers within 35 miles of the summit. Receiving and recording equipment at the University of Washington seismology center in Seattle has been expanded to handle the blizzard of data, and a computer link has been established with the USGS group in Vancouver to speed data transfer and communications between the two centers.
- A network of five tiltmeter stations and their automatic telemetering instruments at distances ranging from less than 2 to about 9 miles from the summit.
- Fourteen reflector-type surveying targets on the mountain, many of them precariously accessible only by helicopter, used in making precision measurements that detect changes such as slumping or swelling of parts of the volcano. Distances between base stations and the targets on the mountain are measured with a geodimeter (electronic laser instrument). Horizontal and vertical angles are measured with a theodolite (manual optical instrument).
- A network of six gravity stations spread over the northwestern, northern, northeastern, and eastern sides of the volcano at distances ranging from less than 2 to about 5 miles from the summit. Each station is visited twice in a typical day, and the gravity is measured with one of three electronic-readout precision gravimeters. These measurements are repeatedly checked against measurements of presumed stable gravity made at a base station about 12 miles west of the summit.
- Three recording magnetometers located northeast, east, and west of the volcano at an average distance of about 2.5 miles from the crater. Magnetic field intensity is automatically recorded on tape every 10 minutes.
- A preexisting network of hydrologic measuring sites expanded by the addition of 33 stream sites for collecting water-quality data (chemical,

biological, and sediment characteristics) and monitoring changes in streamflow. Nineteen of these additional sites are on streams that drain Mount St. Helens; 14 are on other streams likely to be affected by ash from the volcano. Two of the additional sites have monitoring instruments that automatically send telemetered data by way of an orbiting Earth satellite to the USGS office in Tacoma.

- Two time-lapse cameras that are making a photographic record (when visibility permits) of the eruptions and profiles of the volcano.

Thursday, May 1
E Day Minus 17

As the month opens, the mountain is steaming continuously but otherwise is not erupting. USGS observers report that a small lake has formed again in the volcano's crater and has covered one of the steam vents and that gas bubbles up through the water. The most active steam vents, however, are above the lake surface on the southern side of the crater.

The swelling on the northern flank continues. One point on the bulge, according to measurements, moved about 2 feet outward in less than 12 hours.

Earthquakes, too, continue; 26 stronger than magnitude 3 and 5 of magnitude 4 or greater were recorded today.

A seismic station was installed today at Dogs Head to help detect earthquakes that might trigger a major avalanche and to improve the accuracy of earthquake location. Near the 7,500-foot level, it is the highest instrument station on the mountain.

Also today, a new observation station was established on a ridgetop east of the Coldwater I site and 2.7 miles closer to Mount St. Helens. The new site is between the valleys of the North Fork Toutle River and South Coldwater Creek, 5.7 miles north-northwest of the summit. It is at an altitude of about 4,100 feet—about 1,400 feet above the floor of the adjacent river valley. Automatic cameras, other monitoring equipment, and radios for communication have been moved there from Coldwater I. Also, a travel trailer has been brought in to shelter volcano watchers, who now are at the site 24 hours a day. The new station is called Coldwater II (fig. 16).

Friday, May 2
E Day Minus 16

The mountain is not erupting, although it continues to steam. Thirty earthquakes stronger than magnitude 3 were recorded today, 8 of which were of magnitude 4.0 or greater. The bulge is growing outward at a rapid rate, as much as 5 feet a day near Goat Rocks.

Scientists studying a thermal infrared survey made by personnel of the U.S. Naval Air Station at Whidbey Island, Wash., detected a previously unknown area of warm rock in the middle of the bulge on the northern slope of the volcano. Ice continues to break up in this area, which is about 100 feet long and 50 feet wide. No one knows whether it is a new hot spot or one that existed before and has been hidden by a covering of ice.

Skamania County Sheriff Bill Closner accused television newsmen of practicing "one-upsmanship" by flying helicopters into the volcano's dangerous Red Zone, according to an article in the *Seattle Post-Intelligencer.* He is quoted as saying, "The mountain is getting more dangerous all the time. It's getting to the point where somebody's going to get hurt, and we're going to arrest them. . . . " Most news reporters and photographers, however, seem to be responsible and law abiding in their efforts to present the Mount St. Helens story to the public. Some news teams have provided aircraft rides for scientists who otherwise would have had no access to the volcano area.

Owners of some of the many summer cabins in the Spirit Lake area reportedly have refused to make their semiannual property-tax payments because they have not been allowed to use or even enter their property since the area was evacuated after the eruptions of March 27.

Saturday, May 3
E Day Minus 15

The bulge continues to grow as Goat Rocks moves northward at an alarming rate. Although steam continued to issue from summit fumaroles today, there were no eruptions, and seismic activity was down—only 26 earthquakes of magnitude 3 or greater, including 5 exceeding 3.9.

USGS scientists in Vancouver took time out from their measurements to discuss funding for the increasingly expensive volcano watch and whether some of them should return to their regular duties. Volcanologist Johnston, who normally is assigned to the Menlo Park office but who has been involved since the first earthquake on March 20, told newsmen, "We all want to stay. We don't want to be in California, Denver, or Virginia if something happens. I even offered to move here."

Sunday, May 4
E Day Minus 14

The mountain remains quiet, and scientists were able to remeasure the bulge. They confirm that outward movement continues at a rate of about 5 feet a day. USGS geologists are now convinced that some bulging of the northern flank resulted from a magmatic intrusion within the volcano during late March. They do not know yet whether the intrusion is still active or how much of the continuing change in the mountain's shape may be merely a gravitational spreading of the mountain accompanying the settling of the summit graben (fig. 14*A*).

Volcanologist Johnston has been using a spectrometer, which measures the wavelengths of light components, to examine the makeup of the gases emanating from the crater. He uses the instrument at Timberline Viewpoint at

midday when the sunlight shining through the gas is brightest. So far, he has not detected significant amounts of sulfur dioxide, which would indicate that the volcanic gases are from a high-temperature source.

Monday, May 5
E Day Minus 13

Mount St. Helens continued to steam but did not erupt today. Smoke from the burning of timber slash (debris) led to rumors of lava flows, but there were none. Although strong eruptions of ash have not been common during the past 3 weeks, scientists do not think that the volcanic activity is subsiding yet.

Jack Hyde, a Tacoma Community College geologist who has done extensive research on Mount St. Helens and has worked with USGS geologists on studies of other Cascade Range volcanoes, was interviewed today by reporter Jim Erickson of the Tacoma *News Tribune*. "I have a gut feeling . . . that as the bulge continues to grow, something dramatic is going to happen soon," Hyde said. He speculated that the instability of the north-side bulge might result in massive landslides, which could be followed by a "spectacular" explosion of lava, possibly without warning, as lava vents on the northern slope are opened up. When he was told that scientists are watching the northern face of the volcano from nearby ridges, Hyde replied, "I hope they're not in a direct line. That's like looking down the barrel of a loaded gun."

The frequency with which the famous Hawaiian volcanoes erupt and the type of lava flows that they produce have contributed to the popular belief that all volcanoes have fluid, channeled lava flows. Because of this notion and because Hawaiian volcanoes, being less explosive, are much safer than volcanoes like Mount St. Helens, some people who have visited Hawaii do not understand why scientists and officials are being so cautious. "We're logging 10 miles away from the peak," one logger was quoted as saying. "I don't see any hazard. I just came back from Hawaii, where they run tourist buses right up to the edge of a venting volcano."

Tuesday, May 6
E Day Minus 12

Athough clouds obscured the mountain most of the day, there was no reason to suspect that it had erupted. The northern flank continues to bulge at the rate of 4 to 5 feet a day; earthquakes continue at about the same rate as they have in recent weeks.

The relatively gentle behavior of Mount St. Helens so far in this eruptive sequence makes it difficult for those who are unfamiliar with explosive volcanoes to realize the potential danger. For the last 2 weeks especially, the mountain has done nothing to convince a nonscientist that a volcanic hazard exists. If the scientific instruments were not measuring the ominous displacement of the bulge and if the news media were not reporting the scientists' concerns extensively, the public clamor to do away with the roadblocks and entry restrictions undoubtedly would be greater.

Eruptive Activity Resumes

Wednesday, May 7
E Day Minus 11

The volcano resumed activity after a lull of about 2 weeks, sending up eruptions of steam and ash late today as high as 13,000 feet. The northern flank of the mountain maintains its outward creep, but earthquakes are mostly of low magnitude.

Some who are trying to carry on their daily lives in the shadow of the volcano find that their patience is wearing thin. Bombarded by rumors as well as official warnings, some residents say that they glance at "The Mountain" whenever they hear a noise. Several, according to reporters, wish that the volcano would "blow and get it all over with." One was quoted as saying, "Inflation and that damn volcano—it's a wonder we don't have ulcers."

Thursday, May 8
E Day Minus 10

Muddy rain fell on the Timberline monitoring station today, and ash blew to the north and east as the mountain continued its sporadic eruptions. The crater steamed, as did areas near the head of Shoestring Glacier and the Boot, high on the eastern and northern sides of the cone, respectively.

Many geologists agree that it is only a matter of time before the bulge area fails, probably in a gigantic landslide. They are unable to judge, however, when the failure is likely to occur. The strength of the rocks under the bulge and the depth to which they are affected by the deformation are not known. In the meantime, the northern flank continues its outward creep.

Earthquake frequency is about the same as it has been in previous weeks (25 stronger than magnitude 3), but 11 quakes stronger than magnitude 4 were recorded—the largest number of higher magnitude quakes since April 24. The strongest of these registered 5.0, the most powerful single quake to date.

Harmonic tremor returned to the records for the first time since April 12. Tremor was recorded in three bursts, from 4:43 to 5:03 a.m., 10:04 to 10:13 a.m., and 10:03 to 10:12 p.m.

Friday, May 9
E Day Minus 9

The mountain continues to behave as it did yesterday, sending up intermittent plumes of steam and ash, steaming continuously in the main crater, on the upper northern flank, and at the head of Shoestring Glacier, and bulging farther outward on the northern side.

Seismicity, too, is about the same. Twenty-one earthquakes stronger than

magnitude 3 were recorded, including nine that ranged from 4.0 to 4.9, but no harmonic tremor was noted today.

USGS scientists curtailed observations at Timberline Viewpoint because of the increasing danger that a sudden avalanche might reach that site. Many volcano observations now are being made at Coldwater I and Coldwater II, about 6 and 3 miles farther from the crater, respectively (fig. 7.)

Saturday, May 10
E Day Minus 8

The volcano was under cloud cover most of the day, but erupting steam and ash could be seen when the clouds lifted. USGS scientists remeasured the bulge on the northern side when weather permitted and found that the rate of movement apparently has slowed to less than 3 feet a day—about half its average rate for the previous 2 weeks. (The apparent low rate was later thought to be due to an erroneous measurement.) Seismicity continues at about the same level; of 20 events exceeding magnitude 3.0, 10 were magnitude 4.0 or greater.

University of Puget Sound geologist Al Eggers told reporters that tide-producing gravitational forces will be exceptionally strong on May 21, and he warned that the extreme force might trigger a major eruption if the volcano were already set to erupt. Although most USGS geologists do not totally discount this idea, they believe that other factors, such as magmatic pressure inside the mountain, are likely to be much more important.

Sunday, May 11
E Day Minus 7

Although the crater emitted only small bursts of steam and ash, 10 earthquakes of magnitude 4.0 or greater occurred again today. Increased steaming observed at the hot area on upper Shoestring Glacier may indicate changes in the distribution of heat inside the volcano, according to USGS volcanologist Johnston.

Volcanic-hazard scientists and public safety officials are feeling the pressures of responsibility these days. They believe that the volcano is capable of producing dangerous avalanches, mudflows, and explosive eruptions, and they are striving to give realistic warnings and to provide adequate protection for the public. At the same time, they recognize that personal hardships and economic loss to local individuals and businesses could result from an overreaction to the hazards.

Scientists hope to provide advance warning of any impending disaster. They are watching the mountain closely from the observation post at Coldwater II, which is being manned 24 hours a day. Also, a Forest Service observation airplane is in the air around the mountain almost continuously when weather permits. In addition, instruments such as the telemetering seismometers remain "on duty" and are closely monitored around the clock. Most USGS and University of Washington scientists who are studying the volcano believe that any major eruption would be preceded by a change in the seismic activity or in the rate of bulging; therefore, they believe that they can give adequate warning if a dangerous eruption occurs. If, however, earthquake patterns do not change before the onset of a major event—such as the expected massive avalanche—or if the event occurs when visibility is hampered by darkness or clouds, even scientifically trained volcano watchers may not be able to give warning.

Monday, May 12
E Day Minus 6

The mountain continues to erupt ash and steam, and observers today could see a new cluster of fumaroles on the western rim of the crater. The bulge continues to move out in the same direction (fig. 17) at a rate of about 5 feet a day. Scientists agree that the bulge poses a danger, but they still cannot determine how extreme that danger is.

Earthquakes stronger than magnitude 3.0 have increased over the past few days; of the 28 recorded today, 8 exceeded 4.0. One earthquake of magnitude 5.0 triggered an 800-foot-wide ***debris avalanche*** that plunged more than half a mile down the northern flank of the mountain. The avalanche did not take the bulge with it, nor was it the huge avalanche that scientists anticipated. They believe that today's avalanche demonstrates the increasing instability of the northern flank and that it was just a sample of larger events to come.

A University of Washington seismology group moved a portable seismic recorder from a station at Spirit Lake to a ridgetop location northeast of Mount St. Helens. A major avalanche probably would reach the Spirit Lake station and would destroy the instrument if it were to remain there.

Tuesday, May 13
E Day Minus 5

Steam and ash continue to erupt, but the rate slackened in the afternoon. The eruption cloud rose only about 3,000 feet above the crater, and most of its ash fell nearby. However, a false report (of unknown origin) that a "mammoth" eruption had sent ash as high as 18,000 feet above sea level caused the Federal Aviation Administration to issue a pilots' warning that an ash-plume area extended 20 miles north-northeast of the volcano and was "of extreme hazard to aircraft."

The pit at the head of Shoestring Glacier has enlarged, and steam emission from that site has increased. USGS observers reported also that new steaming areas have opened up on the western side of the mountaintop, just outside the crater rim. Geologists noted yellow-green encrustations on the old ash on the upper southern slopes of the volcano, probably from sulfur that was either deposited by the fumes or leached from the ash. Similar

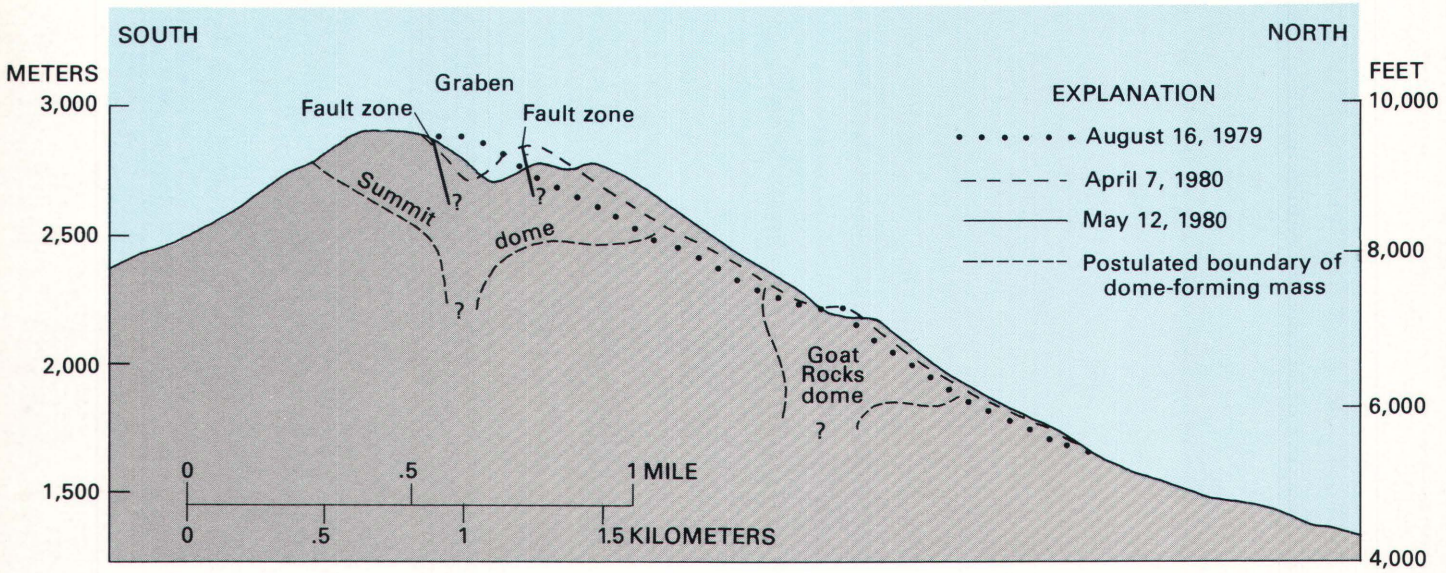


FIGURE 17.—Profile drawing of Mount St. Helens showing the shape of the north-side bulge on May 12, 1980 (solid line), August 16, 1979 (dotted line), and April 7, 1980 (dashed line). Diagram is modified from Moore and Albee (1981).

encrustations have been seen for weeks within the crater and around the rim.

Earthquake activity continued at a lesser rate; 21 events stronger than magnitude 3.0, including 6 of magnitude 4 or greater, were recorded.

Scientists at Vancouver spent much of today quashing rumors about the exaggerated size of the ash plume and also about a nonexistent lava flow, which was reported to have been moving down the side of the volcano.

Wednesday, May 14
E Day Minus 4

Although bad weather obscured the volcano more than half of today, observers did see some eruptions of steam and ash. They noted one new steaming vent between the two small peaks on and just north of the northern crater rim along part of the fault system on the northern side of the summit graben. Instruments show that the northern flank continues to swell at a rate of about 5 feet a day and that seismicity is about the same or slightly less than it has been in recent days.

Scientists from Dartmouth College, who are cooperating with the USGS in studying gas from the volcano, report that sulfur dioxide (SO_2) is being emitted at rates of 10 to 20 metric tons a day during the eruptive pulses and about 1 ton a day between eruptions. These SO_2 rates are much higher than those estimated from samples collected on March 30 (0.3 ton a day). Because volcanic SO_2 requires a very high-temperature source, the increased emission of this gas might indicate that the magma is moving closer to the surface.

Thursday, May 15
E Day Minus 3

The volcano was visible part of the day; USGS observers saw no eruptions, but they could see new ash on the southwestern flank. Some of the summit vents appear to be filled with fallen blocks of ice.

The north-side bulge continues to shift outward at a rate of about 5 feet a day. Seismic activity included one earthquake of magnitude 4.8 early this morning.

Mount St. Helens continues to attract the curious from around the world. Hard-pressed law-enforcement officers, unable to man roadblocks on the maze of logging roads around the mountain, can only check periodically for people trying to get around the barricades and locked gates for a closer look at the volcano. Many roadblocks have become places where visitors congregate—picnicking, socializing, photographing, or just waiting for the clouds to lift and for the volcano to "do something." Their vehicles often clog the very routes that they would need to escape an explosive eruption.

Fifty days have now passed since the March 27 eruption, but no lava has been seen, and no evidence of fresh magma has been found in the ash. Even with the renewal of ash eruptions on May 7, the amount of tephra ejected since March 27 has not been great in comparison with that ejected during eruptions of other volcanoes in the Cascade Range or during previous eruptions of Mount St. Helens itself.

Friday, May 16
E Day Minus 2

The lull in eruptions continues, and seismicity has remained at about the same level for the past few days. Today, there were 28 earthquakes stronger than magnitude 3.0; 10 reached 4.0 or greater. No harmonic tremor has been recorded since May 8.

Airborne observers could see clearly into the growing summit crater and

FIGURE 18.—*A*, This aerial photograph of the northeastern side of Mount St. Helens shows conditions on May 17, the day before the devastating eruption. This quiet scene belies the forthcoming lateral blast. Dark streaks on either side of Sugar Bowl are deposits from avalanches of ice and rock caused by earthquakes and the increased breakup of the northern slope. (Photograph by Robert M. Kimmel, USGS.) *B*, Named features on the mountain and the extent of the north-side bulge are shown on the accompanying sketch.

noted that steam continues to emanate from the summit area, particularly from a large fumarole on the southern wall and from a gradually enlarging pit at the head of Shoestring Glacier. The bulging northern side also was steaming today, especially on its higher parts.

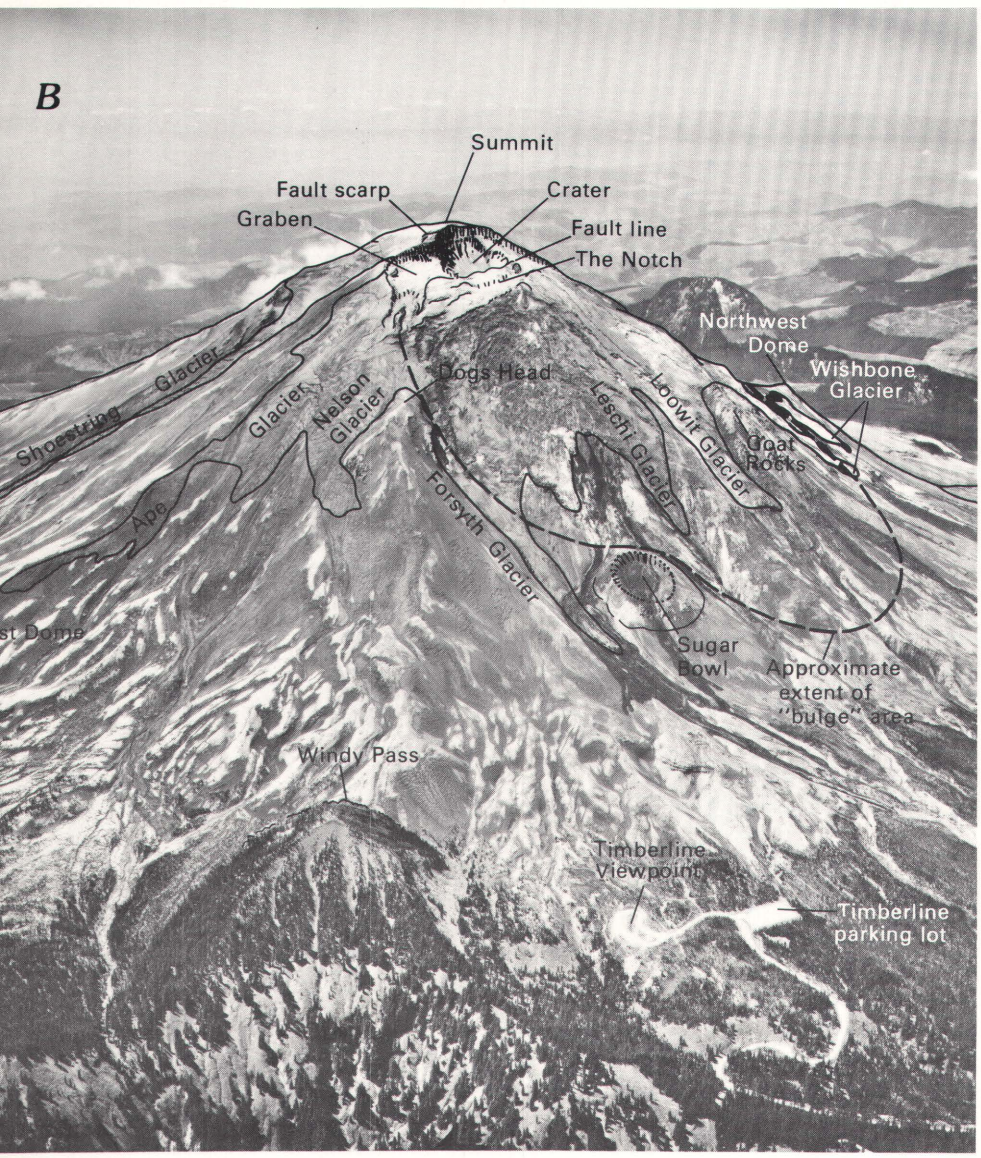
The volcano has changed shape considerably during the last week and a half. The northern and northwestern rims of the crater show abundant cracks, which have been partly filled by snow and ash; this area appears to be moving downward as a mass toward the crater. The bulge area, too, continues to be highly broken and distorted.

Before dawn today, an aerial thermal survey of the volcano was made by the U.S. Department of Energy. Because the results of the survey were recorded as digital data on tape, they are not immediately available for interpretation.

Glaciologists set up a time-lapse camera on Dogs Head, 1 mile northeast of the mountain's crest, and aimed it at the growing bulge. The camera takes a picture every half hour and can operate for more than 5 days without being reloaded.

Cabins and camps at Spirit Lake, at the foot of the volcano, have been deserted for the most part, as they are in the Red Zone. Yesterday and today, however, workers were allowed to remove equipment from the Boy Scout and YMCA camps along the lake. Owners of private property in the no-entry zones are demanding similar access to the homes and cabins that they were forced to leave weeks ago. Some threatened to converge in numbers on the roadblocks and go through "come hell or high water." The penalty for being found in the zone without permission has been set at $500 or a 6-month jail sentence.

The National Weather Service predicts good weather for volcano watching this weekend.



Saturday, May 17
E Day Minus 1

No ash erupted from the mountain today, but the bulge on the northern side continues to expand (fig. 18). Seismic activity decreased to its lowest level this month, which is only slightly lower than the May 7 level. Eighteen earthquakes stronger than magnitude 3.0 were recorded today, six of which were of magnitude 4.0 or greater.

Responding to pressure from property owners and with Governor Ray's consent, law-enforcement officers today escorted about 50 carloads of property owners to their property in the Red Zone to retrieve some of their possessions. Those who entered the zone were required to sign liability releases at the road barricades and to be back out by nightfall. Authorities have agreed to allow a second caravan of property owners to go in at 10 a.m. tomorrow, if the mountain remains quiet.

At least two people have remained in residence in the restricted zones. Harry Truman, proprietor of the Mount St.

FIGURE 19.—This aerial view of Spirit Lake, seen from the southeast on the morning of May 18, is probably the last photograph taken of this popular recreation area before the devastating eruption. At the left end of the lake is Mount St. Helens Lodge, where proprietor Harry Truman presumably was buried a few minutes later beneath hundreds of feet of avalanche debris. (Photograph copyright 1980 by Keith and Dorothy Stoffel.)

Helens Lodge (fig. 19), has stayed in his home at Spirit Lake (in the Red Zone) in defiance of government authorities and the threatening volcano and has become something of a folk hero in the process. Ray Jennings also has not left his cabin in the Blue Zone near Swift Reservoir (fig. 13). Because the road barricades are not difficult to evade, the number of others in the restricted zones is not accurately known.

"No one would listen," Skamanian County Sheriff Closner was later quoted in the Vancouver *Columbian* as saying. "It didn't matter what we did. People were going around, through, and over the barricades. Some were climbing right up to the rim of the crater. Maps were even being sold showing back-country roads around the barricades."

One man will be in the Red Zone legally tonight. He is volcanologist Johnston, who today took up duties at the USGS Coldwater II observation post 5.7 miles north-northwest of the summit of Mount St. Helens. Johnston is taking instrument readings of the distances to targets on the swelling bulge and radioing them to the volcano-watch headquarters in Vancouver. He also has been gathering information about the volcano's condition by studying the volcanic gases—his scientific specialty (fig. 20). He will be alone at the ridgetop site overnight but expects to be joined in the morning by other USGS staff members. Johnston is taking over for geology student Harry Glicken, an intermittent USGS employee who has been at Coldwater II most of the time since May 1 but who left at 9 p.m. tonight to participate in a required college field trip. Geologists Daniel Miller and Donald Swanson plan to visit Coldwater II tomorrow to change film in the time-lapse cameras and to pick up a geodimeter. They expect to leave Vancouver about 8 a.m. Normally, the trip could be made in a few minutes in a charter helicopter. Tomorrow, however, the helicopter will not be available, so they face a 2-hour trip by automobile.

On the next ridgetop beyond Johnston's is the post of Gerald Martin, a retired Navy radioman from southern California, who is one of a team of amateur radio operators serving as volunteer volcano watchers for the Washington Department of Emergency Services. Martin will spend the night in his radio-equipped camper at a site just outside the northern boundiary of the Red Zone, less than 2 miles north of the Coldwater II observation station and about 7 miles north of the volcano's top.

Also staying near the volcano, but not inside the restricted zone is Reid Blackburn, a staff photographer for the Vancouver *Columbian*. Blackburn is at the Coldwater I observation post, which is 8.4 miles northwest of the mountain's summit and 2.4 miles west of the present Red Zone boundary. Blackburn will stay overnight to record images of the mountain at intervals during the night and also to photograph it in the clear light of early dawn. Two of his colleagues, Fred Stocker and Jim McWirter, who also have been camping at Coldwater I, went into Vancouver and "on a whim" have decided to remain in the city overnight.

FIGURE 20.—*A*, On May 17, volcanologist David Johnston collected gas samples from a fumarole recently found high on the unstable north-side bulge (shown by the arrow). (Photograph by David Frank.) *B*, Johnston and assistant Harry Glicken were lifted by helicopter to a precarious landing site nearby. *C*, Johnston scrambled over the chaotic rock mass to crouch at the edge of the fumarole and collect the samples. (Photographs by Harry Glicken.)


A


B


C

In eastern Washington, everyday activities are going on with little or no concern for the increasing instability of Mount St. Helens. In Spokane, Washington's third largest city, the annual Lilac Festival has brought an influx of visitors to the city. Fair weather is expected for tomorrow's festivities, after which many people will be traveling homeward.

In the farming area around Ritzville, the winter wheat is about 20 inches high. Although spring has been cooler than normal this year, good crop yields are expected because precipitation has been abundant, and the soil is moist.

At Yakima, the late spring has delayed crops, but the blossoms are gone from the extensive orchards now, and the tiny fruit is beginning to form. The alfalfa crop is good; the first cutting of hay is about 5 percent complete, and the rest of the fields are about ready to cut.

The Army National Guard's 116th Air Cavalry Squadron is also in the Yakima area with its helicopters for summer field training.

Nearer to Mount St. Helens, about 30 ships are expected to depart at the busy ports of Vancouver and Portland in the next day or two and head down the Columbia River for the Pacific Ocean. About 20 incoming ships are expected to steam upriver to these same port facilities.

Cataclysmic Eruption

Sunday, May 18
E Day

Today began free of clouds and so quietly that some scientists delayed planned reconnaissance flights over the mountain. Seismicity during the early morning was moderate, about the same as it has been in recent weeks. The Oregon Army National Guard flew over the volcano before dawn to make a thermal survey. The infrared scanner in the aircraft recorded the relative temperatures of the volcano's surface on photographic film, which was processed in a matter of hours after the plane landed.

In Yakima, the sky was almost cloudless. Keith and Dorothy Stoffel, geologists working in the Spokane area, were visiting Yakima to attend a meeting. They decided to charter an airplane and fly to Mount St. Helens to photograph and observe the volcano. At about 7:15 a.m., they took off from Yakima airport with pilot Bruce Judson.

At 8:30 a.m., some campers north of the mountain were up and enjoying a clear blue sky and warm gentle breezes from the west; others were still in their tents and sleeping bags. Fishermen, a few loggers, and other early risers had long been on the move. Several volunteer volcano watchers and amateur radio operators were at their posts. Some photographers, cameras cocked, were already awaiting the mountain's next move. The Stoffels and pilot Judson were in the air over the volcano. In Yakima, Robert L. Washburn, geologist for the Washington Department of Transportation, and his friend Chris Linschooten started on a morning run along a road west of the city.

At Coldwater II, Johnston had already made two sets of laser measurements to the growing bulge and had transmitted the last data to Vancouver at about 7:00 a.m.

The quiet was ended abruptly at 8:32 a.m. by an earthquake of about magnitude 5.1, the first in a day-long series of sharp quakes and seismic noise "like we'd never had before." That earthquake started a chain of events that was to leave the mountain and its surroundings drastically changed and was to claim the lives of about 60 people.

The earthquake shook the walls of Mount St. Helens' summit crater and started many small avalanches. Then, a huge slab of the northern slope of the volcano in the area of the bulge began to separate from the main cone along a crack across the upper part of the bulge. As this immense mass of rock and ice plunged northward, small, dark clouds emerged from the base of the slide, followed closely by vertical plumes of steam and ash from the crater area.

As the huge avalanche raced down the volcano's lower flank, black clouds grew from the scar of the mountainside. Within seconds, as more of the northern flank slumped downward, these clouds developed into a large blast, directed outward, that became a devastating hurricane of ash and coarser fragments. The avalanche, now outdistanced by the lateral blast, slammed into a ridge about 5 miles north of the old summit, forming a hummocky debris flow that overtopped the ridge at one place but mostly turned to flow westward down the valley of the North Fork Toutle River as far as 14 miles. Farther east, part of the avalanche debris dived into Spirit Lake, where it displaced the water as a huge swash onto adjacent slopes, buried countless trees already blown into the lake, and raised the lakebed by more than 200 feet.

The major lateral blast probably began about 20 to 30 seconds after the triggering earthquake and spread northward at remarkable speed. Seventy-seven seconds after the earthquake began, a seismic station about 3.5 miles from the blast origin stopped sending signals to the University of Washington seismology center, presumably when the instrument was hit by the blast. That timing suggests an outward speed of 220 to 250 miles an hour for the debris-laden blast cloud.

Johnston was among the first to see the avalanche and the beginning of the eruption. He probably was outside his trailer making measurements to the mountain and recording data. He grabbed his radio. "Vancouver, Van-

couver, this is it," he shouted—then, as the black, hot cloud of the lateral blast raced toward him, a final transmission, too garbled to be understood.

The center in Vancouver did not receive his warning; atmospheric disturbance caused by the eruption probably blocked the radio signals. Johnston's message was received instead on the radio of a private citizen and recorded on an attached tape recorder.

A more detailed warning came from volcano watcher Martin on the ridgetop north of Coldwater II. When the action started, he coolly radioed a description of the avalanche, the beginning of the eruption, and the progress of the blast cloud. "The camper and the car just over to the south of me [Coldwater II] are covered," he reported. "It [the blast cloud] is going to get me, too." He was right. There was no escape from his position.

No one could see what was happening within the spreading dark hurricane, but later observations showed that the blast had spanned an area north of the crater in an arc of nearly 180°, which measured 23 miles across from east to west and extended from the mountain crest northwestward for about 18 miles. Within that area was an inner zone nearly 6 miles wide in which almost all life was destroyed. Trees were stripped of their branches and snapped off near the ground or uprooted, and vehicles were overturned. In an area rimming that zone and extending to near the edge of the blast area, trees were mostly denuded and toppled; on the outer limit, trees were left standing but seared.

How hot the blast was can only be estimated by its effects; melted plastic and charred wood found in its path suggest temperatures as high as 680°F (360°C). Later, scientists made a preliminary estimate that the energy of the blast was equivalent to at least a few megatons of TNT and greater than the first atom bomb, although the sustained volcanic explosion was entirely different in character

VIEW FROM ABOVE

The Stoffels watched and photographed the beginning of the eruption from the air, narrowly escaping the initial blast and the rapidly spreading ash cloud. Here is their story (Korosec and others, 1980):

"At about 7:50 a.m., we entered (with permission) the restricted air space around Mount St. Helens from the northeast and began our first pass in the clockwise direction. We were immediately impressed and surprised by the wet appearance of the north face. We circled above the base of the volcanic cone, at an altitude of about 11,000 feet, taking photographs. The mountain looked serene, with only very minor wisps of steam blowing toward the north and west. Striking features on the north side of the mountain included large wet areas glistening around Goat Rocks and Sugar Bowl, where small avalanches had kicked up rocks and snow. The reddish-brown debris flows surrounding the two domes contrasted sharply with the lighter color of surrounding slopes. We wondered if these flows were very recent features and if they were hours or days old.

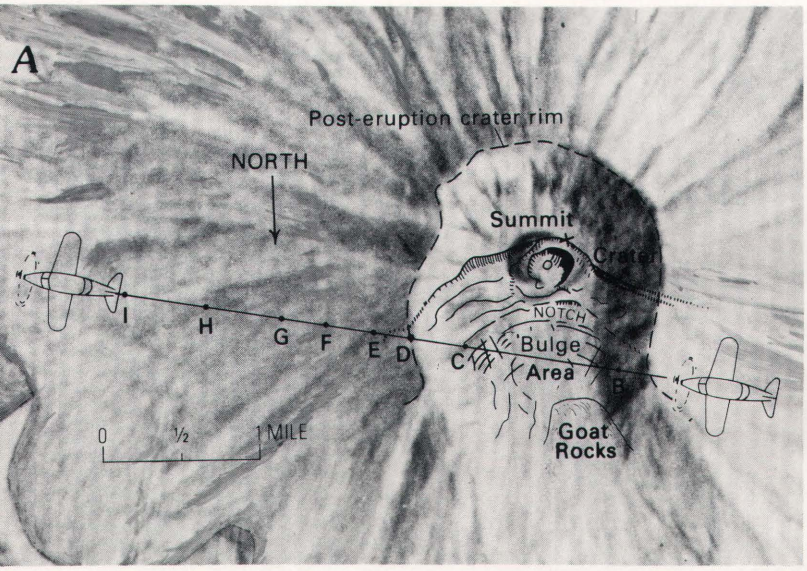
"After we had completed the first pass, we began the second from the north-northeast, with a tight bank and a pass directly over the south side of the summit crater, at an altitude of about 11,000 feet. Again we were impressed by the serenity of the scene below. Activity included very minor steaming from a vent at the bottom of the main crater and from a small hole on the southeast side of the top surface of the raised southern lip of the crater [fig. 21*B*]. We saw numerous wet seeps on the north-facing wall of the main crater, and a small lake had formed on the crater floor just below this area. As we continued westward across the crater's edge, we noted the immense fractures on the top of the south lip.

"After we circled around to the north, we began a third pass along the same path followed in the previous pass, crossing directly over the summit. We didn't notice anything different, but the pilot thought he noticed more extensive cracking.

"The fourth pass began with a wide sweep to the northwest to get a better overview of the entire mountain. We circled clockwise at a distance of about 5 or 6 miles from the summit, passing over the northern end of Spirit Lake, and viewing each of the flanks as we continued the circular path. We turned sharply on the west side of the crater, intending to pass over the summit and continue east back to Yakima.

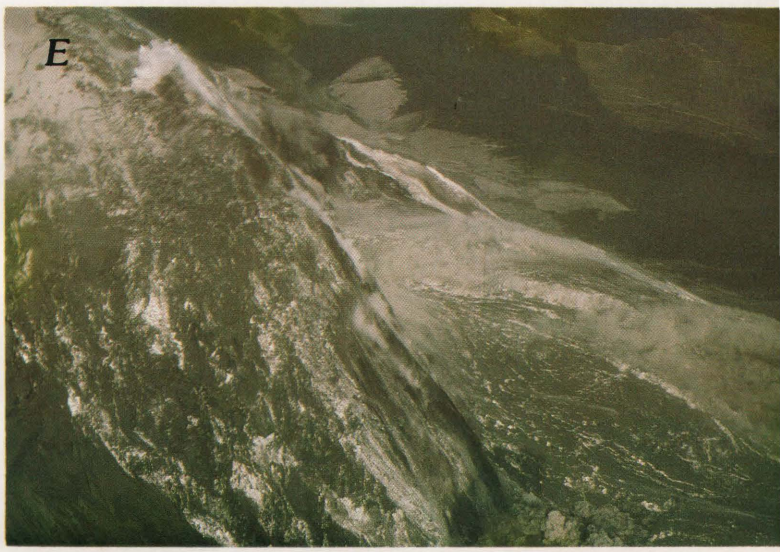
"As we approached the summit, flying at an altitude of about 11,000 feet, everything was as calm as before. Just as we passed above the western side of the summit crater, we noticed landsliding of rock and ice debris inward into the crater [fig. 21*C*]. The pilot tipped the wing towards the crater, giving us a better view of the landsliding. The north-facing wall of the south 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. As we were looking directly down on the summit crater, everything north of a line drawn east-west across the northern side of the summit crater began to move as one gigantic mass. The nature of movement was eerie, like nothing we had ever seen before. The entire mass began to ripple and churn up, without moving laterally. Then the entire north side of the summit began sliding north along a deep-seated slide plane [figs. 21*D, E, F*]. We were amazed and excited with the realization that we were watching this landslide of unbelievable proportions slide down the north side of the mountain toward Spirit Lake. We took photographs of this slide sequence occurring, but before we could snap off more than a few pictures, a huge explosion blasted out of the landslide-detachment plane [fig. 21*G*]. We neither felt nor heard a thing, even though we were


A
Post-eruption crater rim
NORTH
Summit
Crater
NOTCH
Bulge
Area
Goat
Rocks
I
H
G
F
E
D
C
B
0
½
1 MILE


B
NOTCH


D


E


G


H

FIGURE 21.—Aerial closeups of the earthquake-triggered landslide and the beginning of the devastating May 18 eruption of Mount St. Helens. (Photographs copyright 1980 by Keith and Dorothy Stoffel.) *A*, The airplane carrying geologists Keith and Dorothy Stoffel skirted the northern side of the crater during the earthquake that triggered the huge north-side avalanche and the start of the May 18 eruptions. Symbols show the approximate flightpath and positions of the airplane when the accompanying photographs were taken. *B*, View from a position about 1,000 feet higher than the northwestern lip of the summit crater, less than 1 minute before the major eruption. The crater was serene, and there was little steaming. A fumarole in the Notch (fault trench) north of the crater was fuming only enough to show a slight haze. *C*, As the airplane passed just north of the crater, a strong earthquake started avalanches of ice and rock debris on the southern wall of the crater, seen here from the northeast, and also triggered a huge avalanche on the northern side. When this photograph was taken, the area shown in the lower right was "rippling and churning in place" but had not yet slumped downward. A puff of steam that had appeared from the Notch fumarole (shown by an arrow) also shows clearly in *D*, *E*, and *F*. *D*, This view westward across the upper northern side of the crater stops the action as a large slab of the mountainside was dropping to the north and forming an avalanche tongue. The slide mass has detached from a steep slide face, seen here from the edge, to the right (north) of the steaming Notch area (shown by an arrow). Fuming from the slide face also had begun. The northwestern rim of the crater is seen in the upper left of this photograph, and the eastern part of the South Fork Toutle River valley is in the upper center. *E*, Moments later, the slide mass had moved farther down and toward the north (right), and a second slab had begun to slide down after the first. Fume emission increased from the slide face and Notch areas. The first dark ash plumes were seen starting from the lower edges of the slide face—one above and to the left of center in this view and the other at the bottom edge to the right of center. *F*, The initial slide mass had moved even farther down, and the entire remaining mass of rock and ice north of the crater rim (upper left) had begun to slump as this picture was taken. Fume and ash eruptions were beginning from the slide face, the Notch area, and the bottom of the crater itself (just out of view at the upper left). *G*, The eruption cloud grew from emanations from the north-side slide face, the former Notch area, and the bottom of the crater. These sources determined the initial shape of the eruption cloud, here partly hidden from view (see figs. 23 and 24). *H*, Although the vertical crater plume appeared almost stationary, the lateral cloud grew quickly and violently. Note the projectiles (rock and ice) being thrown to the north (right of this view). *I*, This view, photographed shortly after *H*, shows slight further growth of the vertical plume. At this point, the darker cloud (right) was becoming the upper part of the rapidly expanding lateral blast (see figs. 23, 24, 25, and 26). The Stoffels had used all their film, and the pilot opened the throttle and dove the airplane to escape the expanding blast cloud.

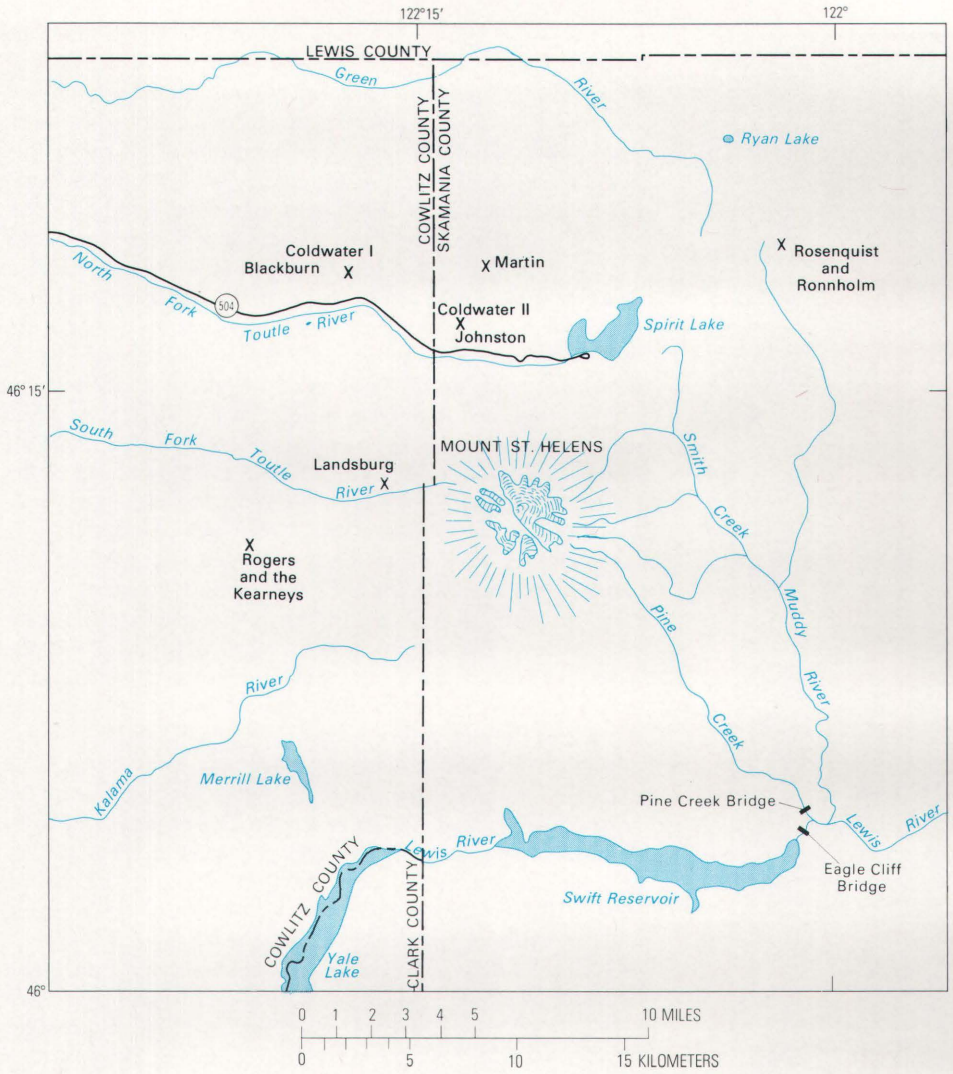


FIGURE 22.—Sketch map of the Mount St. Helens area showing where some of the victims of the May 18 lateral blast and some of the photographers contributing to this report were located. (Modified from Cummans, 1981.)

just east of the summit at this time. Dorothy saw the southern portion of the summit crater begin to crumble and slide to the north just after the initial explosion [fig. 21*I*].

"From our viewpoint, the initial cloud appeared to mushroom laterally to the north and plunge down. Within seconds, the cloud had mushroomed enough to obscure our view. At about this time, the realization of the enormous size of the eruption hit us, and we focused our attention on getting out of there. The pilot opened full throttle and dove quickly to gain speed. He estimated that we were going 200 knots. The cloud behind us mushroomed to unbelievable dimensions and appeared to be catching up with us. Since the clouds were billowing primarily in a northerly direction, we turned south, heading straight toward Mount Hood.

"After a couple of minutes, we felt sure we had outrun the clouds. Behind us, we could see the clouds continue to mushroom to the north and northwest. An ash cloud rolled across the summit and down the south face, completely enveloping the cone and eventually obscuring all but the lower slopes. The pilot suggested turning west and flying around the west side of the cloud, but after we thought about it briefly, we realized that the billowing clouds were moving west faster than we could fly. To the east of the volcano, the ash cloud separated into billowing, mushroom-shaped clouds and a higher overhang of cirrus-type clouds. Ashfall from the mushroom-shaped clouds was heavy. Lightning bolts shooting through the clouds were tens of thousands of feet high. Soon, the ash extended to altitudes higher then 50,000 feet.

"We thought about flying back to Yakima and even turned to the east briefly, but again we decided against it, realizing we could never beat the ash cloud. Sometime between 9:00 and 9:15 [a.m.] we landed at a Portland airport."

VIEW FROM THE WEST

Ty and Marianna Kearney were at a ridgetop site 7.6 miles west of the summit outside the restricted zone (fig. 22). Like Martin, they were amateur radio operators serving as volunteer volcano watchers, and they had been living in their camper van at that site for nearly a week. Also at the viewpoint that morning was sightseer Robert Rogers. The triggering earthquake drew their attention to the peak; they then watched the avalanche and the growing eruption plumes in profile.

Rogers ran for his camera, which was about 60 feet away, and began taking pictures (fig. 23). He was able to expose only a few frames during a span of perhaps 15 seconds before his camera jammed.

Kearney radioed a warning about the eruption and then began using his camera, taking his first picture (fig. 24*A*) several seconds after Rogers' camera failed. The observers heard a roaring sound as the laterally directed cloud began to roll down the mountain, and they could see fires starting as lightning in the cloud ignited trees. They drove southward to safety by roundabout logging roads as winds generated by the eruption rocked their vehicles.

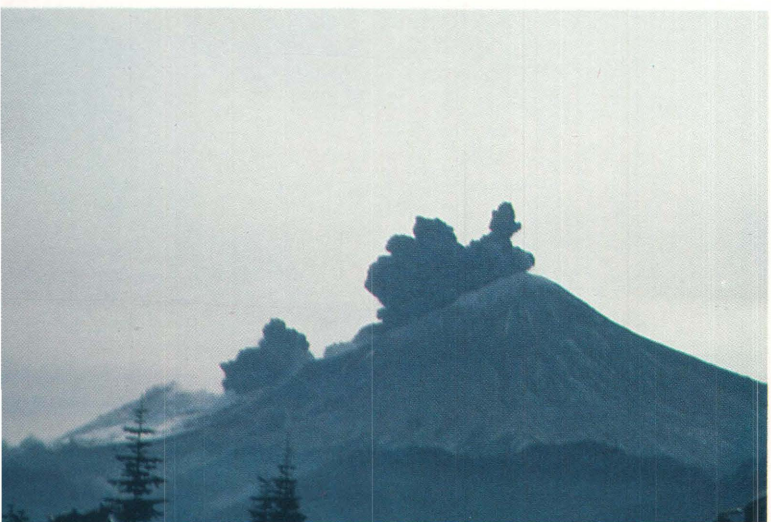


FIGURE 23.—These photographs of the early part of the May 18 eruption were taken from a ridgetop 7.6 miles west of Mount St. Helens. The photographer felt the triggering earthquake, saw the beginning of the eruption, and operated his camera as fast as possible (manually) until it jammed after he took the last picture shown here. He estimated that this sequence required about 15 seconds. Even at this early stage of events, the front of the avalanche was already out of sight below the horizon to the left of the large, streaked hump (which probably was a dust cloud). Marianna Kearney, a volunteer observer and radio operator stationed at the site, is in the right foreground near her camper van. (The earlier development of this avalanche is shown in fig. 21.) These pictures also show the growth of both a lower and an upper laterally directed eruption cloud. Similarities in the sizes and shapes of the eruption clouds show that the second picture in this sequence must have been taken at about the same time as figure 21*G*.


A


B


C

FIGURE 24.—This sequence of photographs, which, like that in figure 23, was taken at a site 7.6 miles west of the summit of Mount St. Helens, picks up shortly after the sequence shown in figure 23 leaves off and covers a time interval of about 15 seconds. It shows the further development of the north-directed blast. The panoramic photograph (*C*) spans an arc of about 90°. Mount Rainier is at the lower left edge; the site of Coldwater II is in the lower center of the left half, obscured (and probably already demolished) by the rapidly expanding lateral blast cloud. The photographs were taken by Ty Kearney, an amateur radio operator and volunteer volcano observer for the Washington State Deparment of Emergency Services. Observers at the site distinctly felt the earthquake that triggered the huge debris avalanche preceding the eruption. (Photographs copyright 1980 by Ty and Alan Kearney.)


A


D


G

FIGURE 25.—This remarkable sequence of photographs was taken by Gary Rosenquist, who was camped at Bear Meadow about 11 miles northeast of the summit of Mount St. Helens. On the morning of May 18, he had mounted his camera on a tripod and was thus well prepared to record the fast-moving events that began at 8:32 a.m. These photographs (copyright 1980 by Gary Rosenquist) are estimated to span about 20 seconds. *A*, This photograph was made at about the same time that Keith Stoffel, flying above the volcano, was taking the picture in figure 21*E*, looking down the avalanching northern face of the mountain. At this early stage, the summit eruption cloud was just beginning to emerge. The first huge avalanche mass was roaring northward; its front was already below the crest of the timbered ridge (lower right), and a second slab of the mountain's northern side was beginning to slump. The beginning of the lateral blast is shown here by small black eruption clouds on the left- and right-hand sides of the scarp left by the avalanches. *B*, and *C*, In these views, the second large slab from the upper northern side was falling and also was beginning to be blown apart by the lateral eruption, and the eruption plume from the summit area was rising rapidly. The left-hand (eastern) side of the avalanche mass consisted largely of ice from the Forsyth Glacier (white area in left center of both views), which was flowing around a dark rock obstruction. (Compare with ice extent in *A*.) *D*, *E*, and *F*, Both the vertical and the lateral eruption clouds enlarged rapidly as the avalanche mass moved downward and to the north (right). *D* stops the action during the collapse of the entire remaining upper northern side of the mountain. At about the same instant, Robert Rogers was taking his first picture (fig. 23*A*) from the west. *G*, The forceful blast cloud overtook the trailing edge of the avalanche mass and may have boosted its upper part (lower right) in its northward rush. *H*, By the time that this picture was taken, the upper (darker) and lower parts of the lateral blast had merged, and the blast was in full force. Most of the upper northern side of Mount St. Helens was involved. Large blocks of rock and ice (right center) were thrown through the air to the north.

VIEW FROM THE NORTHEAST

At Bear Meadow, about 11 miles northeast of the summit of Mount St. Helens (fig. 22), Gary Rosenquist, an amateur photographer, and Keith Ronnholm, a graduate student in the University of Washington Geophysics Program, were camped within a few hundred yards of each other, along with several other parties of campers. Earlier in the morning, Rosenquist had mounted his camera on a tripod and aimed it at the volcano. Thus prepared, he was able to begin taking pictures as soon as he realized that a huge avalanche was occurring. After taking the remarkable sequence of eruption photographs shown in figure 25, he snapped a few more pictures, warned other campers who had not yet stirred, and drove his vehicle to safety northward of the blast zone.

Ronnholm was in his camper when the avalanche began, and he estimates that he did not start taking pictures (fig. 26*A*) until about 10 seconds after the eruption began (compare figs. 26*A* and 25*G*). He waited, taking more pictures from the same site and expecting the blast cloud to be stopped or diverted upward by ridges closer to the volcano. When the turbulent gray

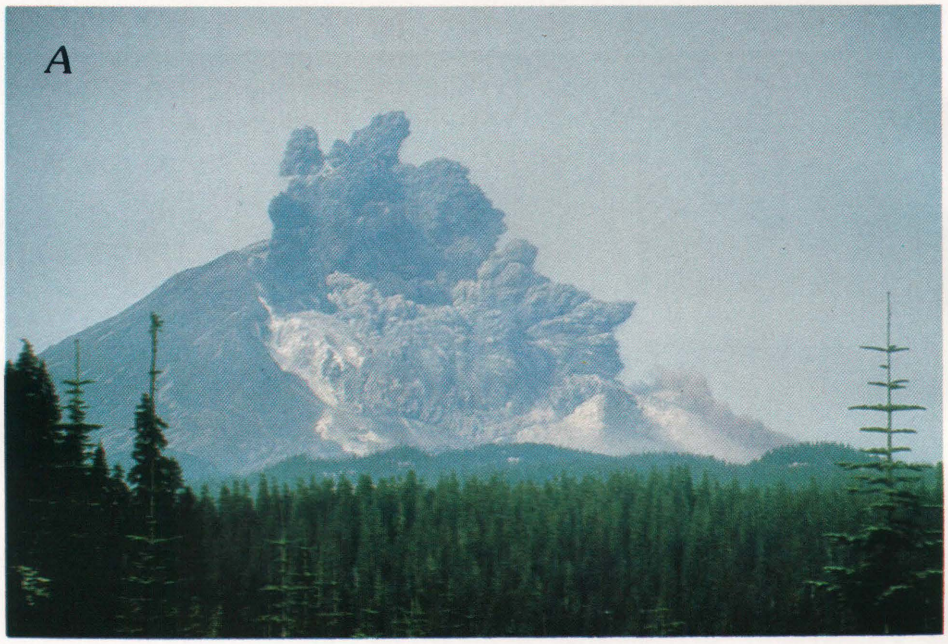


FIGURE 26.—Ground views of the rapidly expanding lateral blast cloud of the May 18 eruption. (Photographs copyright 1980 by Keith Ronnholm, University of Washington Geophysics Program.) *A*, View from about 11 miles northeast of the summit (from Bear Meadow), where geophysicist Keith Ronnholm began taking pictures about 10 seconds after the eruption began. The front of the avalanche was already out of view behind the ridge at the lower right; the upper and lower lateral eruption clouds (figs. 23 and 24*A*) were merging as they grew. *B*, Telephoto view from the same spot about 4 seconds later (about 14 seconds after the eruption began), taken at nearly the same instant that figure 25*H* was taken. Note the streaming projectiles (blocks of ice and rock) being thrown beyond the eruption cloud to the right.

cloud continued rushing toward the camp about 90 seconds after the eruption began, he took one more picture (fig. 26*C*) and began driving northward to outrun the cloud. Keeping barely ahead of the menacing hot cloud, he stopped about 3 miles farther from the mountain to take a picture of the towering front of the cloud (fig. 26*D*). About 8 minutes after the eruption began, airborne ash from the volcano was streaming eastward with the wind (fig. 26*E*). By that time, lightning was flashing, and thunder was a constant rumble. Shortly thereafter, rocks the size of golf balls began to fall on him. Ronnholm's vehicle was soon engulfed in an ashfall so thick and so dark that he could continue driving only by following a logging truck that was being guided by men walking ahead to feel out the road.

FIGURE 26. — Continued. *C*, The blast cloud quickly obscured the mountain and expanded northward. Ronnholm waited at the same site, expecting the cloud to be stopped or diverted upward by ridges between him and the volcano (*A*). When the cloud continued to expand beyond the first ridge and then the second and was still rushing toward him, he took this photograph (about 90 seconds after the eruption began) and then began driving his vehicle northward to outrun the cloud. *D*, Keeping barely ahead of the towering hot cloud, Ronnholm stopped about 3 miles farther from the mountain (about 6.5 minutes after the eruption began) and took this photograph by aiming his camera upward between trees. *E*, This photograph, taken toward the south from the same site about 1.5 minutes later, shows clear sky below the ash cloud, which by then was streaming eastward with the wind. (The volcano is to the right "about two photo widths.") By this time, lightning was flashing, and thunder was a constant rumble. Amid a shower of golf-ball-sized rocks and ash so thick and dark that he could barely see, Ronnholm escaped to the north.

VIEW FROM THE NORTHWEST

Marshall Huntting was up early at his home about 30 miles northwest of the mountain near the town of Silver Creek, Wash. (fig. 13). A former State Geologist, he was very interested in the volcano and had been observing it intently through binoculars during the past weeks as weather permitted. When he learned of the eruption, he made a hasty start in his car toward a nearby hill where he and his neighbors had watched previous eruptions of steam and ash. After a spinout at a road intersection, he got his car back on the road and arrived at the hilltop in time to see a widespread vertical eruption cloud rising to an amazing height and a ground cloud (from the lateral blast) spreading westward, apparently following the valleys of the North Fork Toutle River or the Green River or both. At about 8:42 a.m., the westward front of the ground-hugging cloud appeared to stop at a position about 2 miles upstream (southeast) from Camp Baker (fig. 22). Thereafter, the ground cloud seemed to be "sucked up into the vertical ash plume" rising toward the stratosphere.

About 20 minutes after the eruption began, observers at Silver Creek saw a second ash cloud rise from the direction of Mount St. Helens and begin moving westward near the ground, as the first cloud had. They could not see whether the second cloud originated at the volcano or was some kind of aftereffect of the original lateral blast. About 10 minutes after the second cloud appeared, the observers saw a white halo forming and rising around the vertical eruption plume from the volcano (fig. 27*A*). They noted that the second ground-hugging cloud extended even farther west than the first; according to Huntting, it stopped slightly west of the direction of Camp Baker, at about 9:30 a.m. (fig. 27*B*). Thereafter, the lower cloud seemed to settle rather than to rise. Part of it moved northwestward out of the Green River valley, crossed the Cowlitz River, and, at about 10:15 a.m., stopped at Silver Creek, the northwesternmost extent of ashfall from this eruption. The higher ash cloud gradually drifted eastward as the volcano continued its upward eruption, and the western side of the volcano was clearly visible (fig. 28).

OTHER OBSERVATIONS

After watching the "slow-motion" beginning of the eruption, other observers sought escape as the lateral blast cloud sped outward to the north and overtook dozens of people in a wide area. Some survivors told of racing their automobiles at breakneck speeds along mountain roads to escape the turbulent dark cloud.

At least one couple, however, drove to the mountain after they heard about the eruption. They avoided roadblocks and drove as far as they could up a logging road. Three miles from the mountain, their car was disabled by volcanic ash. Luckily, a passing helicopter crew spotted them and flew them to safety.

A party of 12 climbers had risen early to ascend Mount Adams, 34 miles east of Mount St. Helens. They had reached the false summit, at an elevation of 11,800 feet, when the eruption started. Within 10 minutes, they felt a "heat wave"—a rise in temperature of 30° to 40°F (17°–22°C)—that lasted several minutes. Afterward, a gray cloud cut off the sun, and the atmosphere became charged with electricity.

The climbers heard no sound from the eruption, nor did observers at Silver Lake, 30 miles west of Mount St. Helens, but others 18 miles northeast of the mountain heard a rumbling that sounded like a large avalanche 1 or 2 minutes after the first dark eruption cloud rose. The sound of the initial explosion was heard distinctly in northwestern Washington and southern British Columbia in Canada. Instruments at the National Oceanic and Atmospheric Administration laboratory in Silver Spring, Md., detected an atmospheric wave 3 hours and 20 minutes later; in another 10 minutes, instruments at Columbia University's Lamont-Doherty Geophysical Observatory in New York registered it. The average speed of the wave traveling across country was nearly 700 miles an hour.

Seismograph records show that the triggering earthquake came from a depth of roughly 1,000 feet below sea level and from a point about 1 mile due north of the summit. The initial quake was followed about 2 minutes later by a second earthquake of roughly the same magnitude (about 5). Strong seismic signals were recorded for another 10 minutes (until 8:44 a.m.); then, seismic activity was relatively low for the following 3 hours. At 11:40 a.m., instruments at the University of Washington seismology center began to show a gradual increase in seismic activity. By 1:30 p.m., it was impossible to discriminate individual earthquake traces on the recorder charts

FIGURE 27.—Photographs taken about 1 hour after the start of the May 18 eruption from a spot about 31 miles northwest of Mount St. Helens. (Photographs by Mrs. Jim Lenz.) *A*, This photograph, taken about 9:20 a.m., shows, beyond the distant ridges, the westward-spreading plume of a ground-hugging ash cloud (the second that was seen) when it had reached a position about 14 miles west of the volcano, probably following the valley of the North Fork Toutle River. Also shown is the "halo" that first began to appear around the ash column rising from Mount St. Helens (hidden at left edge of this view) about half an hour after the eruption began. *B*, This view, taken from the same site about 9:30 a.m., shows the second ground plume near its westernmost extent, about 15 miles west of the volcano. The umbrellalike higher cloud from the vertical eruption column first spread outward in all directions but later was swept eastward, and the western side of the mountain was left clearly visible (see fig. 28). The ground plume continued to spread northward, its northwestern edge stopping at about 10:15 a.m. near where these pictures were taken.


A


B

FIGURE 28.—The dense column of ash from the May 18 eruption billowed out of the volcano almost steadily for more than 9 hours after the lateral blast had removed the upper northern side of the mountain (hidden in this view from the south-southwest). The ash reached an altitude of more than 15 miles, well into the stratosphere, but most of it was carried eastward at lesser altitudes by the prevailing winds and often formed distinct horizontal layers in the sky, as seen here. The large white cloud extending above the low layer of ash to the left of the eruption column was rising from large steam explosions in hot avalanche deposits near the southwestern end of Spirit Lake (see fig. 30). Less violent steam vents (left of mountain) were scattered across avalanche deposits that extended into the upper valley of the North Fork Toutle River. This photograph was taken about 11:00 a.m., May 18, 1980, by David Frank (USGS).

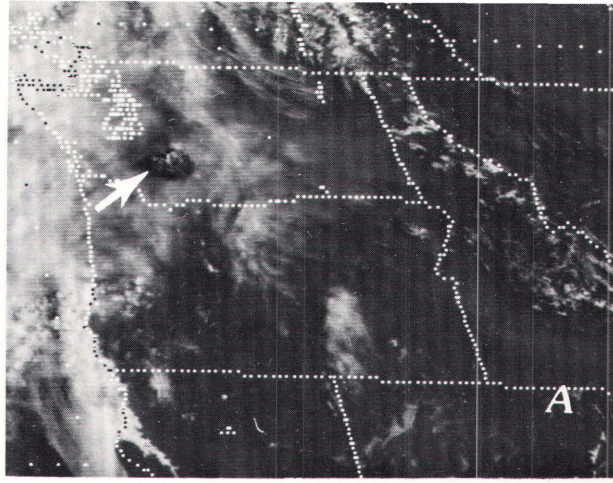
because of the large number of seismic events and the strong harmonic tremor. The seismic activity peaked about 3:40 p.m., declined, and reached "moderate" levels by 5:30 p.m. Harmonic tremor continued at fluctuating levels.

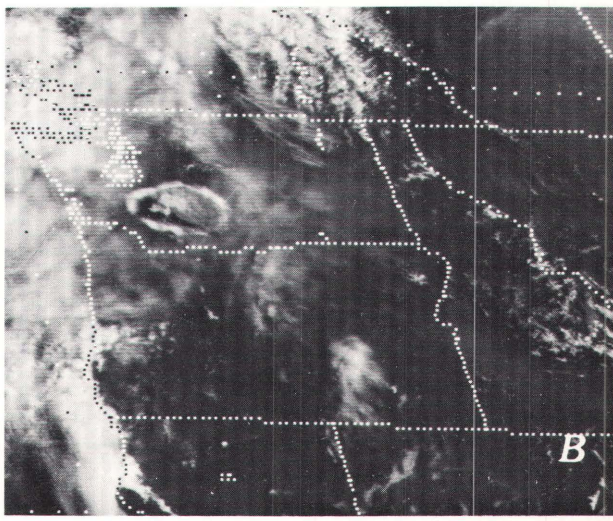
ASH SPREADS EASTWARD

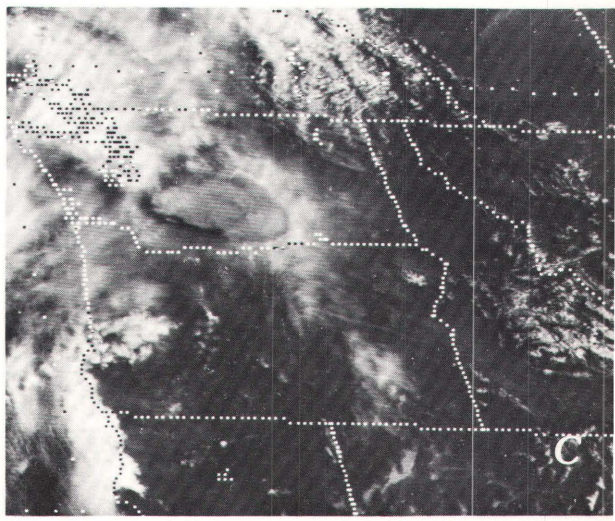
Although vertical plumes of steam and ash accompanied the beginning of the lateral blast (figs. 21*G*, *H*, *I*), the lateral blast was well underway before the strong vertical eruption from what had been the volcano's summit crater began. Ash from the vertical eruption column, which within 10 minutes had risen to a height of more than 15 miles, was rapidly blown to the east-northeast. The ash cloud produced countless lightning flashes that started hundreds of fires in trees and forest debris near the volcano.

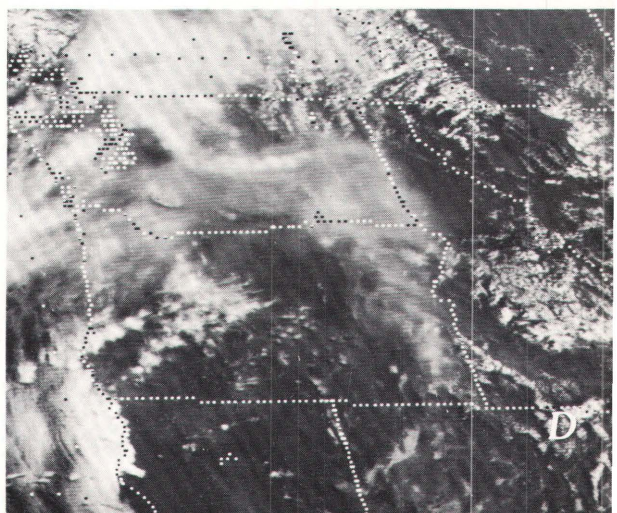
Dense clouds of ash from the continuing eruption turned daytime to darkness as far as 120 miles away, and a lighter covering of ash dusted areas many hundreds of miles away. Ash fell heavily in Montana and visibly as far east as the Great Plains of the Central United States (fig. 29).

By 9:30 a.m., Washburn and Linschooten had run from Yakima toward the community of Cowiche. As they continued running in the warm, clear morning, they began to see what they thought was a very dense rain cloud rising over the foothills of the Cascade Range from the west, the normal direction for storms moving into the area.









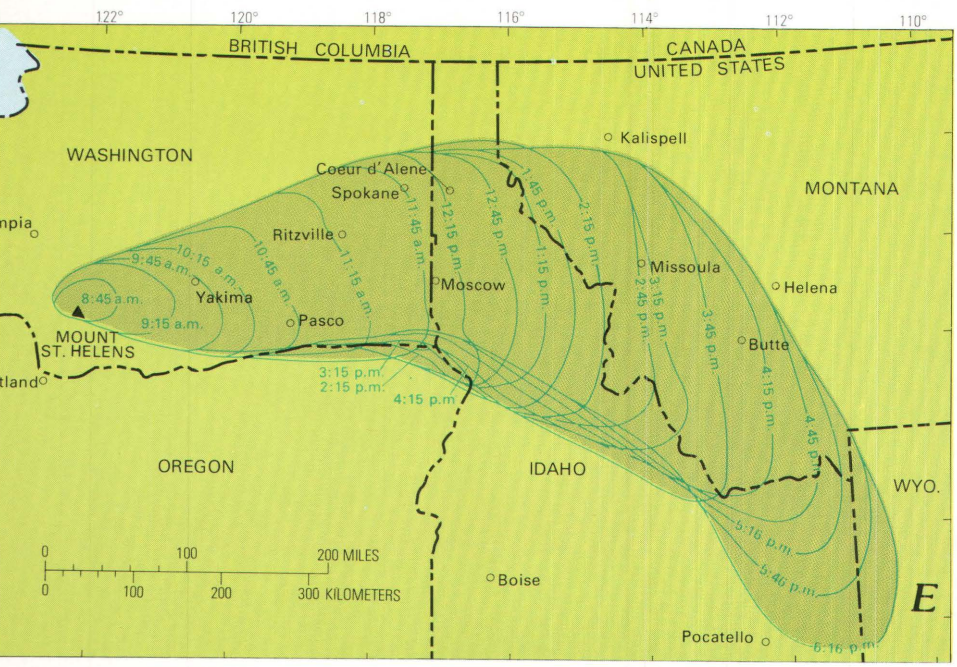


FIGURE 29.—Satellite pictures and map show the eastward spread of the ash plume from the May 18 eruption, which began at 8:32 a.m., Pacific Daylight Time. (Photographs from the National Oceanic and Atmospheric Administration.) *A*, By 8:45 a.m. (eruption plus 13 minutes), the eruption cloud (shown by an arrow) was already large enough to be seen clearly in the image from a satellite more than 22,000 miles above the Earth. *B*, By 9:15 a.m. (E plus 43 minutes), the eruption cloud was spreading rapidly, still expanding in all directions from the volcano. *C*, By 10:15 a.m. (E plus 1 hour, 43 minutes), the ash had expanded eastward across the Cascade Range into eastern Washington, reaching beyond Yakima (see accompanying map). *D*, By 12:15 p.m. (E plus 3 hours, 43 minutes), the ash was falling on Spokane and had extended into Idaho. A dense ash cloud from the continuing eruption persisted near the volcano. *E*, Sketch map showing times of arrival of the airborne ash as it spread across the Northwest. The time lines represent the margins of the ash plume as seen in satellite images at half-hour intervals (from Sarna-Wojcicki and others, 1981).

The cloud appeared very dark blue—the "darkest thunderhead" either had ever seen—and had a very abrupt edge on its northwestern side. Although the cloud looked ominous, they still hoped to outrun the "storm." When they were about 2 miles east of Cowiche (8 miles from home), they were suddenly heavily pelted with sand-sized particles; they then realized that Mount St. Helens had begun a major eruption, and they turned back toward Yakima. The sky very quickly turned black, and the pelting ash particles were accompanied by "bad lightning." They sought shelter under the stairs of an old fruit warehouse near the road. After about 15 minutes, a young man in a flatbed truck came by; the runners flagged him down and were driven back to their homes. By this time (10:30 a.m.), it was black as a dark night, and ash continued to fall. The ashfall diminished, and the sky started to lighten about 3:30 p.m., but soon the darkness and the ashfall resumed.

Just before the ash arrived at Yakima, aircrews of the National Guard 116th Armored Cavalry Squadron quickly detached armaments from their helicopters and scrambled to get the aircraft into the air. Twelve of their 32 helicopters did not get off the ground in time. The other 20 headed north where they "could still see light in the sky." They flew a long route north and then west around the ash cloud and were directed to the Kelso airport and to the Toutle River valley to help with search-and-rescue efforts.

Ground-based radar observations at the National Weather Service's station in Auburn, Wash., showed increases in vertical ash emission at four distinct times—at about 8:40 a.m., 10:15 a.m., 12:45 p.m., and 2:00 to 4:00 p.m. Other observers said that the strength of the eruption at about 4:30 p.m. was second only to the 8:40 a.m. pulse.

The ash column (fig. 28) persisted for more than 9 hours, producing numerous pyroclastic flows. The early ones were mostly ***ash flows***, which were produced as the dense part of the eruption column fell back onto the volcano's flanks and poured downslope at least short distances on all sides. Later pyroclastic flows, from about noon on, consisted of ***pumice***, which was produced by the fountaining of lava froth from the eruptive center and poured out through the giant breach in the northern side of the crater. The pumice and ash flows fanned out over the huge mass left by the debris avalanche and extended part way down the North Fork Toutle River valley. Now and then, explosions caused by water flashing into steam within the hot pyroclastic and debris-avalanche deposits along the former river course blew material as high as 1 mile into the air and left craters as much as 2,000 feet across (fig. 30).

FIGURE 30.—Steam erupting from still-hot parts of the avalanche deposits 18 days after the major eruption. Hundreds of steam vents and craters formed near the site of Spirit Lake and the head of the North Fork Toutle River wherever the very hot volcanic deposits were contacted by water, which then turned to steam and blew out through the overlying deposits. The view here is toward the southeast. The steaming crater in the right foreground is about 250 feet across. The southwestern end of Spirit Lake, largely covered with floating forest debris, is in the lower left. (Photograph by Philip Carpenter, USGS, June 5, 1980.)

MUDFLOWS AND FLOODS

Water from melting snow and ice on the slopes of Mount St. Helens and in the avalanche debris and from the now-buried and disrupted stream channels produced dozens of mudflows, large and small (fig. 31). On or near the blasted mountain, mudflows developed within minutes, some pouring over and eroding deposits of the debris avalanche itself. Many mudflows stopped on the lower flanks of the volcano, and others were dammed temporarily behind debris deposits; many, however, coalesced and began to move through the major drainageways, generating floods all the way down the Toutle River and the Cowlitz River below it (fig. 32) and on into the Columbia River. The mudflows swept

FIGURE 31.—Effects of the May 18 mudflows in the vicinity of Mount St. Helens. (Photographs by Philip Carpenter, USGS, May 20, 1980.) *A*, The mudflow in the South Fork Toutle River reached the Camp 12 logging camp (27 miles downstream from headwaters on Mount St. Helens) about 1 hour and 40 minutes after the start of the May 18 eruption and left a tangled mass of logs and heavy equipment. *B*, The mudflow in the Muddy River left streambanks strewn with logs between ash-coated trees at a reach 16 miles downstream from headwaters on Mount St. Helens. *C*, Mudflows destroyed nearly all the bridges that crossed streams draining from the northern, northeastern, and northwestern parts of Mount St. Helens. This lack of stream crossings greatly hampered ground rescue and recovery efforts. The steel highway bridge shown in *D* was formerly at this site, on the North Fork Toutle River 23 miles downstream from headwaters on Mount St. Helens. *D*, The mudflow in the North Fork Toutle River was dense enough to support heavy machinery and this section of a steel two-lane highway bridge as it carried them downstream. The mudflows moved some of this heavy debris for miles before depositing it at places where the mud lost velocity.

FIGURE 32.—Effects of floods and mudflows in the Toutle and Cowlitz River valleys. *A*, The maximum stage of the May 18 mudflows on the Toutle River reached the second story of this house, as mud coatings on trees and structures show. When the high water (mud) receded, sediment deposits completely covered this homesite to a level about 3 feet above the first floor of the large house. The structure on the right was a large wing of the house that the surging mud ripped off and moved to the position shown here. Many lower or less protected homes were completely swept away by the mudflows or more severely smashed than this house by debris that the mud carried. The shallow, debris-choked channel in the background is the South Fork Toutle River near its confluence with the North Fork. (Photograph by Dwight R. Crandell, USGS, May 24, 1980.) *B*, Debris-laden floodwater from the Toutle River inundated the flood plain of the Cowlitz River, shown here, to a width of about 1 mile at Castle Rock. The volume of flood deposits left on the flood plain and in the channel of the Cowlitz is estimated to be as much as 40 million cubic yards, not counting a huge, unmeasured amount that was carried downstream into the Columbia River. (Photograph copyright 1980 by Bud Kimball, June 20, 1980.)

up thousands of logs (and heavy logging equipment) from timbering operations, destroyed homes, vehicles, roads, and bridges, and inundated broad areas of the Cowlitz River flood plain.

One small mudflow developed in the valley of South Coldwater Creek (fig. 7) from the tongue of avalanche debris that crossed into that valley over the ridge west of Spirit Lake. The mudflow probably buried everything that the lateral blast had carried into that valley from the site of Coldwater II.

Mudflows also moved rapidly down Smith Creek and Muddy River, which drain the eastern side of the mountain, and Pine Creek on the southeastern side. The mudflows, which were laden with logs and forest debris, took out a bridge near the mouth of Pine Creek as well as Eagle Cliff Bridge across the head of Swift Reservoir (fig. 22). A tree-planting crew that had been working near the upper Swift Reservoir opposite the volcano reported that Eagle Cliff Bridge was taken out by a towering flood surge "perhaps 30 feet high" that struck without warning about 9:00 a.m. Observers reported that the flood surge entering the upper (eastern) end of the reservoir caused an initial 6-foot rise in the water level at that end of the reservoir in about 15 minutes; the USGS reservoir gage at the dam 9 miles downstream recorded a rise of 2.6 feet by noon. The reservoir, whose level had been lowered previously, held the added volume and did not overtop the dam; thus, the flooding anticipated along downstream parts of the Lewis River was avoided. The mudflow left the eastern end of Swift Reservoir filled with mud and forest rubble, its brown color contrasting sharply with the clear blue of reservoir water farther west (fig. 33).

FIGURE 33.—Timber and mudflow debris, carried by flooding tributary streams that drain the eastern and southeastern slopes of Mount St. Helens, began entering the eastern end of Swift Reservoir about half an hour after the May 18 eruption began. The flood surge reportedly caused an initial rise of about 6 feet at this end of the reservoir in 15 minutes, but the level of the reservoir had been drawn down about 30 feet in anticipation of floods from the mountain. The mudflows poured about 11,000 acre-feet (about 18 million cubic yards) of mud and debris into Swift Reservoir and caused a water-level rise of 2.6 feet throughout the reservoir. (Photograph by Philip Carpenter, USGS, May 20, 1980.)

It took time for the major floods to build up in the Toutle River drainage system—time that allowed many in low-lying areas to escape with what they could carry. Within minutes of the lateral blast, law-enforcement officers were dispatched to warn people about the danger of flash floods and to police evacuation routes. Cowlitz and Skamania County personnel were ordered to prearranged flash-flood observation positions along the Lewis, Kalama, Toutle, and Cowlitz Rivers. People along these streams were alerted by radio, telephone calls, sirens, and loudspeaker warnings to be prepared for hasty evacuation.

The USGS stream-measuring stations were destroyed or disabled by the muddy floods or the bank-to-bank flood debris. By midafternoon, however, USGS hydrologists were in the area observing the floodflows. Their accounts, other eyewitness reports, partial records from the gages, and communication logs allowed USGS hydrologist John Cummans to reconstruct the downstream progress of the flood crests (Cummans, 1981).

The first of the Toutle River floods began as a major mudflow traveling down the river's South Fork. The mudflow originated in water-saturated eruption deposits on the western flank of the volcano and began developing during early phases of the eruption. By about 10:10 a.m., the mudflow was 27 miles downstream from the volcano at Camp 12 logging camp, where it demolished equipment and left a tangled mass of logs and debris (fig. 31*A*). The flow was swift, perhaps as fast as 20 miles an hour, in headwater reaches, but its speed decreased as the crest swept downstream. As the mudflow progressed downvalley, it battered down streamside trees and carried them along, swept up buildings and automobiles, washed away miles of roads along the channel, and destroyed at least one bridge. No one is known to have drowned in the South Fork flood, however, despite a few close calls.

By 10:14 a.m., the flood crest was nearing the confluence of the South and North Forks of the Toutle River and was described by a deputy sheriff as a 12-foot wall of water containing logs, debris, and buildings. The mass of debris came close to the underside of a bridge across State Route 504, about half a mile downstream from the confluence of the two forks, but floated safely underneath.

Downstream from the confluence, floodwater from the South Fork stayed within the channels, and its velocity decreased. The water level also dropped quickly after the flood crest passed. At a USGS stream gage on the Toutle River about three-quarters of a mile below the confluence of the two forks, the peak flow probably was reached before 11:00 a.m., but mud disabled the recording equipment, and so the exact time is not known. Hydrologists did determine, however, that the flood crest there was about 21 feet high, 1 foot higher than the highest flood recorded at that site since the gaging station was established in 1909. The floodwater apparently had dropped most of its sediment before it reached the Toutle River, where it was described as being very muddy water rather than the mud of farther upstream.

After the crest of the South Fork flood reached the Cowlitz River, its effects diminished greatly. At a USGS gage on the Cowlitz River at Castle Rock 2.7 miles downstream from the mouth of the Toutle River (fig. 6), the flood peak, which occurred there at 1:30 p.m., caused a water-level rise of only 3.2 feet. The arrival of the floodwater at Longview, Wash. (fig. 6), was marked not by a rise of water level but by the arrival of "logs, trees, limbs, and bark," which continued to float down the river past Longview for more than 3 hours.

The South Fork mudflow apparently was not greatly heated by the eruption deposits from which it originated. A survivor described the mud in the upper part of the valley of the South Fork as being like "warm, fluid brown concrete," but no other comment about the warmth of the mudflow was heard.

A second surge of mudflow was observed in the upper valley of the South Fork Toutle River about 2:00 p.m. This mudflow did not reach more than a few miles downvalley, however, and did no further damage.

Before the South Fork flood had reached Castle Rock, airborne observers had already reported that mudflows were developing in the upper valley of the North Fork Toutle River. Search-and-rescue flights into the area by military helicopters were getting underway at the time. No one knew how many residents had chosen to remain in the valley of the North Fork in spite of evacuation warnings or how many survivors of the eruption might be trying to make their way out of the area by the main highway (State Route 504) that follows the valley. More large mudflows, however, obviously would be a major danger.

The mudflow that came down the valley of the North Fork Toutle River originated in water-saturated parts of the debris-avalanche deposit in the upper valley. It was made up of many smaller mudflows and took hours to develop because individual small flows crossing the hummocky surface of the avalanche deposit became ponded in closed depressions and could break out and merge with adjoining mudflows only after filling the depressions. In the process, the mud picked up heat from the volcanic materials in the avalanche deposit and became steaming hot. The crest of the mudflow did not pass the downstream end of the avalanche deposit until after 1:30 p.m. By that time, the crest of the South Fork flood had passed Castle Rock, and the mudflows entering Swift Reservoir had subsided greatly.

The North Fork mudflow moved more slowly than the South Fork mudflow but was much larger and more destructive. The downvalley progress

of the mudflow was complicated by several massive logjams that, when they broke loose, caused flood surges that were especially destructive and that added to the uncertainty of flood-response efforts. The maximum flow at Camp Baker (fig. 22), about 5 miles downstream from the end of the avalanche deposit, came about 3:00 p.m. The mud destroyed most of the camp and carried away hundreds of stored logs as it moved downstream.

Unlike the South Flow mudflow, which became more fluid as it flowed downvalley, the North Fork mudflow remained thick and dense with sediment and thus was able to carry almost anything that it swept up or broke loose. A tongue of the mud flowed upstream into the Green River (fig. 6) and filled the rearing ponds of a fish hatchery with debris that included steel bridge girders. A few miles farther downstream on the North Fork Toutle River, observers said that the mud had the consistency of fresh mortar and that it carried ice chunks, buildings, and a variety of equipment, "riding high." They reported seeing a fully loaded logging truck being carried upright in the mud and submerged only to the lowermost tier of logs. Motion pictures of this steaming mudflow carrying everything from houses to a steel bridge framework, as well as an unimaginable number of trees and logs, were shown in color on local television stations within hours of the eruption. These films were the first visual indication for most people in the Pacific Northwest that such colossal devastation had begun.

When the North Fork mudflow reached the Toutle River valley, it was so great in height and volume that it dwarfed the record flood just established on the South Fork and extended flood damage to higher levels and broader areas. About 6:00 p.m., the mudflow destroyed the bridge at State Route 504, half a mile below the confluence of the North and South Forks of the Toutle River, just as it had carried away several other bridges upstream. Shortly thereafter, it also destroyed the gaging station a quarter of a mile downstream.

By 8:30 p.m., the mudflow reached the mouth of the Toutle River and began to raise the level of the Cowlitz River as well. At 8:41 p.m., a report said that a bridge 6.5 miles upstream from the mouth of the Toutle River had just been destroyed and that the flood level was still rising. This report raised serious concerns about a bridge on Interstate Highway 5 that crosses the Toutle River about a quarter of a mile above the river's mouth. Interstate 5 is the main north-south highway; if this bridge were to be destroyed or seriously damaged, transportation in this region would be severely curtailed. Moreover, if the mudflow were to wash out this bridge, it probably also would destroy a smaller highway bridge less than 1 mile upstream and a bridge for the main railroad just downstream from Interstate 5.

Washington State Patrol officers halted traffic on Interstate 5, as they had done for hours during the South Fork flood. Officials, local residents, and stalled motorists watched in anxious fascination as the mud lapped higher and higher on the concrete bridge abutments. Soon, large pieces of floating debris were scraping and banging on the underside of the bridge. The largest masses, such as cabins and vehicles, began to strike the upstream side of the trestle. They would hang there briefly and then submerge further and roll noisily under the bridge, causing it to shudder ominously. As darkness fell, the flood level was still rising. Then flood waves themselves began lapping the underside of the trestle. Logs could no longer float freely underneath; bark and limbs were sliced from their topsides as they scraped under the bridge. The number of logs banging the trestle forcefully before being carried underneath by the powerful mudflow was increasing.

No one knows how long the bridge and its approaches can withstand this battering from the debris and the erosive power of the mudflow. There are encouraging reports from observers, however, that flood levels upstream are receding.

Meanwhile, the nearby channel of the Cowlitz River can no longer carry the flow; its banks, too, have been overtopped by the muddy floodwater, which is spreading outward and inundating homesites and farms on the flood plain near Castle Rock.

CLOSE OF E DAY

Although the full story of today's events will not be known for months to come, their significance cannot be doubted. Within a few minutes, what was once Washington's fifth-highest peak lost about 1,300 feet of its height. What remains of its top, formerly a glistening white cone, has changed to ashy gray. The scenic view on the northern side has changed to one of stark desolation. Vast green forests have been transformed into jumbles of giant matchsticks. Spirit Lake, once clear and blue, is now a steaming expanse of black water and floating shattered trees. Broad ribbons of mud extend up the valleys of former trout streams and disappear into clouds of ash around the volcano. Gone are most of the glaciers that yesterday mantled the mountain's northern slope. Gone is Goat Rocks, relic of a past eruption episode.

Gone too, are the observation posts called Coldwater I and Coldwater II.

The toll continues to rise as losses and damage are reported. Dozens of homes and camps along the Toutle River and its forks have been destroyed, along with cabins and campsites at lakes north of the mountain. Volcanic ash inches thick is being reported from eastern Washington, although conflicting reports suggest that some of these thicknesses may be exaggerated. The North Fork Toutle River mudflow continues at very high levels, but, so far, it has spared the critically important highway and railroad

bridges that cross the lower Toutle River. The Cowlitz River is flooding extensive low-lying areas near Castle Rock, but it is still staying within its banks in downstream areas.

How many people died or are missing is not known, but some officials say that the total may reach into the hundreds. By dusk tonight, military and other helicopter crews had rescued or evacuated more than 130 survivors. They had also seen grisly evidence in the blast zone that others did not survive.

No one knows whether the worst is over or what the volcano will do next.

Continuing Threats and Mounting Toll

Monday, May 19
E Day Plus 1

The pace of the eruption has slowed. The ash column seldom rises more than a few hundred to a few thousand feet above the volcano; during the night, it appeared to consist mostly of steam. The volcano seems to be quieting. No one knows how long it will remain so.

Earthquakes, too, have diminished. What earthquakes there were today came from depths of 10 to 20 miles rather than from 3 miles or less, as they had before yesterday's eruption. Only three were stronger than magnitude 3.

Daylight revealed that the Interstate Highway 5 bridge was still standing, although it bore a load of mud and debris from last night's battering mudflow. The nearby highway and railroad bridges also survived. The Toutle River was still high, but the flood was diminishing, and the debris that it carried was no longer striking the undersides of the bridges. Mud lay thick on the riverbanks and on the wreckage that they held; it also coated the trunks of surviving trees up to the maximum flood level. Steam from the still-warm mudflow created a mist that added an eerie aspect to the morning's scene of mud and destruction. A bulldozer cleared the mud and debris from the Interstate Highway 5 bridge, which was reopened to traffic about 8 a.m.

Search-and-rescue operations were resumed at dawn but are hampered by ash and unstable deposits. No one knows how much time may be left before the mountain lets loose another killing blast.

Rescue efforts and attempts to assess damage north of the mountain are being made by aircraft only. Access roads in valleys affected by mudflows are largely buried or eroded away, and blown-down trees (fig. 34) block all roads throughout a wide area of the uplands. Ground vehicles also are hampered in other areas by loose, blinding ash, which slickens the roads and chokes engines. Many bridges that provided access across streams east and west of the mountain have been washed out by giant mudflows (fig. 31).

Even aircraft cannot always get close. Visibility is hampered by airborne ash and, in the upper valley of the North Fork Toutle River and near Spirit Lake, by steam from hundreds of new fumaroles rising from the hot volcanic debris. More important to fliers, however, is the danger to aircraft engines. No one knows for sure how much ash an aircraft engine can take in before it stalls. Still, the helicopter sweeps, flown mainly by Army and Army National Guard, Air Force, and Coast Guard aircraft, continue as frequently and as far afield as possible to locate and assist whatever survivors remain. National Guard helicopters alone reportedly helped rescue another 15 people today. (Eight National Guardsmen later would be awarded medals for heroism during the rescues.)

Visibility is hampered, too, by forest and ground fires started yesterday by the lateral blast and by lightning bolts from the ash clouds. Although the ash blanket is acting as a fire retardant, hundreds of fires inside the blast area are burning in wood debris buried beneath the surface. People in the area are too busy rescuing others—or trying to survive—to worry about the fires.

The magnitude of the disaster is just beginning to be realized. At least 5 people are known dead, and 21 are missing. These figures will no doubt swell in coming days as bodies are discovered and as relatives and friends are missed.

Among those known dead are Fred and Margery Rollins of Hawthorne, Calif., who stopped 15 miles from the volcano to watch the eruption. Included among the missing are USGS volcanologist Johnston, who had been at Coldwater II observation station; photographer Blackburn, stationed at Coldwater I; Mount St. Helens Lodge proprietor Truman, who had simply refused to leave; and volunteer radio operator Martin, whose radioed warning about the eruption provided precious lead time for organizing the rescue efforts.

Survivors tell harrowing stories of pumice raining on them, of outracing ash clouds and floods, of seeing others die, and even of seeing crows fall lifeless from the sky. Stranded survivors are being sheltered in churches, schools, and other public buildings in nearby communities.

In the Cowlitz River valley downstream from the mouth of the Toutle River, an area about 1 mile wide near Castle Rock lies under mud and water (fig. 32*B*). The flood crest from the North Fork Toutle River mudflow reached Castle Rock about midnight, causing a maximum water-level rise of 20 feet in the Cowlitz River at that point. That crest was more than 6 feet above the lowest nearby banks of the river. Much of the Cowlitz River flood

FIGURE 34.—Within a few minutes, hurricane-force winds from the May 18 lateral blast transformed vast stands of evergreen forest into drab tangles of giant matchsticks. The trees were stripped of their branches, toppled, and "combed" into patterns. The logging roads shown here are about 12 feet across. (Photograph by Austin Post, USGS, June 30, 1980.)

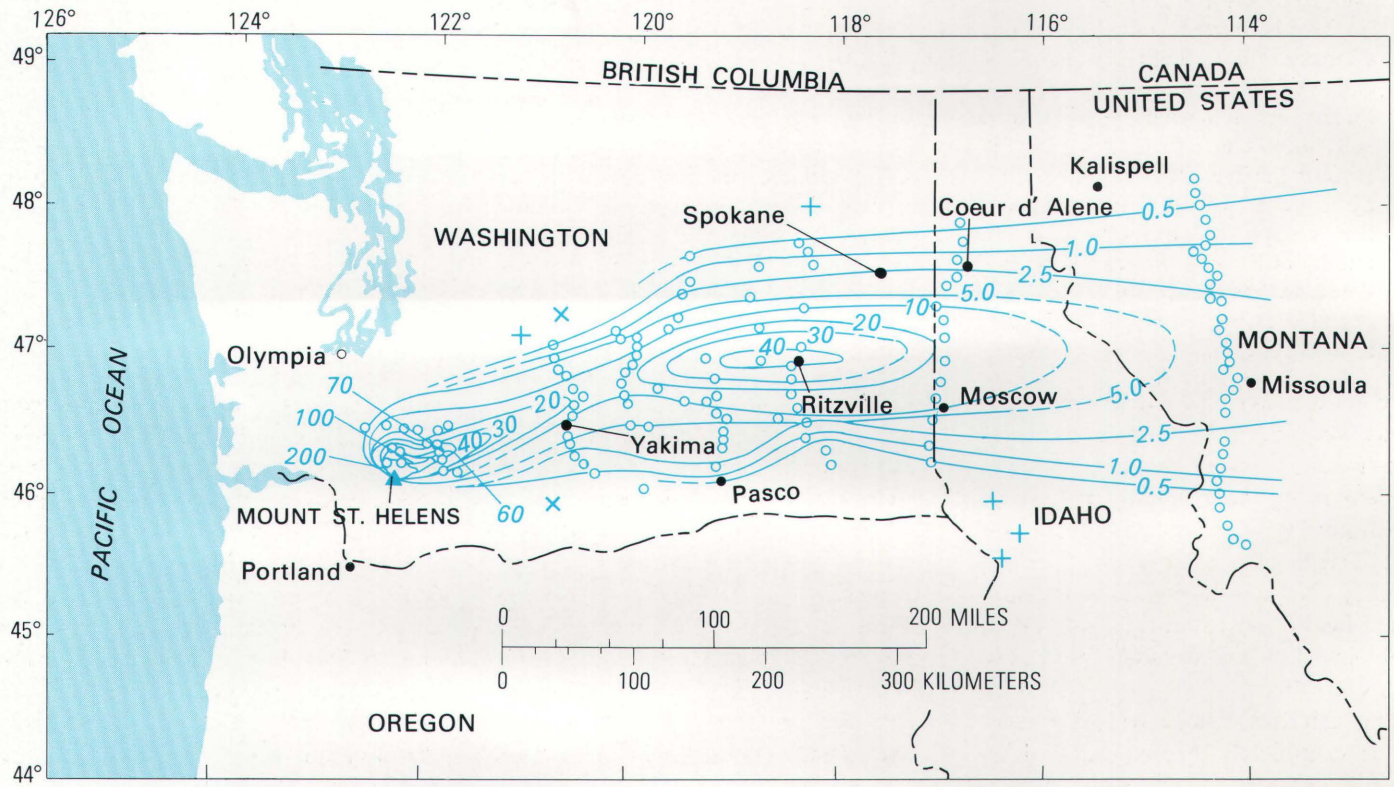
plain farther downstream was inundated to at least shallow depths all the way to a point about 4 miles upstream from Longview at the community of Lexington, where several low-lying homes were flooded. The cities of Kelso and Longview, however, were spared. The flood crest reached Longview about 4:00 a.m. today.

The North Fork mudflow has dumped huge volumes of sediment and debris into the Cowlitz River, which, in turn, is carrying it on to the Columbia River. Tugboat crews worked through the night on the Cowlitz River to keep floating trees and logs from forming logjams that would force water levels still higher. The Coast Guard reported that the Columbia River channel near the mouth of the Cowlitz also is littered with floating debris; another mass of logs and trees about 600 feet wide and extending for about 20 miles reportedly is floating down the Columbia River toward the Pacific Ocean.

This morning, the ocean-going freighter *Hoegh Mascot* went aground in the Columbia River near Longview, the first indication that the navigation channel of that river is blocked by deposits of mud and debris carried into it by the floodwaters from the Cowlitz. A Coast Guard spokesman said that the channel depth had decreased from 40 to 15 feet for a distance of 2 miles, "which severely limits the ships that can come to Portland." The Coast Guard closed the Columbia River to major shipping tonight; the closure strands 24 ships at the mouth of the Columbia waiting to come upriver and another 23 ships in the Portland-Vancouver area that cannot move downstream over the shallows in the navigational channel. The U.S. Army Corps of Engineers dredge *Biddle* is slowly pushing its way through the floating debris in the Columbia toward the shallow area to begin reopening a navigation channel for oceangoing ships.

The North Fork mudflow remained warm throughout its course to the Columbia River. Its temperature as it passed a bridge on the lower Toutle River was 91°F at 9:45 a.m. this morning. At Castle Rock, the mixture of mudflow and Cowlitz River water measured 85°F at 1:15 a.m. and again at 6:30 a.m. At Longview, the water temperature at 8:00 a.m., about 4 hours after the flood crest had passed, reportedly was 90°F. Fish could not

FIGURE 35.—Approximate distribution and thickness of measurable ashfall from the May 18 eruption of Mount St. Helens. Lines represent equal ash thickness, in millimeters (1 inch=25.4 mm), and are dashed where observations were lacking. Circles represent measurement sites; plus signs, sites where trace or light dusting was observed; crosses, sites where no ash was observed. The measurements were made over several days by several investigators. At many of the measuring sites, enough time had elapsed before the measurements were taken for the ash to settle and drift; at some sites, rain had fallen. Therefore, individual reports of ash-thickness measurements, especially those made before the ash had been disturbed by wind or rain, may be at variance with this map. (Map from Sarna-Wojcicki and others, 1981.)



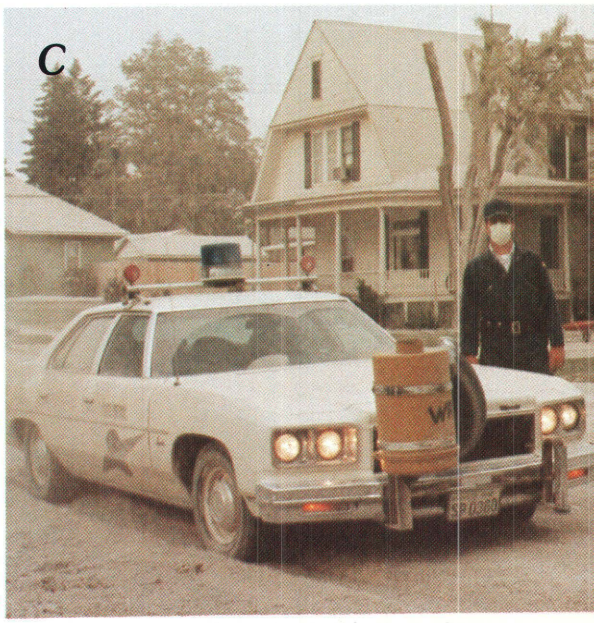


FIGURE 36.—Volcanic ash from the May 18 eruption blanketed much of eastern Washington and caused great disruption, hardship, and economic loss. *A*, Street scene in Yakima the afternoon of May 18. The dense ashfall made the day "black as the darkest night." (Staff photograph from *Yakima Herald-Republic*.) *B*, Many motor-vehicle accidents (most of them minor) were attributed to the ashfall. Most occurred when drivers, blinded by the ash, smashed into stalled vehicles ahead of them or, like the car shown in this photograph, lost traction in the ash and slid off the roadway. (Photograph courtesy of U.S. Soil Conservation Service.) *C*, Dozens of emergency vehicles in the "ash belt" were disabled, mostly by ash that clogged engine cooling systems or air filters. Several ingenious modifications were tried to keep vehicles operating, including large diesel truck air cleaners, like the one seen on this Washington State Patrol car. Because the fine ash rose in clouds at the slightest disturbance, the dust mask worn here by Trooper Leonard Whitney was an essential part of his outdoor uniform. (Photograph by Carolyn Whitney, May 19, 1980.) *D*, By May 19, the farming community of Ritzville was beginning to dig out from an ashfall of more than 3 inches, at the same time that it was providing emergency accommodations for more than 2,000 stranded travelers. The ash "drifted like snow but did not melt." (Photograph by Ronald Hartman, U.S. Soil Conservation Service.)

survive in water this warm, and hundreds were found floating dead on the floodwater.

Meteorologists tracking the eastward-moving airborne ash estimate that it will take 3 days to cross the country. No one knows how dangerous to health the ash may be, but other problems that it is causing are almost overwhelming.

The ash has halted transportation almost completely throughout most of central, eastern, and southeastern Washington, as well as in parts of Idaho and western Montana (fig. 35). State and local police have banned driving on the most dangerous roads and highways, and the Federal Aviation Administration yesterday closed all airports in affected areas. Westbound trains stopped today as far away as Billings, Mont., and Minot, N.D., to avoid entering the equipment-damaging ash.

In ash-blanketed areas of eastern Washington (fig. 36), thousands of motorists have been stranded by continuing poor visibility or by disabled cars. They spent last night wherever they could find shelter from the choking ash. One traveler in eastern Washington described the ashfall as "like being in a desert sandstorm without the wind." Minor highway accidents were reported in which cars ran off roads after losing traction in the ash or smashed into stalled vehicles that drivers could not see (fig. 36*B*), but no deaths have been reported.

Law-enforcement and other emergency-services crews struggled to keep patrol and service vehicles running, but about 200 patrol cars were disabled by ash yesterday and today. The damage to vehicles included seized engines that overheated after their cooling systems were clogged with ash, ruined vital parts that were just "worn out" by the abrasive ash, and clogged carburetors and air filters (fig. 36*C*). The fine ash, blown into clouds by each passing vehicle or gust of wind, enters every crack and crevice of a vehicle and seems impossible to control. Where the ash is deep, highway snowplows are at work in sometimes futile attempts to clear the ash off the roadways. Washington Department of Transportation officials said that highway-clearing work is being slowed up because the plows have to stop every 100 miles or so to have the ash blown from engine air filters. The ash drifts like snow but does not melt. It often blows back into cleared areas as fast as the crews can scoop it off.

The heavy ash, frequently described as being like Portland cement, has flattened many field and row crops in central and eastern Washington. State officials and various agricultural experts expressed deep concern today that agricultural production, one of the mainstays of Washington's economy, could be greatly curtailed by the volcanic ash. They are concerned that a dense covering of volcanic ash could damage orchards, hayfields, grazing lands, and extensive grain acreages. It all depends, said one, on the buildup of ash and on the amount of water (rain and artificial sprinkling) available to wash the plants.

The results of both the May 16 and the May 18 thermal surveys of the mountain are now available. They show that, in addition to the warm areas found during the May 2 survey, a new hot spot had appeared at the top of Shoestring Glacier and that the upper area of the bulge had been "perforated" with new warm areas. Thermal features detected in both the surveys were very similar. Geothermal specialists interpret the images as proof that the magma had moved up to a very shallow position—perhaps within a few hundred yards of the surface—before yesterday's eruption.

At 5:09 p.m. this evening, an eruption produced what appeared to be a

FIGURE 37.—The avalanche deposit, largely the remains of the bulge mass from Mount St. Helens, included hot parts of the volcano as well as blocks of ice from destroyed glaciers. *A*, USGS hydrologist J. R. Williams examines a fumarole area within the cooler avalanche deposit at the northern base of Mount St. Helens. The heat was derived from hot rock material buried within the deposit. (Photograph by Philip Carpenter, USGS, June 5, 1980.) *B*, The huge debris avalanche that "uncorked" the lateral blast included ice from five glaciers on Mount St. Helens. Barry Voight of Pennsylvania State University examines this ice block, which was rafted along on the avalanche debris in the North Fork Toutle River valley. A small pond of water was forming as the ice melted in the warm springtime. Another ice block, found closer to the mountain and not shown here, had a diameter of about 300 feet, the length of a football field. (Photograph by Robert L. Smith, USGS, June 2, 1980.)

small pyroclastic flow, which prompted officials to call back rescue units from the Toutle River valley. However, the volcano soon returned to a quiet state, and no evidence of the pyroclastic flow was found.

At dusk, the level of the Cowlitz River at Castle Rock was still about 10 feet higher than it had been before the eruption, and the channel downstream from the mouth of the Toutle River remained choked with mud, logs, and wreckage, most of it from the valleys of the Toutle River and its two forks. Much of the lower Cowlitz River flood plain remains inundated. USGS hydrologists warn of even more serious flooding if water trapped in the debris-dammed Toutle River system, including the area of Spirit Lake, were to be suddenly released.

Tuesday, May 20
E Day Plus 2

Sporadic eruptive activity is producing mostly steam. Seismicity, too, has declined to a level lower than any since March 22; no earthquakes registered more than magnitude 3 today.

Scientists in the field are finding that the debris flow that rushed down the upper valley of the North Fork Toutle River immediately after the initial Sunday morning blast includes hot areas as well as cold ones. Scattered warm masses in the avalanche debris, which is largely the remains of the "bulge" mass from the mountain, probably came from hot parts of the volcano, and colder parts are blocks of ice from the destroyed glaciers that were caught in the flow (fig. 37). The debris-avalanche deposit is riddled with fumaroles, and, now and then, scientists hear explosions, which, no doubt, occur when the buried heat in the deposit causes subsurface water to flash into steam.

Field crews also have measured the temperature of some of the pyroclastic flows that followed the initial blast (fig. 38). At a depth of about 2 feet, they obtained readings of nearly 150°C (300°F).

FIGURE 38.—Mount St. Helens pyroclastic deposits. *A*, Geologists R. P. Hoblitt of the USGS (left) and Edward Graeber, Jr., of Sandia Laboratories (right) use a thermocouple probe to measure the temperature in a pumice slope north of Mount St. Helens. Although the pumice at the surface was cool enough to walk on, at a depth of a few inches it was hot enough to boil water. (Photograph by Terry Leighley, Sandia Laboratories, May 30, 1980.) *B*, Hobblitt digs into a deposit of pyroclastic material near the head of Smith Creek, about 2 miles east of Spirit Lake, for samples of charred wood (see piece below his foot in left foreground). The dark-gray deposit is overlain by several inches of light-colored airfall pumice, which, in turn, is overlain by a thin layer of gray ash that developed mud cracks when it dried. (Photograph by Robert L. Smith, USGS, June 6, 1980.)

No one yet knows how much of a flood threat the "new," higher Spirit Lake may be. One crucial unknown factor is the stability of the debris-avalanche deposit that buried the lake's former outlet (to North Fork Toutle River) and impounded the lake at its new, higher level. Another uncertainty is whether the lake, now that its former outlet is blocked, will rise until it overtops the debris dam. Although most of the water displaced from the lake by last Sunday's giant avalanche already has drained back, the lake continues to receive inflow from its various tributary streams. If the dam is overtopped, Crandell said, "It will be like water going over a spillway; but, in this case, the spillway is not made of concrete, but of very unstable material." The spilling water could quickly erode a channel through the debris dam that would release more floodwaters, perhaps at catastrophic rates, to downstream areas.

Scientists who are watching the lake (as best they can) report that the water level thusfar has remained below the top of the debris dam, and no flooding from this source is imminent. They cannot measure the lake's level directly, and aerial observation of the deposits southwest of the lake, in the area that might be overtopped, is greatly hampered by steam pouring from dozens of fumaroles. However, aerial radar imagery has shown no signs that the area of the lake is enlarging, and some observers have seen water seeping through (or beneath) the debris dam and flowing westward. If this seepage keeps pace with inflow to the lake, the chances that the lake level will stabilize below the dam crest and that the dam itself will hold are greatly increased.

If the dam does fail, it might go quickly and (if visibility were poor when it failed) with little warning. A flash-flood watch remains in effect along the Toutle River, and Washington State Patrol officers are stationed at the Interstate Highway 5 bridge across the Toutle River to close the highway again, if it becomes necessary. Hydrologists working with limited data are trying to estimate the likely height and speed of the flood crest that would occur if the dam is breached. On the basis of the available information, they cannot guarantee even a 1-hour warning for downstream areas.

Mapping specialists from the Forest Service, USGS, and the Washington Department of Natural Resources met today to coordinate production of aerial photographs and maps of areas affected by the eruptions and flooding. New aerial photographs of the modified areas will be obtained as soon as weather permits. In the meantime, a new color topographic map of Mount St. Helens and vicinity, showing features as they were just before the March 27 eruption, will be prepared from existing data as soon as possible. These maps are urgently needed for evaluating changes in landscape, lakes, and streams and for guiding rehabilitation efforts and further scientific studies.

Existing maps of the Cowlitz River channel and flood plains are as obsolete as preeruption maps of the Spirit Lake area. Today, hydrologists began remapping the debris-choked channel in order to evaluate the continuing flood hazard. They are finding that the river bottom is as much as 15 feet shallower than it was before the mudflows and that the water-carrying capacity of the channel is greatly reduced.

Since the May 18 eruption, nearly continuous bad weather has prevented flying over the mountain to obtain accurate data on changes in heat emission. An aerial infrared survey flown by a U.S. Navy airplane at midday, however, and a daytime helicopter survey over the accessible western and southern flanks of Mount St. Helens revealed no new sources of volcanic heat emission outside the crater.

The City of Yakima has declared itself a disaster area, and Washington Governor Ray telegraphed President Carter to ask that the entire State be declared so. Many schools and roads are still closed, and the Columbia River remains closed to most shipping, but people are digging out of the ash.

Residents of Ritzville, which received more than 3 inches of ash, have an especially difficult cleanup problem. After spending most of Sunday and Monday helping each other (and about 2,000 stranded travelers) survive, they are now seeking places to dump the ash where it will not just blow back into town.

Although people in areas where volcanic ash is present are still being cautioned to avoid breathing it, agronomists are now predicting less long-term harm to animals and crops than they had expected. Some say that the effects in most of the "ash belt" will not be much worse, if any, than those of a bad dust storm. Much of the first hay crop, however, apparently has been lost.

The airborne ash cloud from last Sunday's eruption is still moving eastward and has now reached beyond the Mississippi Valley. USGS Chief Hydrologist Philip Cohen assigned the task of mapping the areas of noticeable ashfall beyond the Pacific Northwest to USGS hydrologists in the other States along the path of the ash cloud (fig. 39). Some meteorologists had expected the ash to fall in trace amounts, at least, on every State east of the Rocky Mountains except Texas, Louisiana, and Florida.

Ben Bena, Cowlitz County Deputy Sheriff, has compiled a "scorecard" of the number of people rescued from life-threatening situations by aircraft crews: Air Force, 61; Washington Army National Guard, 28; Coast Guard, 6; Army, 4; and Civil Air Patrol, 1. These same crews have plucked dozens of other people from less desperate situations. Several rescues also have been made by scientists and news reporters in other helicopters. Ninety-eight people are now on the official "missing" list.

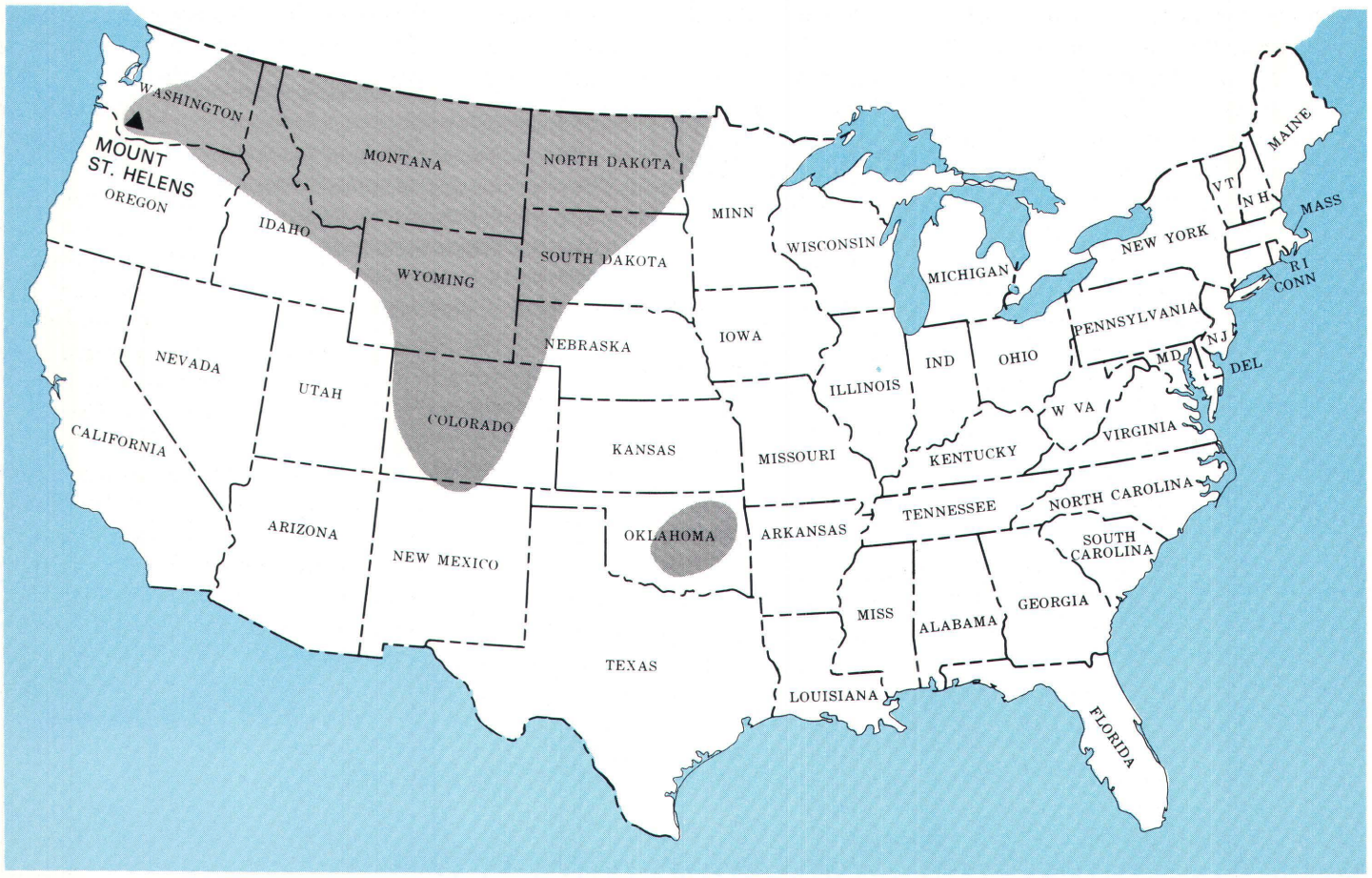


FIGURE 39.—Approximate distribution in the United States of noticeable ashfall from the May 18 eruption of Mount St. Helens, as of May 23, 1980. Most of these ashfall areas, which were identified during a rapid reconnaissance by USGS hydrologists and others, received only trace amounts. Other areas to the east probably received minute amounts of ashfall. Minor concentrations of ash from the same eruption were suspended in the stratosphere (above 36,000 feet) and carried slowly in convoluted paths around the world.

Wednesday, May 21
E Day Plus 3

Eruptive and seismic activity continues at a low level. The mountain vented only plumes of steam today, and only two earthquakes greater than magnitude 3 were recorded.

Scientists flew to Spirit Lake and found the level to be about 150 feet below the top of the debris flow; although the danger of an outburst flood is thus lessened somewhat, they nevertheless placed markers along the lake to help maintain a watch on its level.

The Federal Aviation Administration today warned flyers that volcanic ash can pock aircraft windshields and clog engines. The ash cloud in the stratosphere reached the Atlantic coast.

Reporters in Yakima, after establishing a grid within the city and sampling and weighing ash from grid locations, determined that about 600,000 tons of ash from Sunday's eruption have fallen on the 12.9-square-mile city.

Spokane and several smaller communities have been forced to ration city water because residents' attempts to wash ash from cars, streets, and buildings have depleted reservoirs. The City of Longview has instituted emergency water-use measures for another reason. Intake pipes from the Cowlitz River, which normally supply the city's reservoirs, have been clogged by mud and debris from the flooding that began on May 18. The mass of muddy debris so far has resisted all efforts to remove it from the intakes.

Electrical utility crews in the "ash belt" are busy removing accumulations of ash from high-voltage powerline insulators by using high-pressure air and water jets. Although the ash is an insulator when it is dry, it conducts electricity when it is wet and causes high-voltage arcing and power surges that damage electrical equipment. Electrical service has been interrupted because power must be switched off during the cleaning operations.

Airports and roads in eastern Washington have begun to reopen. Washington Department of Transportation officials report that about half of the 1,100 miles of State roads that were

closed because of ash have been reopened.

President Carter today declared Washington State a disaster area, and major Federal aid to victims of the volcano's devastation can begin.

The Coast Guard reported that 31 oceanbound ships now are tied up at Portland and Vancouver awaiting the reopening of the Columbia River shipping channel. Another 10 ships are waiting at Astoria, Oreg., to come to those upriver ports. Several incoming ships originally scheduled to call at Columbia River ports now have been diverted elsewhere.

Thirty military helicopters scheduled to search today for survivors and victims of the catastrophe were grounded because of cloudy weather. The official count is now 14 dead and 90 missing. The body of photographer Blackburn was recovered today from Coldwater I observation station. He had been seated in his car, which was mired in ash to the windows (fig. 40*A*).

Thursday, May 22
E Day Plus 4

Eruptive activity has slowed to a steady pattern. Eruptions of steam are frequent or nearly continuous, and the plumes sometimes rise 18,000 feet above sea level when the wind is light. Little or no ash darkens the plumes, although the familiar "rotten egg" smell attests to the presence of hydrogen sulfide.

Earthquake activity has diminished. Small quakes recorded today were from deeper sources; some originated northeast of the volcano.

Crandell reports that the water level in Spirit Lake behind the debris dam is declining; the water seems to be flowing out through the debris-avalanche deposit and gravel in the old channel that was buried by the avalanche deposit. Geologists have determined that the avalanche deposit is hundreds of feet thick near the southwestern end of Spirit Lake. Scientists now think that the avalanche deposit can retain

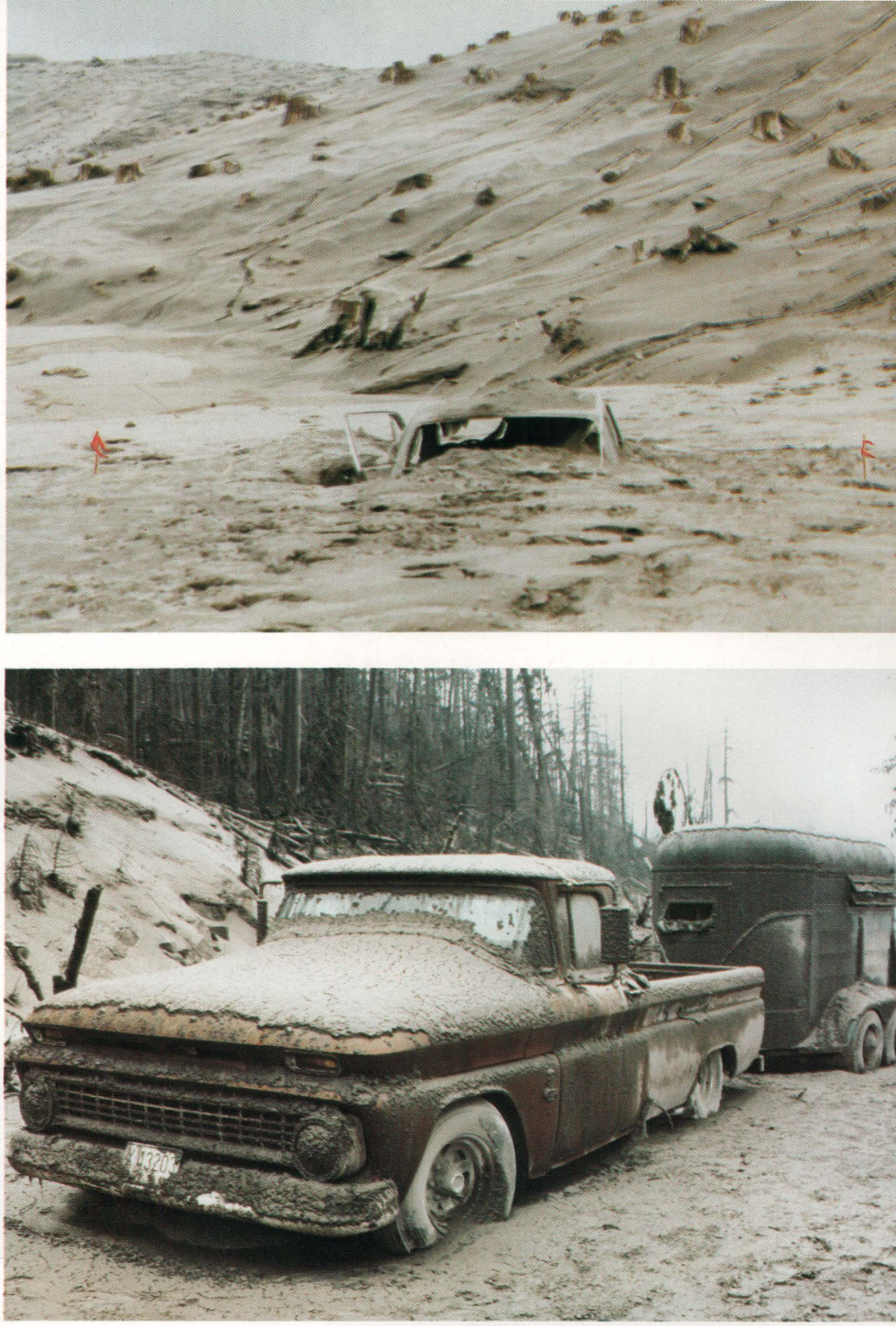


FIGURE 40.—Desolate vehicles in the blast zone created by the May 18 eruption. *A*, The body of photographer Reid Blackburn was recovered from this car on May 21, 1980, at Coldwater I observation station. None of the photographic film in the car produced a discernible image. The small red flags indicated to other searchers that the vehicle had been checked. (Photograph by Terry Leighley, Sandia Laboratories, May 28, 1980.) *B*, An ash-covered truck and horse trailer near Ryan Lake, more than 12 miles northeast of Mount St. Helens. The vehicles were parked at the edge of the area in which trees were blown down by the lateral blast. Two men, one the owner of these vehicles, were camped at the lake nearby and were asphyxiated by the hot volcanic ash, which covered this spot to an average depth of about 6 inches. The blast temperatures were hot enough to melt the plastic of the truck grill, trailer window, signal indicators, and a lunch box. The tires and glass truck windows, however, were intact. (Photograph by Daniel Dzurisin, USGS, May 27, 1980.)

the lake indefinitely unless its water level rises greatly.

USGS geologist David Dethier was among the first to get a broad view of the huge new crater. He was riding in a Forest Service airplane that was flying an observation and radio-relay mission at an altitude of 18,100 feet above the general cloud cover that has persisted since the night of May 18 and 19. (Although helicopters have been able to edge up to the crater, clouds and steam have obscured the interior.) About 6:00 p.m., the clouds began to open, and the pilot spiraled down steeply to a lower altitude over the devastated area north of the volcano, from where the observers got the first spectacular view of the mountain's interior and from where Dethier took the photograph in figure 41. They saw a greatly shortened peak, now crested by a jagged rim enclosing a huge, steaming crater shaped like a giant amphitheater open to the north.

James Moore and Peter Lipman, also of the USGS, were the first scientists to get a close look at features inside the volcano's crater today. Lipman said that there is now a second crater inside the larger one. A ridge rising above the middle of the large crater's floor forms the rim of the smaller crater, which lies in the southern half of the large amphitheater. Small pools of muddy water are collecting in depressions in the amphitheater floor, which is about a third of a mile wide. Much of the steam creating the plume above the volcano is jetting upward from several large vents within the central crater, which form a ring around the deepest part of the crater and probably mark the volcano's central "throat."

Short-term plans for scientific studies give first priority to mapping the devastated areas and evaluating the flood hazard that may still remain. Lost or damaged scientific instruments will be reinstalled as soon as conditions are considered safe.

Spokane International Airport reopened today "under limited conditions" after an all-night cleanup effort,

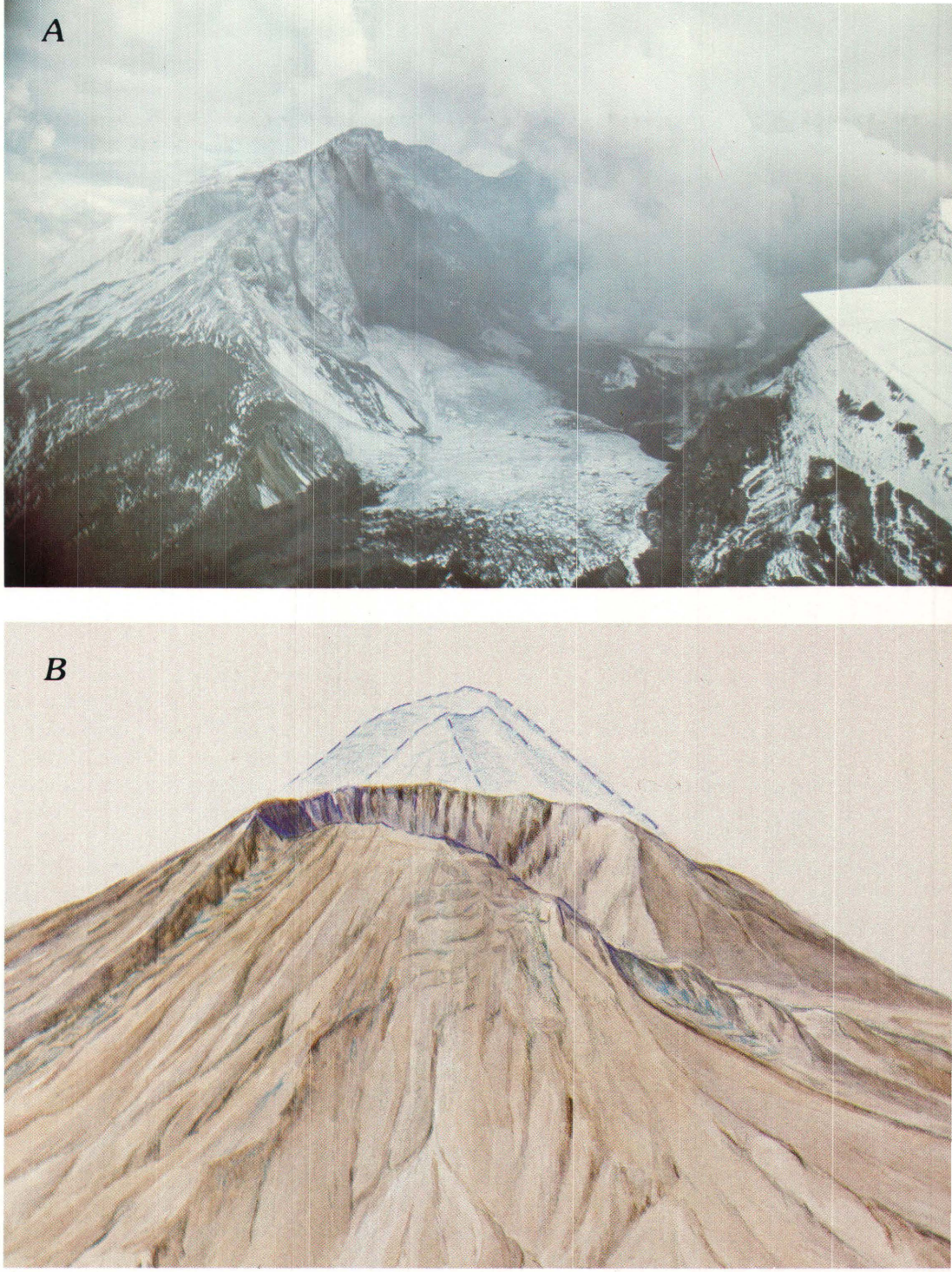


FIGURE 41.—The "new," shorter Mount St. Helens. *A*, The first opportunity for a broad view of Mount St. Helens after the May 18 eruption came on May 22, when clouds that had obscured the area since the eruption parted to reveal the stubbed-off, hollowed-out volcano, newly coated with 4 to 6 inches of snow. This photograph looking into the open mouth of the amphitheaterlike crater was taken from an airplane about 3 miles north-northwest of the crater's center at an altitude of 6,000 to 7,000 feet. The new 8,364-foot "summit" of the mountain (the highest part of the crater rim on the southwestern side) was obscured by vapor clouds. (Photograph by David P. Dethier, USGS.) *B*, The cratered stump of Mount St. Helens as viewed from the northeast. The dashed lines show the height lost (about 1,300 feet) in the May 18 eruption. This painting by Dee Molenaar (USGS) also shows remnants of Shoestring Glacier, descending from the notch in the left side of the crater rim, and of Forsyth Glacier (right center).

but most airports in the "ash belt" remain closed. Trains in the region are running on near-normal schedules, and interstate bus service is resuming. Idaho police lifted a travel ban on their State's ash-covered highways, but they cautioned motorists to drive with care.

State of Washington health officials said that crystalline silica, which can cause chronic lung disease, has been found in the ash. Available information, however, is not adequate for judging the actual risk to the general population. Also, postal officials warned the public not to mail "souvenir" ash in paper envelopes that can leak and damage postal machinery.

President Carter toured the stricken area today in company with Governors Ray of Washington and John Evans of Idaho. The eruption was, President Carter said, "a natural disaster of unprecedented proportions."

The Corps of Engineers began dredging mud and debris from the Columbia River shipping channel near the mouth of the Cowlitz River. Thirty-one vessels remain stranded above the shoal waiting to move downriver and out to the Pacific Ocean.

The Forest Service began ground searches today for more victims of the eruptions.

Friday, May 23
E Day Plus 5

Although the weather was very cloudy until late afternoon, the clouds finally broke up, and today was one of the best days for viewing the mountain since May 18. Today's eruption pattern in the crater was similar to yesterday's; plumes of steam and other volcanic gases were rising above the crater rim. Observers saw one small ash cloud but concluded that the ash had avalanched down from the walls of the crater and was not new material.

There is a lull in seismic activity; no earthquakes registered above magnitude 3 today. Although there were several smaller quakes, they were spread over a larger area than the quakes before May 18 had been. At a seismic station at Elk Rock about 10 miles northwest of the crater, one of several instrument stations that had been destroyed by the lateral blast, instruments were reinstalled today to help supply data for continuing studies of earthquake activity.

A large area north of Mount St. Helens is dotted by steam vents and craters from steam explosions. The steam is from underground water that is heated by hot avalanche and blast deposits. One vent near the southwestern end of Spirit Lake (fig. 30) erupted steam 5,000 to 6,000 feet into the air early this evening, startling the pilot and passengers of a Forest Service airplane that happened to be flying over the area.

A chemical analysis shows that the glassy ash blown out of the volcano on May 18 and since has the composition of dacite; this rock is formed from a type of magma that has a moderately high silica content and is generally quite viscous.

The first Disaster Assistance Center, mandated by President Carter and Governor Ray, opened today in Kelso, Wash. The center is operated by the Federal Coordinating Office of the Federal Emergency Management Agency in cooperation with the Washington Department of Emergency Services. In addition to the Kelso center and the temporary Federal Emergency Management Agency headquarters in Vancouver, other centers will be opened as needed in eastern Washington and in Idaho communities.

Governor Ray called out the National Guard to help clean up volcanic ash in eastern Washington this weekend. A major manufacturer of dust masks donated 21,000 of them for use in ash-covered areas. Hay is being sought for animal herds in areas of thick ashfall in eastern Washington and for surviving animals near Mount St. Helens.

By the end of the day, USGS hydrologists had installed new streamflow-measuring stations equipped for radio telemetry on the Cowlitz River at Castle Rock, on the Toutle River about 6 miles upstream from its mouth, and on the North Fork Toutle River farther upstream.

State of Washington officials this evening released an estimate of more than $1 billion for most of the losses suffered in the State as a result of the May 18 eruption.

Today is the beginning of the Memorial Day weekend, a time when eastern Washington normally would receive hordes of vacationers from western parts of the State and from the Portland area. The Washington Department of Transportation, however, warned of windblown ash, continuing restrictions on road use, and limited public transportation in ashfall areas. These warnings, as well as the continuing closure of traditional recreation areas around Mount St. Helens, are expected to cause unusually heavy use of recreation areas in western Washington, especially the Pacific Ocean beaches.

The number of bodies recovered from the Mount St. Helens area rose to 17, but 71 people are still missing. The body of one man was found on the seat of his car; his camera was still held toward the volcano.

Saturday, May 24
E Day Plus 6

The volcano ejected plumes of ash and steam about 15,000 feet above the crater twice today, at about 2:30 p.m. and 11:05 p.m. Ash sprinkled towns as far south as Salem, Oreg. Harmonic tremor, which has continued at varying weak levels throughout the past week, was somewhat stronger most of today.

USGS scientists installed new targets on the mountain for laser distance-measuring instruments today. They also measured temperatures of about 540°F (280°C) in pyroclastic flow deposits on the volcano's northern flank. Geologists mapping in the devastated area found that the lateral

blast had carried stones as large as grapefruit that undoubtedly caused much of the stripping and battering done to the exposed surfaces of trees (fig. 42).

About 45 National Guardsmen arrived today in Ritzville, which has received the heaviest ashfall of any community away from the volcano. They began shoveling ash from some of the town's flat roofs to reduce the danger of collapse.

Scientific instruments and related equipment lost as a result of the May 18 eruption include:

- One electronic laser distance-measuring instrument, 1 theodolite, and 18 surveying reflector targets—destroyed. Three other reflectors—damaged.
- Three telemetered seismic stations and two 5-day recorders—destroyed.
- Two automatic platform tiltmeters—destroyed.
- Two recording magnetometers—buried (one may be shallow enough to recover).
- Three time-lapse cameras, two video cameras, and several hand-held cameras—destroyed.
- Several communication radios and two satellite-relay data transmitters—destroyed.
- One portable spectrometer—destroyed.
- One stream-gaging station and its instruments and two water-quality monitoring stations and their instruments—destroyed by mudflows.

Another Explosive Eruption and Its Aftermath

Sunday, May 25
E Day Plus 7

Shortly after 2:30 a.m., the volcano began ejecting a huge vertical column of ash, the most vigorous eruption since last Sunday. Airborne observers could see that the column reached a height of 24,000 feet in about 7 minutes and began to mushroom at the top. The National Weather Service radar operator in Portland watched it reach an altitude of 45,000 feet by 2:45 a.m. Because winds were moving in different directions at different altitudes today, the ash was scattered over wide areas of western Washington and Oregon.

The eruption was heralded at 2:32 a.m. by an increase in the amplitude of harmonic tremor, which had been present at a very low level since about midnight. A swarm of small earthquakes began at 2:40 a.m. and continued at a rate of one or two an hour, all originating about 5 miles beneath the mountain. By 8:00 a.m., the intensity of tremor had diminished, and the earthquake swarm began to subside, although the volcano continued to erupt.

Aerial surveillance was continued from a Forest Service airplane through the early morning, but only once could observers see the volcano itself. That brief glimpse revealed that the ash was rising from two vents—one in the northeastern part of the crater and another in the southwestern part. A new, small mudflow had descended south of Shoestring Glacier on the southeastern side of the mountain but did not extend beyond the base of the cone. Even aerial observation, however, was halted when Portland International Airport closed because of the ash, which had begun to fall heavily in Portland and Vancouver as early as 6:00 a.m.

Most people still living near the volcano on the southern side—about 200 in all—were evacuated this morning. Flood warnings were issued for

FIGURE 42.—This shattered tree stump on an exposed ridge about 5 miles north of the crater is striking evidence of the tremendous force of the May 18 lateral blast. The handle of the folding shovel is 1.7 feet long. (Photograph by David Frank, USGS, August 19, 1980.)

most rivers draining from Mount St. Helens, in case renewed eruptions should trigger new mudflows or floods that might spill out of river channels still choked with debris from the May 18 eruption.

The top of the ash column remained between 13,000 and 20,000 feet above sea level most of the day. By early evening, the erupted column, as seen on the weather radar, was only a few thousand feet above the crater rim; as of midnight tonight, activity had returned to its former subdued level.

Measurements of the sulfur dioxide (SO_2) content of an ash-laden eruption plume this afternoon showed the highest concentrations found to date According to Richard Stoiber, a Dartmouth College air-quality specialist, the amounts measured were equivalent to an emission rate of 2,400 metric tons of SO_2 a day.

The ash content appeared to lessen as soon as the column began to mushroom, and the height of the column decreased within the first hour; still, the quantity of ash was so great that it hampered visibility throughout the day at places in nearly every direction from the volcano except northeast. Most airports in southwestern Washington and northwestern Oregon were closed at various times during the day because of poor visibility and the fear that the ash would harm vital aircraft parts. Airports in the Seattle area also were closed briefly.

The latest ashfall at it heaviest is much less than the thickest deposits laid down last week in eastern Washington; it has been troublesome nonetheless and has affected several urban areas that had received only light dustings before. Traces of today's ash reached as far north as Seattle in western Washington and south of Portland in western Oregon. The bulk of the ash, however, blew to the northwest (fig. 43). Chehalis, 50 miles northwest of the volcano, received about half an inch of ash. Light ashfall reached the ocean beaches of southwestern Washington and northeastern

FIGURE 43.—Generalized distribution of ash from the May 25 eruption of Mount St. Helens, as compiled by Sarna-Wojcicki and others (1981). Lines represent equal ash thickness, in millimeters (1 inch=25.4 mm), and are dashed where observations were lacking. Circles represent measurement sites; plus signs, sites where trace or light dusting was observed; crosses, sites at which no ash was observed. Other observers reported that ashfall in the areas of Olympia, the Washington coast, and the Portland-Vancouver metropolitan area was greater than the map indicates.

Oregon. In areas of densest ashfall, the sky stayed dark until midmorning.

While the ash was still falling in many areas, the rain started. As one observer said, "It was raining mud." Many traffic accidents were attributed to a combination of roads made slick by wet ash and visibility obstructed by the muddy rain. Drivers reported that they could drive only so long as their windshield washers operated—and then only if they could keep their vehicles on the slippery roads. These conditions resulted in a 15-vehicle pileup, with injuries, on Interstate Highway 5 near Chehalis. For much of its route between Olympia and Vancouver, Interstate Highway 5 was in the path of the densest ashfall. Officers of the Washington State Patrol and

sheriffs' departments closed that highway and others while driving conditions were most dangerous. Portland Mayor Connie McCready limited traffic in that city to 15 miles an hour to help avoid stirring up the fallen ash.

The ashfall disrupted business as well as travel. In Kelso, even the Disaster Assistance Center was closed. Road and airport closures temporarily stranded thousands of travelers this Memorial Day holiday weekend. Ironically, many travelers were in ashfall areas because they had been warned away from traditional recreation areas in eastern Washington. Major traffic jams were caused when motorists returning early from the coastal areas converged on population centers in the Puget Sound and Portland-Vancouver areas.

Travel in eastern Washington was restricted, too. Interstate Highway 90 was closed through most of the eastern part of the State as winds stirred up blinding clouds of the fine ash that fell last Sunday. Busloads of National Guard troops from Seattle, on their way to help clean up at Moses Lake, were stranded overnight at Ellensburg, Wash. (about 30 miles north of Yakima). Nine pieces of cleanup equipment already had been trucked to Moses Lake, but no one arrived to operate them.

Emergency crews in areas blanketed by wet ash worked rapidly to clean transformers and insulators, so that electrical systems shorted out by the sticky ash could be restored.

Participants in the Mount St. Helens Technical Information Network, a group newly organized by USGS scientist Robert L. Wesson under a directive issued by President Carter and Governor Ray, met in Spokane today. Their purpose is to find answers to health, agricultural, and transportation problems caused by volcanic ash. Because solutions to many of these problems do not now exist, the group, which consists of specialists in various fields, will summarize what is known about volcanic ash hazards and focus research on what is not.

The Corps of Engineers reported that the removal of approximately 300,000 cubic yards of material from the Columbia River channel has deepened it to a minimum water depth of 20 feet—about half the 40-foot depth of the normal shipping channel. The dredged material is being dumped on islands in the Columbia River and along parts of the riverbank. The Cowlitz River, engineers estimated, also will have to be dredged upstream at least to Lexington (9 river miles upstream from the Columbia) and probably beyond Castle Rock (to river mile 21) for flood control.

The levee along the Cowlitz River near Castle Rock is being built up 5 feet along a front 2,000 feet long. At Lexington, 300 feet of the levee was raised 3 feet, and, at Kelso, the levee was raised 2 feet. Cowlitz County has been given 40,000 sandbags to help in flood control.

USGS geologist Crandell today presented a new map showing the volcanic hazards of the Mount St. Helens area to Governor Ray. He pointed out that the main dangers from the volcano still consist of ash, mudflows and floods, pyroclastic flows, and lateral blasts. The history of this volcano, however, and that of others like it suggest that lava flows are an unlikely event.

Governor Ray, by executive order, extended the Red Zone around Mount St. Helens out to 20 miles in all directions from the volcano (fig. 13). Only people on official business (including approved scientific work) or holding special permits are to be allowed in the zone. The penalty for unauthorized presence in the Red Zone was set at a fine of $1,000 or a year in jail or both.

Monday, May 26
E Day Plus 8

Although both the volcanic eruptions and their seismic accompaniment have settled down, ash continues to fall during the day and to be picked up again by the wind. Observers in the round-the-clock surveillance plane can see the volcano now and then; when it is visible, it seems to be emitting steam almost entirely, although occasional traces of gray ash are sighted. No earthquakes above magnitude 3 were recorded.

By 10:00 a.m., only four State highways in Washington were still closed, three of them being in the southwestern part of the State near Mount St. Helens. Interstate Highway 5, which received a troublesome amount of ash between Portland and Olympia, is no longer closed, but blowing ash along that reach of highway remains a hazard to the still-heavy Memorial Day traffic.

The Federal Aviation Administration lifted the restrictions imposed yesterday on air travel in the ashfall area. Air traffic in the vicinity of the volcano, however, is still restricted.

A National Guard helicopter crew rescued five hikers who were in the Red Zone illegally. All five were nearly blinded by ash; one was hospitalized.

Communities near the volcano have suffered from either too much or too little water during the previous week and a half. A flash-flood watch continues on the Toutle River and parts of the Kalama, Lewis, and Cowlitz Rivers. At Longview, water intakes from the Cowlitz River remain clogged and have caused the water system to go dry in part of the city. In eastern Washington, ash clogging the sewage-treatment plants in Spokane and Yakima has forced officials to dump raw sewage into the Spokane and Yakima Rivers.

The Port of Portland reports that closing of the Columbia River to shipping has meant a revenue loss of $4 million a day. The Port of Vancouver, across the Columbia from Portland, estimates losses of $1 million a day.

The first autopsies conducted on victims of the May 18 eruption indicate that they were suffocated by hot ash or gas, not killed by burns or other injuries.

A group calling itself "The Friends of Washington" announced its intention to sell ash at $1 a packet to benefit search-and-rescue groups. It was, however, only one of many ash sellers in the stricken area. "Volcanic Ash—U Haul," one wag advertised. (By midsummer, many advertisements running in magazines and newspapers throughout the country were offering samples of Mount St. Helens ash at various prices.)

Many large blocks of ice on and in the rubble north of the volcano might seem to have been thrown out by the May 18 lateral blast. Most, however, are actually chunks of glaciers that were part of the huge initial avalanche and were carried along with the avalanche debris to their present locations (fig. 37). Scientists paced off the diameter of one ice block that is mostly buried in debris overlooking the North Fork Toutle River and reported that it is about 300 feet across—the length of a football field.

Farther west along the North Fork (beyond the avalanche debris) and in valleys where other major mudflows occurred, much of the bottomland is "flat as poured concrete" and just as gray (fig. 44). Mud from the mudflows of May 18 now fills most depressions and is still too soft to walk on in many places.

USGS hydrologists today completed their first appraisal of the debris-choked Cowlitz River channel downstream from the mouth of the Toutle River. They found that mud and debris from the Toutle had reduced the depth of the Cowlitz channel by as much as 12 to 15 feet and probably had accounted for about 40 million cubic yards of new flood-plain deposits and channel fill between the Columbia River and the mouth of the Toutle River.

FIGURE 44.—The May 18 mudflows from Mount St. Helens reached levels much higher than those of any earlier recorded floods in the major valleys that carried them. (See the highest mud marks on the tree in the foreground and on trees in the right background.) When the mudflows receded, they left tangled masses of assorted debris such as this jumble of boulders, branches, and machinery pieces. The rock particles in the mud stripped and abraded the trees left standing and sharpened trailing tree limbs to tapered points. As the mud settled out of the receding floodwater, it filled and buried former depressions and left much of the valley floor "flat as poured concrete." In this view, looking downstream along the Muddy River 9 miles southeast of Mount St. Helens, a hydrologist (yellow figure on boulder in center of background) is surveying the mud marks to determine the downvalley slope of the mudflow at its highest position. (Photograph by Philip Carpenter, USGS, June 4 1980.)

Yakima reopened its downtown district today. Officials said that the citizens have done a remarkable job of "pitching in" and cleaning up. In the city, a block-by-block cleanup was organized and supervised by "block captains." Outside of town, property owners volunteered parts of their land as dumps for ash cleared from the city.

Tuesday, May 27
E Day Plus 9

Seismicity was very low during the day, and eruptions of mixed ash and steam were mild.

USGS scientists examined ash from Sunday's eruptions and found it to be a mixture of pumice, glass shards, crystal fragments, and fragments of older rock — similar to the composition of the May 18 ash. Field crews saw younger pyroclastic flows on top of the May 18 deposits. The pumice in the newer deposits is of two types—one a light-colored, frothy rock and the other darker and more dense.

As the ash from last Sunday's eruption dries out, motorists along Interstate Highway 5 find that problems with visibility and clogged air cleaners are increasing. The Washington State Patrol imposed an emergency speed limit of 25 miles an hour, but, according to reporter Kerry Webster of the Tacoma *News Tribune*, it was being ignored by so many impatient drivers that "dust clouds were spread for miles obscuring both sides of the highway." State Patrolmen were greatly hampered in enforcing the new regulation because speeders were creating dense "smokescreens" of ash dust. Finally, according to Webster, after a multicar accident had delayed northbound traffic for more than 1 hour, truckdrivers took matters, into their own hands. Communicating by citizen's band radios, they maneuvered their rigs into three-abreast formations and formed moving roadblocks traveling at the emergency speed limit. The trios of trucks spaced themselves about 7 miles apart, just about far enough for the dust from one convoy to settle before the next arrived. A State Patrol sergeant who was interviewed by Webster reported that the accident rate dropped immediately and that the dust began to clear. He added that, although the State Patrol did not condone the truckers' action, it certainly kept the highway open and probably saved some lives.

Gifford Pinchot National Forest Supervisor Robert D. Tokarczyk today announced preliminary estimates, prepared by his staff, of damage caused by the Mount St. Helens eruption (fig. 45). The total loss of $114 million worth of timber and resources within the national forest, not including damage to private timberlands, is as follows:

- One billion board feet of timber, valued at $100 million, has been damaged or destroyed. This amount is nearly a thousand times as much timber as the Lassen volcanic eruption of 1915 destroyed.
- Two lakes, Crane and Hoo Hoo, covering a total surface area of 6 acres, perhaps have been destroyed. Spirit Lake and 26 other lakes have been severely damaged. No estimates were given of how long it might take for aquatic life to return to the lakes.
- Valley floors of the North and South Forks of the Toutle River, Pine Creek, and the Muddy River have been buried by mudflows, and Coldwater Creek has been severely disrupted, as have the lower reaches of Spirit Lake tributaries—a total of 152 miles of streambed. Forest Service biologists surmised that only pockets of aquatic life survive in the 297 miles of heavily damaged streams. In addition, more than 2,000 miles of stream channels were moderately or lightly damaged. The damage to stream channels will be especially disastrous to fish, including the anadromous species that spawned in these waters.
- About 59,200 acres of deer and elk habitat reportedly have been completely or almost completely defoliated. An additional 62,080 acres have been moderately damaged. An estimated 2,000 blacktailed deer have been killed, as were 300 elk, 30 bear, and 12 mountain goats. Mount St. Helens' ptarmigan population, the southernmost known in the Cascade Range, probably has been destroyed. (This estimate does not take into account the smaller mammals, birds, reptiles, and amphibians that have been killed. Wildlife loss is not included in the $114 million damage figure.)
- Twenty-seven Forest Service recreation sites in the devastated area have been destroyed; the largest of these was Spirit Lake Campground. All Forest Service administrative buildings in the blast area, including the Visitor Center and the Spirit Lake Work Center, have been destroyed totally. The St. Helens Ranger Station has been abandoned. Four private areas under Forest Service use permit, primarily used as summer camps for organizations, also have been destroyed.
- Sixty-three miles of road within the blast and mudflow areas have been totally obliterated, and 154 miles of paved road and 1,560 miles of gravel road have been covered with 1 to 8 inches of ash. Seven permanent road bridges, five logging-road bridges, and five trail bridges are known to have been destroyed. Also 97 miles of national forest trails have been obliterated, and 30 miles are covered with ash.

Governor Ray estimates that total eruption damage, of which national forest losses are but a small part, is "$1.1 billion and might go higher."

Flash-flood warnings for the Cowlitz River were cancelled today by the National Weather Service. The flood watch for the Toutle is still in effect.

The death toll now stands at 21. Sixty-eight are still missing.


A

FIGURE 45.—A shaded relief map of the Mount St. Helens vicinity after the devastating May 18 eruption and before (inset).(Painting by Dee Molenaar, USGS.) *B*, Map labeling features shown in *A*.

Wednesday, May 28
E Day Plus 10

The amount of ash in the eruptive plumes has been generally decreasing since the last big ash eruption of May 25, and little was emitted today. Although the weather has been poor for viewing the volcano, radar images by the Oregon Army National Guard showed an area that could be either a dome or a ridge of ash and pumice within the large amphitheater and south of its open end. During the night, observers using light-enhancing binoculars reported seeing bright spots in the crater, which led to speculation that molten lava may be nearing the surface of the crater floor.

Seismicity was low, and quakes were centered near Mount Margaret (fig. 7) to the north. Although two earthquakes were of magnitudes 4.0 and 3.8, seismologists found no indication that these were directly connected with the eruption of Mount St. Helens.

An evaluation committee, headed jointly by John Eliott Allen, professor emeritus at Portland State University, and retired Oregon State Geologist Ralph S. Mason, was formed to process applications for permission to conduct scientific research in the closed areas around Mount St. Helens. The committee was charged with making certain that the applications were for legitimate scientific research by competent scientists.

The Mount St. Helens Technical Information Network issued its first bulletin—"The Nature of Mount St. Helens Ash." The ash from the May 18 eruption, it says, consists of three layers. The bottom layer, which erupted first from the volcano, is a dark-gray ash composed of tiny fragments of older rocks and mineral crystals. The middle layer is a mixture of pumice and crystal fragments. The top layer, which forms the bulk of the ash that overlies much of eastern Washington and Idaho, is a light-gray ash composed mainly of fine particles of volcanic glass and mineral crystals. Geologist Washburn of the Washington Department of Transportation, stationed at Yakima, described the thickness of the three layers that fell on that city as about one-sixteenth inch for the dark basal layer, about one-half inch for the middle layer of "beach-sand-size" particles, and only a "final dusting" of the upper fine, light-gray ash.

Although too few analyses of the ash have been made to predict long-term effects, two fears were allayed. First, the ash is not sufficiently acidic to form "acid rain" or to increase the acidity of streams and lakes markedly. Second, the fluorine content is low; thus, the amount of fluorine leached from the ash will not be significantly greater than the amount of fluorine found in fluoridated city water systems. The amount of free silica in the ash, which might constitute a long-term health problem, and the quantity of trace elements are still being studied and debated.

In its second bulletin, the Technical Information Network gave "Precautions for Handling Volcanic Ash." These precautions include moving the ash only in well-ventilated areas or outdoors, keeping it wetted if possible, and using dust masks to protect respiratory systems.

All of Washington and eight Idaho counties are now considered disaster areas by the Federal Emergency Management Agency. About 300 houses in western Washington have been destroyed or badly damaged, mostly by floods and mudflows, according to estimates prepared by the American Red Cross and the Skamania County Assessor. The Washington Department of Emergency Services estimated private timber loss at about $143 million.

The death toll reached 22 when one man, hospitalized earlier for burns, died today.

Thursday, May 29
E Day Plus 11

An Air Force SR-71 reconnaissance aircraft today flew a mission to take photographs showing topographic features of the altered mountain. Radar imagery obtained by the Oregon Army National Guard and reportedly showing a recently formed hump on the floor of the Mount St. Helens crater led to speculation that the volcano may be producing a lava dome. The presence of a lava dome, however, could not be checked by direct observation because steam and clouds permitted only occasional glimpses into the crater.

Emergency-services officials announced a critical need for hay and grain to feed animal survivors, both domestic and wild.

Because of the danger of flooding on the Cowlitz River, the USGS issued an updated Hazards Watch to local officials. They pointed out that the capacity of the Cowlitz River channel has been reduced about 85 percent, from about 76,000 cubic feet per second down to about 10,000 cubic feet per second, a flow rate that usually is exceeded at least once every year.

Airborne search-and-rescue operations were ended at 5:00 p.m. today. Altogether, nearly 18,000 manhours have been spent in the extensive and dangerous search for victims and survivors. More than 100 people have been rescued since the May 18 eruption. The toll stands at 22 dead and 71 missing. Ground searches, however, continue.

Friday, May 30
E Day Plus 12

The crater was cloud free for probably the first time since May 18, and the crater floor was visible through the steam plumes that rose from dozens of vigorously fuming vents within. Observers could see that the hump

detected by radar is not a dome but is, instead, a ridge, or "rampart," of ash and pumice that has built up between the most active steam vents and the open end of the amphitheater on the north. South of the rampart, an irregular crater (fig. 46) occupies only a fraction of the broad floor of the huge May 18 crater. In addition to the steam spewing from the vents, a burst of ash rises now and then, and, even less often, a block of pumice is thrown upward and tumbles back into the crater.

According to the tiltmeters that have survived the two major eruptions, the ground near the volcano has deformed only slightly. One tiltmeter about 4 miles south-southwest of the volcano's center has shown an almost continuous slight inflation of the volcano since before May 18; instruments farther away show little or no change. Seismographs today recorded a few periods of weak harmonic tremor, which died out within a few hours.

Costs for flood-control, navigation, and water-supply rehabilitation projects necessitated by the eruption of Mount St. Helens could reach $219 million, according to preliminary estimates made by the Corps of Engineers. Of this amount, $44 million will be needed to restore the Columbia River channel, where 22 million cubic yards of material will have to be removed. The shoal near the mouth of the Cowlitz River extends farther upstream in the Columbia than engineers first believed. The channel-filling debris from the Cowlitz River may have caused the Columbia River itself to deposit much of its sediment load where it encountered the shoal.

The Corps of Engineers estimated that the cost of clearing intakes and rebuilding or restoring water-supply systems in Toutle, Castle Rock, Longview, and Kelso will be about $14 million. An additional $28 million will be needed to restore the Cowlitz River channel, including dredging an estimated 25 million cubic yards of

FIGURE 46.—View of the "crater within a crater" between the May 25 eruption and the June 12 eruption, looking into the north-facing mouth of the main crater from the northeast. The smooth slope in the right foreground is a rampart of pyroclastic debris and ash that built up in front of the main eruption center, which is at the base of the large steam plume. The rock ridge on the left side is old volcanic rock, formerly buried, that was exposed for the first time in centuries by the May 18 eruption. (Photograph by Terry Leighley, Sandia Laboratories, June 4, 1980.)

volcanic and flood debris. All Corps of Engineers dredges on the west coast have been assigned to work on rivers affected by the eruption.

USGS hydrologists have now made preliminary calculations of the size of the May 18 mudflows down the major valleys radiating from Mount St. Helens. The volume of water in these mudflows is estimated to have been more than 100 million cubic yards, or more than 20 billion gallons—enough to supply household water for every person in the United States for 1 day. The mudflow from the South Fork Toutle River, which crested at the steam-gaging station on the main Toutle River about 11:00 a.m. on May 18, 2.5 hours after the main eruption began, reached a peak stage (high-water level) that would be equivalent to a water-flow rate of 46,000 cubic feet per second, or 1,700 cubic yards per second; the actual flow rate was less (by an unknown amount), however, because the mud slurry could not flow as fast as water.

The mudflow from the North Fork Toutle River, which destroyed the Toutle River gage about 6:00 p.m. on May 18, left high-water marks that indicated a peak flow roughly two to three times that of the previous mudflow from the South Fork. The peak stage near the mouth of the Toutle River was equivalent to a water discharge of about 100,000 cubic feet per second, but, again, the actual rate of flow into the Cowlitz was less because of the lower velocity of the mud slurry.

Hydrologists also completed and released to emergency-services agencies the first computations of probable flood levels in the mud-choked Toutle and Cowlitz River valleys if various amounts of storm runoff were to occur. They found that a wedge-shaped mass of mud even extended upstream in the channel of the Cowlitz for 2.5 miles above the mouth of the Toutle River; the volume of this upstream deposit, however, was only a small fraction of the amount deposited downstream. The volume of sediment left in the channel and on the flood plain of the Cowlitz River between Castle Rock and the Columbia River (not including the vast, but unknown, amount that flowed through to the Columbia) is estimated to be as much as 40 million cubic yards. This volume, if it were the concrete that the wet mud resembles, would be enough to pave an eight-lane highway between Mount St. Helens and New York City.

Daily checks of 40 hospitals in Washington, Oregon, Idaho, and Montana have failed to reveal any severe respiratory ailments caused by ash from the May 18 eruption, according to information released by the National Center for Disease Control.

Ray Jennings, the south-side resident who had resisted earlier evacuation attempts, and his four dogs were airlifted out of the Red Zone today by a National Guard helicopter. He had been in his cabin on the volcano's flank since before the May 18 eruption, but, because his whereabouts were known, he was never on the list of missing persons.

Saturday, May 31
E Day Plus 13

Travel in the Northwest is nearly normal again. Only four sections of State highways are still closed, and two of those allow local traffic. No airports are closed on account of ash. On the Columbia River, nearly 550,000 cubic yards of material have been dredged to form a shallow navigation channel, which has allowed 18 vessels to move upriver and 10 to move downriver.

The volcano steamed more strongly today than it has in the immediate past; clouds reached an altitude of 15,000 feet. Seismic activity was low, and small earthquakes—none greater than magnitude 3—centered near Mount Margaret, 8 miles northeast of Mount St. Helens.

The volcano is still emitting sulfurous gases, even though there were no eruptions of ash; the emission rates are several times higher than those measured before May 18. Concentrations of sulfur dioxide (SO_2) measured by Thomas Cassadeval on May 26 and 31 averaged about 150 tons a day, in contrast to the few tens of tons a day measured before May 18. The team of gas specialists reports that the volcano is also emitting at least as much hydrogen sulfide (H_2S) as SO_2.

Forest Supervisor Tokarczyk announced that the Forest Service probably will recommend that Mount St. Helens and some of the devastated areas surrounding it be designated a "National Volcanic Area." Others are proposing that the area become a national monument or a national park.

The Mount St. Helens Technical Information Network issued two bulletins today; one gives advice on driving in heavy ash areas (drive slowly; change oil, air filters, and other filters; and clean brakes occasionally), and the other suggests that exposure to the ash may have reduced the insect population significantly. Honey bee colonies, although damaged, apparently were not obliterated.

Rod Preston of the Washington State University Animal Sciences Department reported that the only elements in the May 18 ash that concern animal scientists are copper and molybdenum. Although the concentrations of these elements in the ash are small, they might cause illness in livestock that eat feed containing unusually large amounts of ash.

At the month's end, no lava has appeared at the surface. Recently, however, there have been several night observations of incandescent rocks, which probably are caused by hot gases streaming through the vents from a magma body not far below.

Sunday, June 1
E Day Plus 14

The month has opened quietly. The volcano continues to vent steam, which rises in clouds to about 12,000 feet. Poor weather has prevented good

aerial observation, but field crews, transported by helicopters, continued making ground observations (fig. 47) and deploying monitoring instruments today. Measurements of the "new" Spirit Lake revealed that its depth is now about 100 feet or less, instead of its former depth of about 200 feet. The lake-water temperature was measured at 97°F (36°C) at the surface and 95°F (35°C) on the bottom.

Earthquakes were small and few, and harmonic tremor, which returned to the mountain a few days ago, decreased in amplitude by about two-thirds early this morning. This decrease could mean that movement of magma under the volcano is subsiding, but no one knows.

Winds blowing at about 25 miles an hour plagued parts of eastern Washington and northern Idaho by redistributing ash deposits from the May 18 eruption. Poor visibility caused temporary closure of sections of two highways in east-central Washington.

USGS geologists warn that, although the volcano appears to be relatively quiet now, it still remains dangerous to anyone nearby. If a lava dome were to build in the crater—an event that would be in character for this volcano—the dome building would likely be accompanied by more explosive eruptions, pyroclastic flows, and mudflows.

Search dogs have been used in ground searches for survivors and victims of the May 18th eruption; however, these searches have now been suspended. From now on, special search-and-rescue missions will be conducted only if the last known location of a possible victim can be closely fixed. The count now stands at 22 dead and 53 still missing.

Monday, June 2
E Day Plus 15

Both eruptive activity and earthquake activity are quite low today. Ash plumes barely reach the crater rim, but the ash from the May 18 eruption has circled the Earth in the high-altitude air mass. A meteorologist with the Air Resources Laboratory of the National Oceanic and Atmospheric Administration said today, "The ash is over the Aleutian Islands in Alaska, possibly up to the North Pole, and then extends south through Canada." He added that the ash is in the 20,000- to 40,000-foot altitude zone and is in such low concentrations that it is invisible to the eye.

Scientists generally agree that, although the worst dangers from Mount St. Helens may be over temporarily, the volcano remains dangerous. USGS geologists Crandell and Mullineaux, in a hazards statement, said, "At present there is a relatively high degree of risk in working in areas near the volcano. The degree of risk varies according to wind direction (for ash) and according to topography (for pyroclastic flows). By comparison with an ashfall of about 4,000 years ago [table 2], a major eruption now could result in the deposition of as much as 3 feet of ash at a distance of 20 miles and 1 foot at 50 miles. The sector affected would depend on wind directions and strengths.

"Pyroclastic flows tend to move down valleys and other depressions, and clouds of hot ash accompanying them may affect areas beyond the sides and ends of pyroclastic flows. There is some risk even beyond the pyroclastic flow limits shown on [previous] volcano hazards maps because of the possibility that some will occur that are longer than those of the past.

"A sector directly north of the volcano will be especially hazardous if and when a dome is formed in the crater because of the possibility of strong lateral blasts.

"There is no unequivocal boundary anywhere around the volcano that sharply divides areas of risk from areas of no risk. Risk increases toward the volcano in all directions for all kinds of volcanic events, but the rate of increase is different for different kinds of volcanic events.

"It is not possible to predict now what the volcano will be doing a month from now, or even a week from now. It should be assumed, for planning purposes, that a major explosive eruption could begin and progress to a climax very rapidly, so there would be essentially no time for warning."

Governor Ray today changed the executive order that established the restricted zones around Mount St. Helens (fig. 13). The exact boundary of the Red Zone was defined, and new rules for entry were set forth. The Governor also asked today for more Federal aid, saying, "Clearly, neither this State nor its local sub-units of government can continue [on their own] to cope with the physical effects of the disaster, let alone the financial burden."

A second manufacturer of dust masks suitable for use in volcanic areas donated 160,000 of them to the State of Washington to distribute to people in the "ash belt."

A new report by the Mount St. Helens Technical Information Network said that, when the May 18 ash is viewed under the microscope, two main ingredients can be seen: (1) pumiceous volcanic glass and (2) crystal fragments of the mineral feldspar, which is composed of sodium, calcium, aluminum, and silica. These ingredients are "new" (juvenile) volcanic material, mixed with variable, small quantities of other minerals and particles of the "old" volcanic rock torn from the walls of the eruptive vent.

When USGS researchers examined the ash, they found only minute amounts of the free-silica minerals (quartz, cristobalite, tridymite, flint, chalcedony, and opal) that have been of such great concern as a potential long-term hazard to the health of those breathing the ash.

The ash is about as abrasive as finely crushed window glass. Its density is about two or three times as great as that of water, but it is almost insoluble in water. For that reason, it should


A
B

FIGURE 47.—Fieldwork in the avalanche deposit. *A*, Geologists collecting samples at a weakly steaming fumarole in the May 18 debris-avalanche deposit. The view here is eastward; the fumarole is in the valley of the North Fork Toutle River, just south of the destroyed Coldwater II observation site and about 5 miles north-northeast of the crater's center (see fig. 51). The debris-avalanche deposit, derived from the upper northern side of the mountain, here is about 300 feet thick. Part of a new pond, covered with floating pumice and wood debris, is at the lower right. (Photograph by David Frank, USGS, June 7, 1980.) *B*, USGS geologist Robert L. Christiansen is dwarfed by the jagged landscape formed by debris from the avalanche and a tangle of uprooted trees at this site north of the western lobe of Spirit Lake. The view here is toward the southwest. (Photograph by Robert L. Smith, USGS, May 30, 1980.)

weather slowly, giving up some plant nutrients such as lime, potash, and phosphorous in the process. Some potentially harmful substances—chiefly acids and salts—cling to the tiny particles, but the amounts of these substances are small.

The USGS completed a new topographic map showing preeruption features in a 2,700-square-mile area surrounding the volcano. An accurate single map showing features in the degree of detail needed for posteruption planning and rehabilitation had not been available previously. (Some earlier USGS maps showing features at a larger scale and in more detail are badly out of date with regard to roads, trails, and logged-off tracts.)

Athough the death toll remains at 22, the list of missing persons is shrinking as some people, initially reported missing by worried friends or relatives, come forward to tell authorities that they survived.

Tuesday, June 3
E Day Plus 16

Harmonic tremor, which has been fluctuating in a range of low amplitudes for the past several days, fell off to a very low level last night; then, about 2:00 a.m., it began to increase strongly. The University of Washington seismology center contacted USGS scientists in Vancouver and informed them that this pattern of harmonic tremor was similar to the one that had preceded the May 25 eruption. Furthermore, no earthquakes ("none at all") have occurred since Monday morning, reminiscent of the gradual decrease in earthquakes that took place before the May 18 eruption. Because of these similarities, scientists are keeping an especially careful watch on the volcano. As of midnight, however, no eruption is evident.

Measurements of sulfur dioxide production from Mount St. Helens today show that the volcano is emitting about 200 tons of SO_2 a day. This emission rate is about the same as the rates measured in late May.

Two men, an injured professional photographer and his uninjured helper, were picked up from the flank of Mount St. Helens by a Forest Service helicopter and brought to Vancouver early this evening. They reportedly have been in the restricted zone taking pictures and eluding airborne observers most of the time since before the May 18 eruption. They may face both State and Federal prosecution for deliberately entering the restricted area.

The Corps of Engineers reports that its plans for flood control and water rehabilitation include not only dredging the rivers and raising dikes along the Cowlitz but also constructing rockfill dams and settling ponds on the two forks of the Toutle River. The dams and settling ponds are intended to catch additional sediment eroding from the area of the volcano blast and carried by the two river forks and, thereby, to lessen the filling of channels downstream. The captured sediment reportedly will be removed from catchment ponds later by earth-moving equipment.

The National Weather Service office in Seattle began issuing "St. Helens plume trajectory forecasts" warning where ash will fall if more erupts. Enough rain fell today in Portland to permit cancellation of an "air-pollution alert" that has been in effect since the May 25 eruption dusted that city with fine ash.

Automatic banking machines are the latest victims of the ash. Two bank machines in Yakima and 40 in Portland reportedly have been disabled by ash that has blown into their mechanisms.

The ash may be useful in some manufacturing processes, however. A California firm announced that, when the ash is mixed with a plastic resin, it forms a porcelainlike material that can be used to make bathroom fixtures and other products. An instructor at Spokane Falls Community College (near Spokane) previously had reported that the ash is a "ready-made" glaze material for some ceramic products.

Wednesday, June 4
E Day Plus 17

The volcano's plumes continued to be principally steam, which rose regularly to altitudes of 12,000 to 14,000 feet. Earthquake activity was low. Harmonic tremor, which yesterday was stronger than it has been at any time since May 25, decreased in amplitude. Upward (inflationary) tilting on the volcano's southern side continues at a very slow rate, quite unlike the rapid bulging of the northern side before the May 18 eruption. Scientists continue to warn that the apparent quiet may be misleading—the volcano may be poised for another eruption. Despite the continuing apprehension of scientists, however, the Red Zone is scheduled to reopen today for loggers, residents, and news reporters if the volcano remains quiet.

A hospital patient died today of burns received during the May 18 eruption. A body discovered about 3 miles west of the crater was identified as that of a missing Portland photographer, Robert Landsburg. These two events brought the death toll to 24 and reduced the missing persons total to 50.

Thursday, June 5
E Day Plus 18

Eruptive and seismic activity at Mount St. Helens remained low today. USGS and University of Washington scientists have concluded that the ominous pattern of earthquakes and harmonic tremor earlier this week, which had been thought to indicate an impending eruption, "must be considered a false alarm."

The Forest Service announced that it will set up seismographs at the visitor centers on Interstate Highway 5 southwest of Mount St. Helens and at Lewis and Clark State Park northwest of the mountain, so that visitors can follow the recording of the volcano's earthquakes as they occur.

Washington State University scientists in Pullman have determined, on the basis of experimental work with chickens, that the ash is not acutely toxic to domestic animals. Scientists are still concerned, however, that eating and breathing ash will have some effect on larger animals.

There is no evidence that food raised in ashfall areas poses a health threat, the Technical Information Network reports, but careful cleaning of fruits and vegetables is recommended.

The Coast Guard office in Portland reports that dredging of the Columbia River shoal has deepened the navigation channel to 33 feet, more than three times deeper than the 10-foot depth left after the May 18 and 19 floods from the Cowlitz River.

Colleagues of photographer Blackburn, who died in the May 18 eruption, found one of the remote-controlled cameras that he had been operating from Coldwater I observation station. Film from the battered camera was processed, but it had been fogged by the heat and showed no clear images of the May 18 blast that killed Blackburn.

Friday, June 6
E Day Plus 19

Seismic activity remained low, and plumes consisting mostly of steam rose only about 15,000 feet above sea level.

Loggers and property owners "swamped" State offices today seeking permits to get into the Red Zone, as Governor Ray's most recent executive order allows.

Emission of SO_2 has increased significantly between June 3 and today. Today's measurement of about 900 tons a day is nearly four times greater than the June 3 measurements.

Researchers from the National Center for Disease Control who analyzed four samples of volcanic ash for free silica found concentrations to be low—about 6 percent of the respirable size (less than 10 microns) by weight. Of this, two-thirds was in the form of the mineral cristobalite, and one-third was quartz. (Some chemical analyses previously had reported a high percentage of silica in the ash; most silica, however, was chemically bound in various other minerals, and it was not the dangerous "free silica," or SiO_2.) Although exposure to free silica for many years can cause silicosis and exposure to large concentrations for a short time can cause an acute form of the disease, Federal health scientists do not think that short-term exposure to the ash is a significant public health hazard. They suggest that persons working in the ash, as well as those having respiratory diseases, should wear dust masks. Children should be cautioned not to play strenuously in ash-filled air, and they should not be allowed to play in deep ash.

Tourists, the lifeblood of Washington's ocean beach communities, are "staying away in droves" after the traffic jams and accidents, strandings, and other problems that ashfall from the May 25 eruption created for Memorial Day travelers. The Ocean Shores Chamber of Commerce, according to the Tacoma *News Tribune*, reports that business in that normally busy resort community is "down 60 to 70 percent."

One huge industrial vacuum cleaner was operated for 2 days to remove 17 tons of volcanic ash from the roof of the Yakima City Hall.

Saturday, June 7
E Day Plus 20

Mount St. Helens continued its low eruptive activity today, sending steam plumes, but little ash, to an altitude of about 11,000 feet. No earthquakes were recorded, and harmonic tremor was as low as it has been since May 18.

USGS water-quality specialists say that the chemical constituents of Mount St. Helens ash should not affect water supplies significantly. They soaked ash samples collected in Spokane and Richland, Wash. (near Pasco) (fig. 29*G*), and in Helena and Kalispell, Mont., in water for 4 hours and then analyzed the leachate (soaking water). The test simulated the effects of rain falling on one-half inch of ash. The test was designed to show a "worst case"—that is, to produce the highest likely concentrations of chemicals in water draining through the ash.

The first water draining through the ash did contain some chemical ions (including chloride, fluoride, sulfate, ammonium, manganese, boron, cadmium, and selenium) in concentrations that exceed the water-quality standards for public water supplies. Later soakings yielded much lower concentrations of these ions. Under natural conditions, reactions within the soil and dilution by other ground water or surface water would lower these concentrations in the runoff or in water infiltrating from ashy lands.

Manganese, one element that could prove to be annoying, was present in the leachate in concentrations as much as 100 times the recommended level. Although manganese could impart an objectionable taste to water and perhaps cause staining of light-colored objects washed in affected water, it should not be a health hazard.

Boron concentration in the leachate was as much as 2.5 times the maximum recommended for long-term irrigation of such boron-sensitive crops as apples and some berries. Under natural conditions, however, such strong concentrations would be unlikely to reach the

roots of the plants before irrigation water had diluted them adequately.

The ash could change acidity levels slightly but reportedly not enough to damage crops. The pH of the leachate was about 6.0 (very mildly acidic), slightly less acidic than the average for rainfall in the Northwest, which generally has a pH of about 5.

The new State system for gaining entry to the Red Zone provides "blanket" 30-day permits for logging corporations and other companies. To qualify, each company must:

- Have a method for identifying and locating each employee, agent, and (or) contractor authorized to be in the Red Zone.
- Inform each employee of a predesignated escape route.
- Monitor radio frequencies established by the local sheriff's department or other governmental agency for transmitting emergency signals about Mount St. Helens.
- Check each authorized employee in and out daily.
- Issue an identification card, tag, or other form approved by the Washington Director of Emergency Services to each worker.
- Provide the foreman of each work crew with a two-way radio and require him to make regular contact with a central dispatcher.
- Inform each worker that he must stay within a 15-minute walking distance of his vehicle.

Weyerhaeuser, one of the largest owners of timberland in the Mount St. Helens area, reports that most of its downed timber seems to be salvageable and that the company expects to begin immediately restoring its equipment, facilities, and routes into the blowdown area.

Loggers in ash-coated timber areas report that they must sharpen their saws about three times as often as they did before May 18.

The Federal Emergency Management Agency closed most of its remaining disaster assistance centers in eastern Washington and northern Idaho this evening. Only the centers at Kelso, Spokane, and Moses Lake remain open. Agency officials report that more than 3,700 people have registered at centers in the two States to inquire about or apply for disaster assistance loans or grants or to seek counseling.

Scientists are still warning that the volcano could explode or send out eruptions of pumice and ash. USGS geologist Richard Waitt said today that a larger eruption plume and a thicker ashfall are still "very possible."

Scientists in the field report the reappearance of small plants of the horsetail rush type, as well as small animals, in the devastated area. They also have seen fresh deer and cougar tracks in the ash.

News reports remind the public that Mount St. Helens is not the only volcano now active. Mount Etna in Sicily is erupting and reportedly has killed nine people. Worldwide, probably 30 to 40 volcanoes are active now.

Sunday, June 8
E Day Plus 21

Several nervous residents called the Mount St. Helens coordination center today to ask if the sharp lightning flashes visible over the volcano meant that it was erupting. It was not.

The mountain remained quiet again today; only very low level harmonic tremor was recorded at the University of Washington seismology center. Rain and clouds kept observation aircraft grounded, but an Oregon Army National Guard airplane flew over the mountain to obtain radar and thermal infrared images. Radar showed the base of a steam plume that rose lazily through the rain clouds to an altitude of about 12,000 feet. The thermal infrared images showed a general heating, since late May, of the eruptive center that was active May 18. The images also showed that heat was still being emitted by the pyroclastic flows.

Scientists used the sporadic periods of clear weather this weekend to reestablish some of the survey lines on the southwestern side of the mountain for ground-deformation studies. The lines are to be measured as regularly as weather conditions permit.

Observers are watching closely for the formation of a dome—a buildup of extruded lava that is too pasty to flow far from the extrusion vent. A dome could signal a rebuilding of the mountain, although not necessarily the end of danger. Following previous eruptions, Mount St. Helens has formed other domes; the now-vanished Goat Rocks was probably the latest such dome (table 2). Dome-building activity in the inner (May 25) crater has been reported but not verified.

Monday, June 9
E Day Plus 22

Steam plumes and some ash continue to be vented. No harmonic tremor was recorded today, and seismicity was low. New avalanches took place under the persistent cloud cover, but none was observed in progress.

When observers were able to see into the crater, they noticed a new, crescent-shaped lake in the northern part of the crater floor. It was about 1,000 feet long and 300 feet wide.

On Friday (June 13), the moon will be at its closest proximity to the Earth since May 17, and strong tides will result. Although geologists generally agree that tides, by themselves, cannot cause volcanic eruptions, some concede that strong Earth tides might be "the straw that breaks the camel's back" if the volcano is already primed for an eruption.

The persistence of ash from the May 18 eruption has caused the Army to cancel its usual summer exercises at the extensive desert training center near Yakima. Normally, one or two battalions at a time would be using the Yakima Firing Center, but uncertainty about the effects of the dry, blowing ash on the health of soldiers and on precision equipment prompted the cancellation.

Because volcano damage has been rare in this country, no one is certain how much of the private losses caused by the eruption will be covered by insurance. People who are listed as missing pose special problems for life-insurance companies and claimants.

Tuesday, June 10
E Day Plus 23

The mountain remained quiet again today; only minor amounts of ash were vented in plumes of steam that rose less than 2,000 feet above the crater rim. No harmonic tremor and no earthquakes were recorded

USGS scientist Arnold Okamura says that one tiltmeter on the southern side of Mount St. Helens has been showing a slight inflation of the southern flank for the past month. The rate of tilt has been relatively constant since about May 9, even through the eruptive periods of May 18 and 25.

The Corps of Engineers reports that the dredge *Art Riedel* began operations in the mouth of the Cowlitz River. Previous dredging has been concentrated in the Columbia River navigation channel.

Nearly 4,200 people reportedly had visited Federal disaster assistance centers in Washington and Idaho by this evening, when the centers in Spokane and Kelso were shut down. Plans call for the center at Moses Lake to be closed Thursday evening and for a new center to be set up in Centralia, Wash., that same day.

Governor Ray, in an appearance yesterday before the U.S. Senate Appropriations Committee, had praise for the "timely warnings" about the Mount St. Helens eruptions. "We were warned of all possible consequences and tried to have a general plan, and as a result of that I believe many, many lives were saved," she said.

No major population centers have reported serious problems with drinking-water quality as a result of volcanic ash, although some smaller water systems have been plagued by turbidity and equipment damage, nor has anyone reported toxic levels of metallic ions or other chemicals derived from ash in drinking water. However, washing away the ash taxed some water supplies, particularly at a time when many normal surface-water supplies were not usable.

Wednesday, June 11
E Day Plus 24

No harmonic tremor, no unusual earthquake activity, and no strong eruption changed the even tenor of the day at Mount St. Helens.

Officials of Federal agencies and the State of Washington told Congress today that the bill for damages caused by the Mount St. Helens eruptions will be about $2.7 billion. The total would have been even greater if volunteers had not assisted the State and Federal governments, according to the Washington Department of Emergency Services. Besides volunteer service groups, such as the Tri-County Search-and-Rescue Association, the Lower Columbia Amateur Radio Association, the Salvation Army, and the American Red Cross, many individual volunteers have been working steadily throughout the emergency.

A machine specially designed to lift, comb, and shake ash-coated alfalfa is being manufactured in eastern Washington and is expected to salvage part of the hay crop in the "ash belt."

Salmon can be killed if sharp ash particles damage their gills, according to a Washington Department of Fisheries investigation. The department concluded that fish probably could not survive a swim through the ash-filled Cowlitz River.

The official death toll remains at 24. The removal of four more names from the list of missing persons has reduced its number to 46.

Third Explosive Eruption

Thursday, June 12
E Day Plus 25

The third explosive eruption of Mount St. Helens occurred tonight. It was preceded by a buildup of harmonic tremor, which began at low levels about midday and increased in amplitude throughout the afternoon. The University of Washington seismology center notified the Vancouver coordination center and the Washington Department of Emergency Services that a buildup in tremor similar to the one that preceded the May 25 eruption was occurring. A marked increase in the harmonic tremor was noted at 7:05 p.m., and reports of an eruption cloud rising to an altitude of at least 13,000 feet were received 5 minutes later. Tremor dropped off in strength immediately after the eruptive pulse and fluctuated at moderate amplitudes for more than 2 hours.

This temporary lull was broken dramatically by a large increase in tremor amplitude at 9:11 p.m. Shortly thereafter, observers in a Forest Service airplane witnessed the very rapid climb of an eruption column to an altitude greater than 35,000 feet. About 400 families living in the latest Red Zone were warned to evacuate, but many reportedy declined to do so. A flash-flood watch was put in effect for the Toutle, Cowlitz, Kalama, and Lewis Rivers.

National Weather Service radar observers in Portland tracked the eruption plume to an altitude of 50,000 feet at 9:18 p.m. Forest Service airborne observers reported that the column was "several kilometers wide" at its base and was producing lightning. Cloud cover, however, prevented observers from seeing whether new mudslides or pyroclastic flows were occurring. The plume height as detected by radar fluctuated between about 15,000 and 35,000 feet above sea level until about midnight, when it diminished.

Prevailing winds are carrying ejected ash to the south and southwest, and pumice particles as large as one-half inch across are falling "like hailstones" on Cougar, about 11 miles downwind from the volcano. Ashfalls began in Vancouver and Portland about 10:50 p.m. and are still continuing as of midnight.

Recognition of the preeruption pattern of the harmonic tremor warned

emergency-services officials of the impending eruption and allowed them to warn the public quickly. No casualties were reported.

Friday, June 13
E Day Plus 26

The eruption that began last night apparently continued sporadically into the early hours of this morning. At 2:02 a.m., the Portland office of the National Weather Service reported that its radar showed "a heavy plume" up to 15,000 to 16,000 feet above sea level. The pilot of the Forest Service observation airplane reported at 2:31 a.m. that, at his position 22 miles northwest of Pendleton, Oreg., he was "in ash" at an altitude of 24,000 feet and that the plane was being peppered with pumice particles as large as one-eighth inch in diameter. (The plane outdistanced the eastward-moving ash and landed safely in Spokane after having been warned away from Portland area airports). At 4:00 a.m., the National Weather Service radar showed the plume top to be at 13,000 feet and the ash content to be slightly reduced. At 6:00 a.m., the University of Washington seismology center reported that steady, low-level harmonic tremor was being recorded.

The Federal Aviation Administration closed airspace and airports as far away as 150 miles from Mount St. Helens (Portland International Airport reopened about 7 hours later). The National Weather Service issued travelers' warnings for anyone using roads within 50 miles of the mountain. By 6:00 a.m., the Washington Department of Emergency Services had announced that all Red Zone entry permits had been suspended and that only permanent residents would be allowed in the area. This action will keep more than 200 loggers out of areas where they had resumed work only a few days ago.

Although last night's eruption was shorter than the one on May 25 (about 5 hours as opposed to more than 12 hours), it may have spewed more ash, according to USGS geologists. The prevailing winds at most altitudes reached by the ash plume seem to have spread the ash mostly in the quadrant extending south to west from the volcano (fig. 48). Traces of ash, however, were reported falling as far away as Seattle to the north and Salem (and perhaps Medford) to the south. Vancouver received about one-eighth inch, and Portland received about one-sixteenth inch. The coastal city of Tillamook, Oreg., nearly 100 miles southwest of Mount St. Helens, apparently lay directly in the path of the plume that reached the Oregon coast. As much as one-eighth inch of ash reportedly fell on that city, but little or none fell on nearby communities to the north and south.

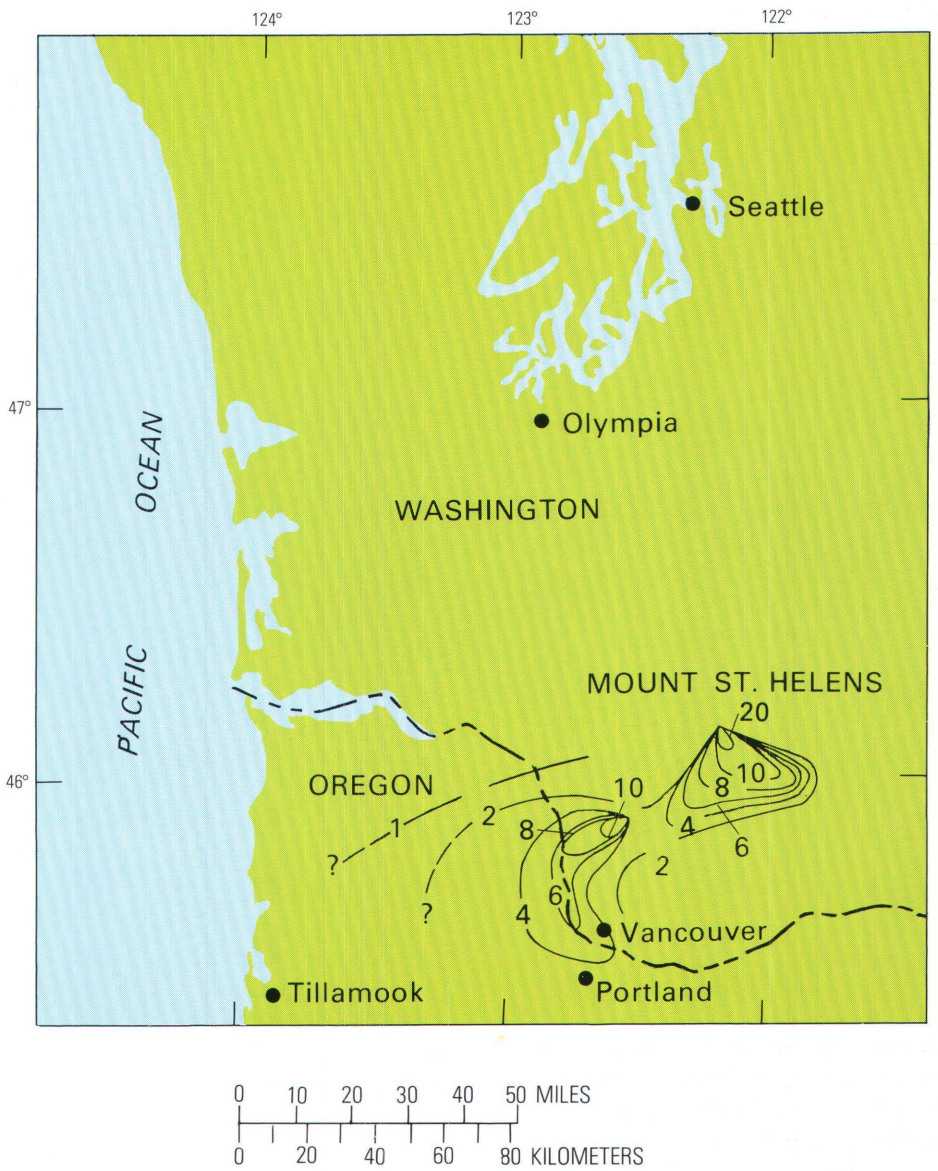


FIGURE 48.—Generalized pattern of ashfall thickness from the June 12 eruption of Mount St. Helens (modified from Sarna-Wojcicki and others, 1981). Although winds at the different altitudes reached by the ash were blowing in different directions, most of the ash was distributed to the southwest of the volcano. Information on the extent of trace amounts of ash was not available. Lines of equal ash thickness are designated in millimeters (1 inch=25.4 mm).

The National Weather Service, which has been monitoring the movement of the airborne ash, predicts that some of the ash carried out over the Pacific Ocean last night will be blown back over northern California by tonight. (The curved path of the ash cloud may account for reports that ash reached Medford, near the southern border of Oregon.)

Day-long rains in much of the ashfall area settled the ash and helped cleanup efforts, but the rain also formed slick mud that made driving hazardous. A speed limit of 15 miles an hour that was imposed in Portland during the ashfall was lifted by midmorning. The flash-flood watch for the Toutle, Cowlitz, Kalama, and Lewis Rivers, which was imposed last night, also was cancelled.

In the 8 hours following last night's eruption, many small "aftershocks" were recorded at the University of Washington seismology center. Twenty-one of these shocks were strong enough that preliminary locations could be calculated. These quakes originated at depths of about 4 to 7 miles below the surface and were located just west of the volcano's crater.

Bad weather and the fuming volcano prevented observation of the crater today, but radar imagery obtained at about 2:00 p.m. by the Oregon Army National Guard clearly shows that the amphitheater and rampart are about the same as they were when last seen and that what appears to be a dome now is in the position of the former inner crater.

Helicopter reconnaissance around the mountain today could not verify the presence of the dome, but observers could see that the eruption had caused extensive new pumice flows north of the volcano and also minor mudflows that ended on the mountain itself. The pumice flows had poured out of the open end of the amphitheater and rushed downslope to the north, completely burying the ash flow from the May 25 eruption and filling steam-explosion craters that formed in the May 18 debris-avalanche deposits (fig. 30). One lobe flowed nearly 5 miles, stopping within 30 yards of Spirit Lake. Another extended westward more than 1 mile in the upper part of the North Fork Toutle River valley. USGS geologist Peter Rowley said that the material ejected in the eruption was from fresh magma rather than old rock or ash from the larger (May 18) crater. Like those from the May 25 eruptions, the latest pyroclastic deposits contain dense dark-gray pumice and vesicular tan pumice. The deposits also contain blocks of dense gray dacite rock. Temperatures measured in the June 12 ash flows are more than 1,100°F (600°C)—hotter than any measured in the May 18 ash flows and nearly hot enough to melt aluminum.

USGS volcanic hazards geologists today described the effects of the eruptions and the outlook for continued explosive activity to a U.S. Senate subcommittee hearing in Portland called by Oregon Senator Robert Packwood.

By this evening, the volcano was still emitting steam but little or no ash.

Saturday, June 14
E Day Plus 27

Although avalanches in the crater could be heard from the ground, the mountain itself was quiet today. All that could be seen was a small steam plume rising to an altitude of about 15,000 feet. Poor visibility prevented viewing of the crater. Although the strength of the harmonic tremor continues to diminish, the University of Washington seismology center says that the mountain still is more seismically active than it was before the last eruption.

Scientists began installing new tiltmeters near the cone, but they could not reach gravity-monitoring sites because of poor flying weather. Ground parties found that pyroclastic deposits from the eruption of Thursday and Friday were still very hot, coated with sulfur in places, and dotted with fresh pumice blocks. Temperature measurements made at a depth of 10 feet in deposits filling an old steam-explosion pit near the downslope end of the pyroclastic flows registered nearly 1,100°F (600°C).

Ash from the eruption of June 12 and 13, collected dry in Vancouver, was soaked with distilled water, and the leachate was analyzed, as was that of the earlier ash. The chemical constituents of the leachate were about the same as those of the earlier ash, except that this leachate was more acidic (pH 3.6–4.2).

Designated State of Washington offices began reissuing permits today allowing residents to return to their homes in the Red Zone.

Washington Department of Fisheries biologists say that salmon are "bleeding to death" in the ashy mud carried by the lower Cowlitz River; they doubt that fish will ever be able to adapt to river water made muddy by the ash. Dissection of the fish shows tiny, razor-sharp particles of silica lodged in their gills "cutting them to shreds."

Agricultural experts, however, are now saying that ash damage to Washington's agriculture industry (fig. 49) is less than originally estimated. Scientists from Federal and State

FIGURE 49.—Effects of ash from the May 18 eruption on agricultural areas in eastern Washington. *A*, Compacted ash 0.75 to 1 inch thick smothered lentil plants in this field about 25 miles south of Spokane. The severe damage to this crop is obvious, but many crops in the "ash belt" produced profitable returns in 1980 despite the ashfall. (Photograph by Earl Baker, U.S. Soil Conservation Service, July 1980.) *B*, Tractor towing a disc cultivator through a field at the Lind Agricultural Experiment Station, about 12 miles southwest of Ritzville. As much of the ash as possible was mixed into the underlying soil in this manner. The thick cloud of ash dust raised by this rather gentle cultivation method shows why dust respirators were strongly recommended for agricultural workers in the "ash belt." (Photograph by C. Kelley, U.S. Soil Conservation Service, summer 1980.)


A


B

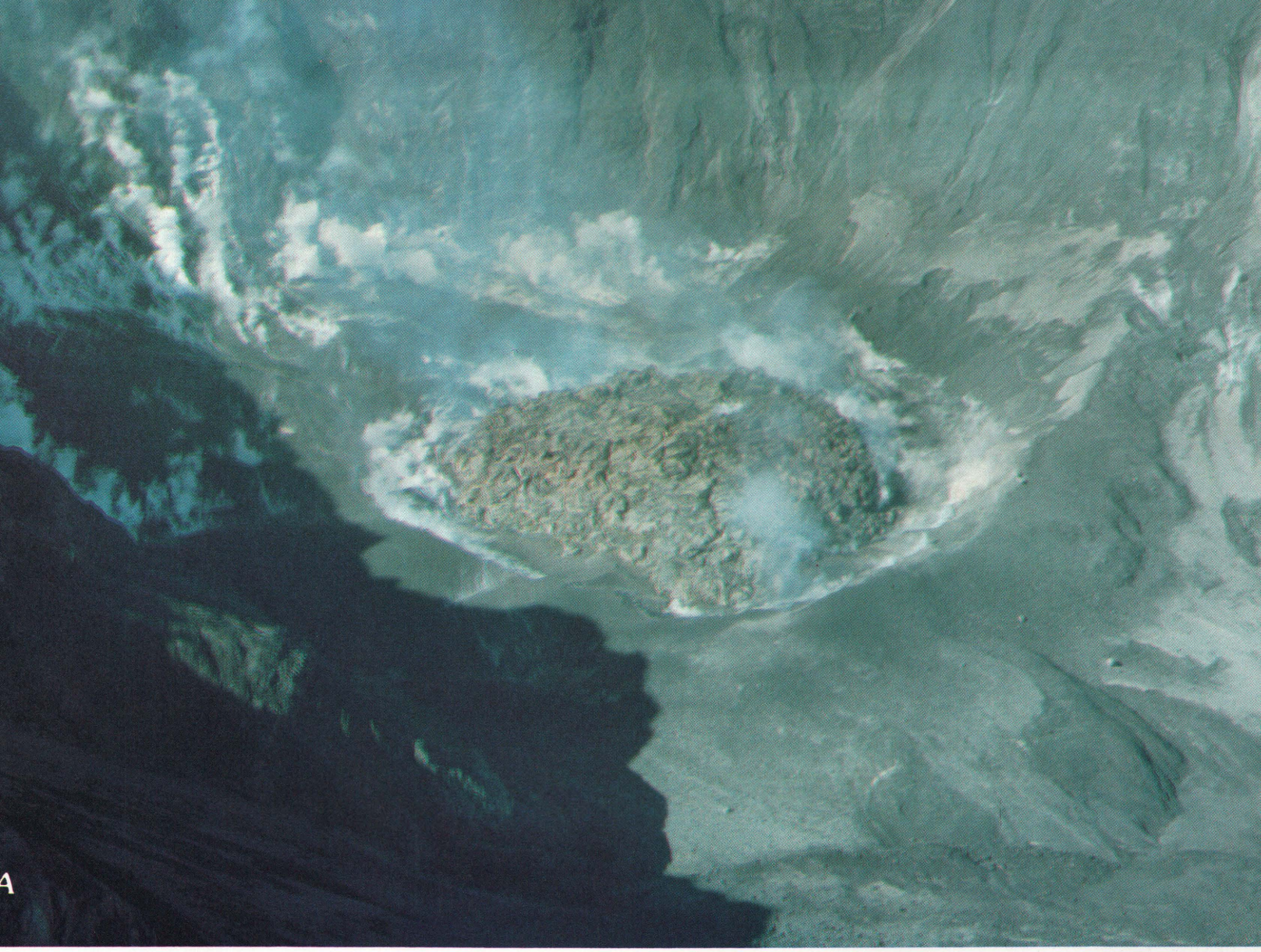
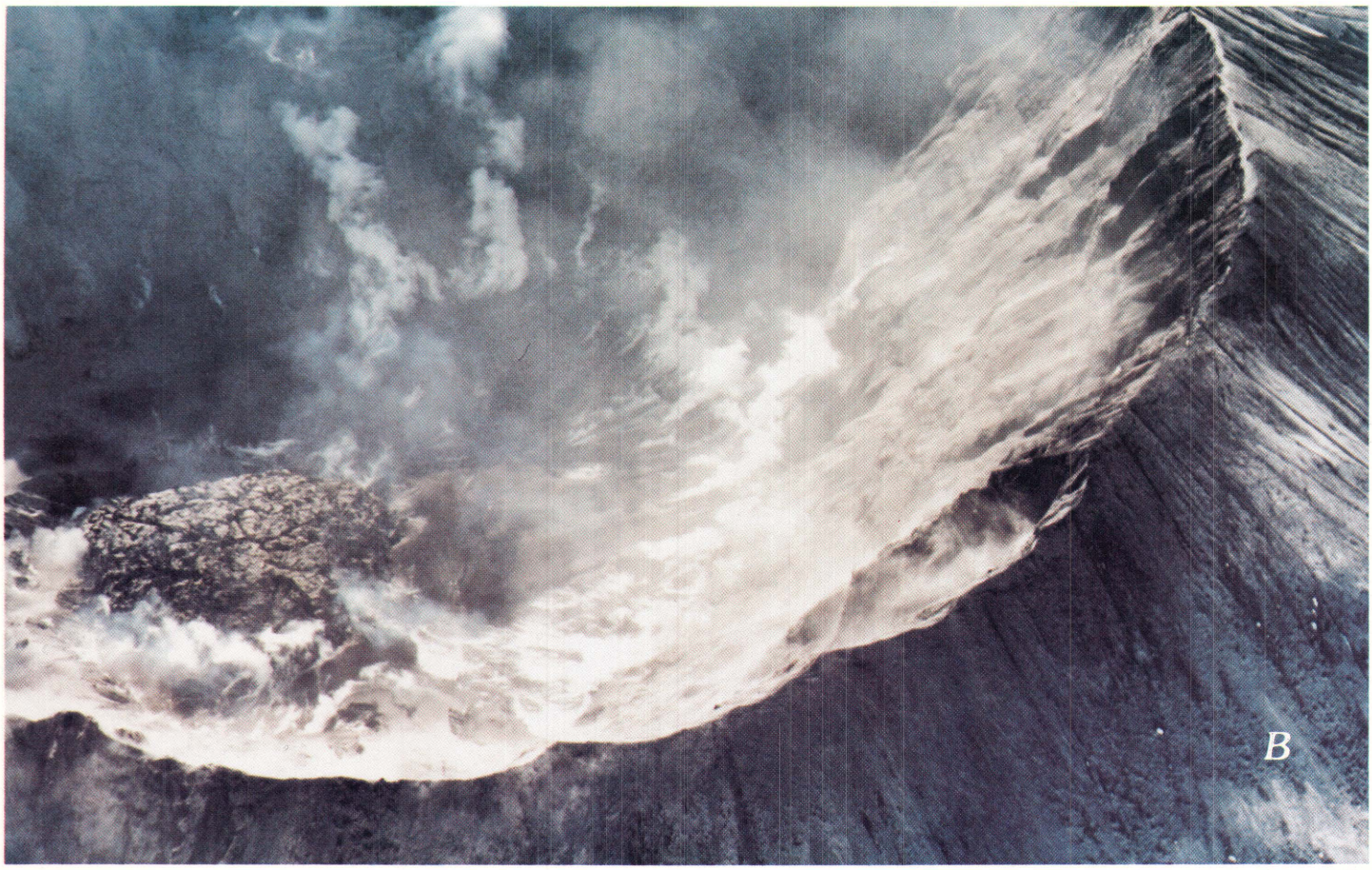


FIGURE 50.—Aerial photographs of the lava dome that extruded into the crater of Mount St. Helens during the latter part of June 1980. The volcano's dacite lava has a pasty consistency when it is molten, and it tends to pile up rather than to flow laterally. This dome, which was largely destroyed in a subsequent eruption on July 22, 1980 (fig. 61*B*), was, at this stage, about 1,200 feet across and 200 feet high. Its rough, shattered appearance resulted mainly from the expansion and shattering of the solidified outer crust as more molten lava was forced upward by the great pressure in the magma chamber underlying the volcano. *A*, View through the amphitheater mouth from the northeast (direction of view same as that in fig. 46 but farther out). The lava extruded into a depression left by the June 12 explosive eruption. The curved ridge, or rampart, across the inner crater mouth is clearly visible in the middle of this photograph. At this time, fuming was strongest in the southern and eastern parts of the crater floor and inner crater walls and at places in the "moat" around the base of the dome. Two cracks in the crater floor, radiating outward from the dome, are marked by rows of faint vertical vapor plumes (white streaks) at left center. (Photograph by Michael P. Doukas, USGS, June 28, 1980.) *B*, View from the west over the crater rim from a helicopter taking geologists to collect samples and measure temperatures inside the crater. The breadcrust texture of the dome's surface is well shown here. The white area inside the crater rim in the left foreground is sunlight reflecting from vapor and light-colored tephra. The tephra rampart is at the extreme left. (Photograph by Jules D. Friedman, USGS, June 29, 1980.)

agricultural agencies today placed the total agricultural damage at between $175 and $186 million. Previous estimates were $200 million or more.

Volcanic activity at Mount St. Helens has caused renewed concern about Mount Baker, the northernmost steaming volcano in Washington. The interagency "Mount Baker Information Committee," formed in 1975 when that volcano heated up, has been reactivated. Recent flights over Mount Baker by USGS observers and others, however, have not yielded any indication of an increase in volcanic activity.

Many "volcano watchers" in Vancouver are getting their first real taste of the aggravating personal effects of the persistent ash—effects that have



been all too familiar to residents in the eastern Washington "ash belt." These include wearing dust masks whenever there is a need to go outside; careless drivers whose vehicles raise unnecessary dust clouds; the slipperiness of ash during a rain and the return of dust almost as soon as the rain stops; and the continual presence of ash on hair, clothing, furniture, and equipment.

Lava Dome Grows

Sunday, June 15
E Day Plus 28

Weather conditions today permitted detailed observations of the crater's interior for the first time since the latest eruptions, and the presence of the dome shown on radar images last Friday was confirmed visually (fig. 50). The dome was seen first this morning by observers in a Forest Service airplane and later from a helicopter at crater level. The dome is a symmetrical mass, circular in area, about 700 feet in diameter and rising 130 feet above the level of the crater floor. It is tan to light gray, and its surface is cracked into a pattern resembling large-scale breadcrust texture. A slight red glow emanates from within the hot dome through cracks in the crust of solidified lava. Almost its entire margin was fuming today, as was much of the crater floor near the steeper crater walls. Small steam explosions, concentrated mainly at the northeastern edge of the dome, were periodically spouting small amounts of gray ash up to heights of about 300 to 700 feet within the crater. A shallow moatlike depression lies between the dome and the rampart to the north. The dome is the cooling top of a column of magma rising from beneath the volcano. No flows or other obvious signs of rapid growth were seen today, however.

The appearance of the dome does not, scientists say, change the assessment of hazards from the volcano. Although the dome may represent a late, less highly explosive stage in this eruptive sequence, the flank of the volcano directly north of the breach in the crater (fig. 51) is still subject to small explosions, partly because of the crater's shape and partly because of the position of the new dome. Furthermore, the record of Mount St. Helens' previous eruptions shows many highly explosive eruptive sequences within long-term eruptive episodes. There is "life in the old girl yet," scientists point out, and highly explosive eruptions of both tephra and gas could reach into the stratosphere, and pyroclastic flows could speed down the volcano flanks into adjacent valleys. Although the dome may cap the present volcanic vent, it could be blown away by eruptions, or explosions from beneath

FIGURE 51.—Aerial photograph of Mount St. Helens taken from about 7 miles to the north-northwest, looking over the site of the demolished Coldwater II observation post (marked by an X) and debris-avalanche deposits in the eastern part of the North Fork Toutle River valley. The location of the geologists shown in figure 47*A* is indicated by the vertical arrow (center foreground). (Photograph by Austin Post, USGS, June 30, 1980.)

could direct lateral blasts down the slopes at high speeds.

University of Washington seismographs recorded vibrations caused when sections of the crater rim avalanched back into the crater; low-level harmonic tremor also was recorded, but there were no actual earthquakes.

A few measurements of sulfur dioxide gas taken since the eruptions of Thursday night show that the emission rate has averaged about 1,000 tons a day during the initial growth of the dome.

The most consistent of the Mount St. Helens tiltmeters, located about 3.5 miles south-southwest of the volcano's center, stopped sending data today. That instrument, which had been operating during all three of the major eruptions, had indicated a nearly constant, though very small, inflation of the southern flank throughout May and early June but had shown little or no change in tilt beginning the second week of June.

Warm, dry weather and light breezes combined to create zero-visibility conditions in some parts of northwestern Oregon that had received a substantial dusting of ash during last Thursday night's eruption. In the Vancouver-Portland metropolitan area, blowing ash also was causing problems. In Portland, a speed limit of 15 miles an hour was reimposed to reduce traffic hazards. Area residents spent much of their weekend hosing ash from cars, homes, sidewalks, and streets. Flushed-off ash clogging the filters of sewage-treatment plants necessitated dumping partly treated sewage into the Columbia River.

Dust masks were a common sight on area residents and even on participants in the Portland Rose Festival, which ended today. The parade, a major event of the festival, took place yesterday despite ash-related problems. Three airlines temporarily suspended flights into Portland International Airport for fear that the ash would damage airplane engines.

The Corps of Engineers reports that a second dredge has now begun working in the lower Cowlitz River channel to remove debris deposited by the flood of May 18 and 19. A third dredge is expected to move into the lower Cowlitz tomorrow.

Monday, June 16
E Day Plus 29

It was a quiet day on the mountain; no harmonic tremor or significant earthquakes were recorded. Poor visibility prevented scientists from observing the height and size of the new dome. Mullineaux reminded news reporters that, although the dome represents the first lava to be seen during this year's eruptions, the building and destruction of lava domes have been repeated occurrences in the 40,000-year history of Mount St. Helens. The previous summit was formed by a dome extruded 400 to 500 years ago, and Goat Rocks was a dome formed in the mid-1800's (table 2).

The Corps of Engineers reports that five dredges now have scooped out a narrow channel in the Columbia River shoal, off the mouth of the Cowlitz River, that will allow passage of ships having a maximum draft of 36 feet.

The volcanic ash that powdered many forests may reduce the danger of forest fires in central and eastern Washington and northern Idaho this year, according to University of Idaho scientists. They say that the ash looks and acts just like some fire retardants now in use. They concede, however, that blowing ash could hinder fire-fighting efforts and also could reduce visibility from fire-lookout stations and thus allow small fires to grow before they are spotted.

The Mount St. Helens Technical Information Network suggested ways to suppress the volcanic dust that has fallen so widely on the Northwest. One method is to mix the ash with agricultural lime and use the mixture as a cementing agent to form a windproof crust over ash dunes and other loose ash. A crust also could be formed by using lignin sulfonate (a byproduct of wood-pulp industry), asphalt components and emulsions, or soft asphalt itself.

Tuesday, June 17
E Day Plus 30

Mount St. Helens has remained quiet since its eruption on June 12. Today was partially clear, but steam and gas continued to rise from the crater and formed clouds too dense to allow observation of the new dome. Shortly after 4:00 p.m., the volcano briefly ejected a plume of dense ash—the "most significant" since last week's eruption. The top of the dark plume leveled off at about 12,000 feet above sea level, and, because the air was still, most of the ash fell back into the crater. Seismographs recorded no significant local earthquakes and no harmonic tremor.

Field crews remeasuring the deformation network on the mountain have found no appreciable change. A week ago, the southern side of the mountain was swelling slightly; now, it is stable.

A light rain last night reduced the air pollution caused by persistent volcanic ash in the Portland-Vancouver metropolitan area. Most of the time since last Thursday night's eruption, both cities have been shrouded in a foglike cloud of ash dust that makes breathing uncomfortable and occasionally disrupts automobile and aircraft traffic.

Autopsies have been performed on 22 of the bodies so far recovered from the blast area. Sixteen deaths resulted from inhalation of hot ash, three from

burns, and three from head injuries (two of these caused by falling trees). Two other people rescued as they were fleeing later died in the hospital from burn-related injuries. The death toll now stands at 24, and 45 are still officially missing. The Skamania County Coroner has been holding hearings about the last-known activities of persons still listed as missing. These hearings could result in the issuance of "presumptive death certificates" for some or all of the missing.

Wednesday, June 18
E Day Plus 31

The mountain was quiet today. The University of Washington seismology center recorded one minor seismic event at 7:00 a.m. that may have been caused by an avalanche in the crater or by cracking of the new dome's outer crust. Forest Service airborne observers said that the 7:00 a.m. seismic event was followed about 3 minutes later by a burst of steam and ash that rose a few thousand feet above the crater before dissipating. An earthquake that was recorded at about 11:00 a.m. registered as magnitude 2.8 and was located to the north of Mount St. Helens. About 5:30 p.m., the volcano again shot a plume of steam up to about 13,000 feet and then lapsed back to minor activity.

The new dome has grown 60 feet in height since Sunday, or an average of about 20 feet a day. The height of the dome is difficult to estimate because the crater floor is irregular and largely obscured by steam. Another major eruption could destroy the dome entirely, or the dome could continue to grow, perhaps for decades. If the dome were to continue rising and if it were fluid enough, it could begin moving out to the north through the breach in the crater. If and when that were to happen, volcanologists say, the thick lava probably would flow downhill at a rate of no more than a few feet a day—a rate much slower than that of the more fluid basaltic lava flows from erupting Hawaiian volcanoes.

The U.S. House of Representatives today passed a supplemental appropriations bill that includes more than $783 million for disaster relief programs in response to the Mount St. Helens eruptions. The funds will be used to reimburse State and local governments for cleanup costs and to pay for dredging and debris removal, streambank restoration, construction of sediment-retention dams, restoration of farmlands, loans to businesses that suffered economic loss, and continuation of scientific study and monitoring of the volcano.

USGS scientists Moto Sato and Ken McGee installed a hydrogen gas sensor today on the southern flank of Mount St. Helens at an altitude of 7,000 feet. The instrument will continuously monitor the hydrogen emissions from a cool crack (not a steaming fumarole) in a prehistoric lava flow; the data will be transmitted by radio to Vancouver. This information and other data being gathered about gas emanations from the volcano should lead to a better understanding of the volcano's internal processes.

Oregon Governor Victor Atiyeh asked President Carter to declare Oregon a major disaster area. The Governor also called up 100 National Guard troops to help clean up the volcanic ash in Portland this coming weekend.

Local newspapers report that a man with a gun commandeered a Portland city bus for a trip 30 miles east into the Columbia River Gorge after telling the driver, "I want to get out of town—out of all this ash." The hijacker ordered the driver to stop and fled on foot after an Oregon State Police car began following the bus.

A meeting with officials of the Washington Department of Emergency Services was held in Kelso to present arguments for moving the Red Zone boundary 12 miles closer to the volcano. Mullineaux said that the basic issue was not that of being "safe" at some specific distance from the volcano but rather "the difficult decision of what is an acceptable risk."

An early warning system is planned to alert those who might be endangered by floods during the coming winter. Floods may be worse than usual this year because waterways already clogged with sediment and debris will be filled further when more sediment washes downstream from the blast area. Although the Corps of Engineers has been dredging and today brought in a fourth dredge to speed sediment removal from the lower Cowlitz River, how much of the clogged channel can be opened up before the next flood is not known. In order to monitor flood threats more closely, 22 new river gages will be installed; the Corps of Engineers plans to install 8, the USGS 2, and the National Weather Service 12. The Weather Service also plans to install nine new precipitation gages linked by radio to emergency-services centers.

USGS hydrologists completed detailed surveys of the Cowlitz and Toutle Rivers and computed a second set of floodwater profiles for several postulated conditions of runoff from rainfall and snowmelt. These data were sent to the Federal Emergency Management Agency. They showed that, if no changes are made in the choked channels, Castle Rock could be flooded this year by runoff from precipitation that is no greater than normal. If the channels are not opened up and the winter brings an extended period of moderate rainfall, the result could be a record-breaking flood at Castle Rock, as well as severe flooding on the Cowlitz in the area of Kelso and Longview.

The missing-persons list was reduced to 44 today when a Seattle man called authorities to report that he is alive and well.

Thursday, June 19
E Day Plus 32

The weather today was clear enough for good viewing of the crater and for aerial photography. Photographs to be used in mapmaking were obtained by the National Aeronautics and Space

Administration and by a contractor for the Washington Department of Natural Resources.

Mount St. Helens was inactive today, except for steaming inside the crater. The dome has grown another 6 to 10 feet since yesterday, and its top now stands about 200 feet above the crater floor.

Thermal infrared surveys of the volcano were made from U.S. Navy and Oregon Army National Guard aircraft. These surveys reveal a circular pattern of fumaroles on the crater floor southeast of the dome and about the same size as the dome. Some scientists speculate that the circular area may be a forerunner of a second lava dome or of a new lobe on the present one.

A new instrument station was established this morning on the high point of a ridge about 5 miles north of the crater floor (fig. 52). The ridgetop provides a good view directly into the crater, and several distinctive features of the dome top can be tracked from there with a theodolite (telescopic surveying instrument). The station is

FIGURE 52.—A scientist aims a laser beam at one of several reflecting targets on steaming Mount St. Helens to measure precisely any change in distance that might indicate swelling of the mountain or provide other clues to the likelihood of an eruption (see fig. 3). This instrument site is about 5 miles north of the crater floor on a ridge informally called "Harry's Ridge" because it overlooks the former location of Mount St. Helens Lodge (out of view to the left), where proprietor Harry Truman presumably died during the May 18 eruption. (USGS photograph.)

informally known as "Harry's Ridge" because it overlooks the now-buried site of Mount St. Helens Lodge, where proprietor Harry Truman presumably was killed during the May 18 eruption. Use at this station of other instruments, including a remote-controlled television camera, is planned.

Friday, June 20
E Day Plus 33

No sizable steam or ash plumes were seen today. No seismic events were recorded, other than those that could be attributed to avalanches down the inner slopes of the crater. Cloudy weather prevented measurements of the dome. Last night, however, observers again saw the glowing red cracks in the lava dome, as they have for the past few nights.

Clement Shearer, USGS hazards geologist, said that there is no way to know whether the dome will eventually build up to become the mountain's new top, as at least one volcanic dome became in the past (table 2), or whether this dome will be blasted out in a new series of eruptions.

University of Washington geologist Anthony Irving believes that the growth of the dome is "probably the best thing that could happen" because, as long as the lava oozes out, the pressure in the magma chamber beneath Mount St. Helens is unlikely to build up to an explosive eruption. If the growth stops "for a period of weeks," he says, the danger of an explosion will increase.

The Washington Department of Emergency Services announced that it has decided not to decrease the size of the Red Zone (fig. 13), as had been requested last Wednesday.

Several streams that formerly flowed into the upper (eastern) part of the North Fork Toutle River were blocked near their mouths when the May 18 avalanche sent debris into that part of the river valley. These tributary streams include Coldwater, South Coldwater, and Castle Creeks (fig. 7), Studebaker Creek (fig. 5), and a few smaller streams. Ponds have formed behind dams of avalanche debris, and water levels generally have been rising since May 18 as the streams continue to flow into these ponds (fig. 45). Some of the ponds, which already contain large volumes of water, might continue to grow until they overtop or break through the debris dams. The consequent outflows could increase in volume as they incorporate the easily erodible debris, and a major mudflow coursing down the channel of the North Fork Toutle River and further damaging downstream areas might result. Geologists are assessing the stability of the debris dams, while hydrologists are calculating how much water is in the ponds and watching the rates of water-level rise to determine whether and when steps should be taken to drain the ponds artificially.

Saturday, June 21
E Day Plus 34

The volcano is very quiet. When the dome was measured last on Thursday, it was growing at a rate of about 6 to 10 feet a day, and so the crater area still must be considered unstable and dangerous. Clouds and plumes of steam that rose to an altitude of about 11,000 feet obscured the view into the crater. Seismometers on the mountain's flanks were jiggled today but only by avalanches of rock crashing down the inner walls of the crater.

About 180 National Guardsmen used shovels and powered street-cleaning equipment today in Portland to assist in cleaning up ash from the June 12 eruption. About 235 of an estimated 350 miles of main streets already had been cleaned before the Guardsmen started. Air quality generally improved throughout the city. The Oregon Department of Environmental Quality suspended an air-pollution warning for the Portland metropolitan area, but it kept in effect the warning for Tillamook County on the coast.

The mayor of Ritzville, a farming community of less than 2,000 people that received more than 3 inches of ash on May 18, said that conditions are far from normal now, more than a month after the ashfall. The ash is still very troublesome, despite valiant cleanup efforts by local residents and National Guard troops. The town is surrounded by flat to gently rolling farmland, and, when the frequent winds blow, the ash cannot be prevented from "redistributing itself." The mayor added that, although about 65 percent of the ash in town has been cleaned up, it is the other 35 percent that is causing much of the problem.

Sunday, June 22
E Day Plus 35

Mount St. Helens has spent a quiet weekend. No earthquake or harmonic tremor was recorded, but there were minor seismic jiggles, probably caused by avalanches. Persistent clouds of steam and fumes continue to rise above the crater to altitudes as high as 14,000 feet. Although the dome could be glimpsed within the crater, visibility was too poor to permit measurements of its growth.

The scientific team continues to work hard to learn as much as possible about Mount St. Helens and, consequently, about this type of volcano in general. The main thrust of the work so far has been hazard evaluation; in this effort, many team members have been voluntarily working 16 to 18 hours a day. Geologist Rowley says that they really believe that they will learn enough from Mount St. Helens to help save many lives during future eruptions of other volcanoes. The USGS crew at Vancouver numbers about 20 to 25 at any given time, but many more can be recruited, if needed, from other USGS installations. At the pace now being maintained, "people get 'burned out,' " Rowley said, "and we bring others in."

The official casualty count—24 dead and 44 missing—presumably will

change tomorrow. A geologist riding in a Forest Service helicopter today spotted another body, which will be recovered tomorrow, if possible.

Monday, June 23
E Day Plus 36

This morning, a steam plume rose briefly—first to about 13,500 feet and then to only 11,000 feet—before dissipating. Otherwise, neither eruptive nor seismic activity was recorded on the mountain. Most of the day, the mountain again was shrouded in clouds, and scientists could not see into the crater to observe the dome.

USGS scientist Joseph Rosenbaum has reported on some of the details of the lateral blast—the great north-directed "wind" caused by the sudden release of gases that had been held within the magma. Blast damage was caused, he believes, not by a shock wave or by an ultrahigh-speed wind but by a hurricane-speed wind heavily laden with debris. Such a particle-laden wind that could "sandblast" everything in its path would explain the pattern of destruction, according to Rosenbaum. Trees, stumps, and even soil were removed from exposed ridges nearest the mountain; only bare rock was left. Farther from the volcano, trees were snapped off at the ground, and bark was cleanly removed from trunks. A normal wind would have had to reach speeds of 150 to 200 miles an hour to destroy the trees in that manner. If the density of the "wind cloud" were increased by suspended rock particles, however, a wind moving at lesser speeds could achieve the same results. Investigations in the devastated area give ample proof that the blast wind was carrying pulverized rock (stones up to 4 inches across carried at least 8 feet off the ground) as well as other debris picked up in its outward rush.

The Forest Service is asking Congress for additional funds to pay for monitoring smoldering timber debris under the ash and blast deposits on and near Mount St. Helens. Several hundred fires caused by lightning and hot ejecta from the May 18 eruption still burn beneath the ash. The ash is acting as a fire retardant, but Forest Service officials expect that, when it dries and the wind blows it away, flames and sparks could spread fires to neighboring timber stands.

Governor Ray announced today that tourism in Washington so far this year is only about half the amount expected, largely because of adverse publicity about ash dangers.

Financial institutions across the country apparently are wary of investing in some Pacific Northwest bond issues because of disruptive effects and economic risks attributed to the ashfall from Mount St. Helens. A San Francisco bank official estimates that this perceived increase in financial risk could drive up interest rates for borrowers such as school districts and city or county governments in affected areas.

The body sighted yesterday was recovered by a helicopter team today and identified by Lewis County officials. The official number of dead is now 25; 43 are still missing.

Tuesday, June 24
E Day Plus 37

The crater remained obscured by clouds all day, and light snow began falling on the mountain tonight. The volcano emitted only occasional bursts of steam that rose above the clouds. Tonight, two episodes of harmonic tremor were recorded—the first since June 15. The tremor was very weak, and it was detected only by the seismometer nearest the mountain.

USGS glaciologist Melinda Brugman reports that about 70 percent, or 170 million cubic yards, of Mount St. Helens' glacial ice mass was lost during the May 18 eruption. All of Leschi and Loowit Glaciers, most of Wishbone Glacier, and the upper parts of Forsyth, Nelson, Ape, and Shoestring Glaciers (fig. 5) disintegrated on May 18. Toutle and Talus Glaciers now appear to be significantly thinner than they were before; large amounts of snow were removed from the surfaces of these two glaciers and Shoestring Glacier by both the heat of tephra and scouring. Only Swift and Dryer Glaciers appear largely unchanged. Surprisingly, the melting rate of the surviving glaciers at their surfaces of contact with the mountain's rock flanks does not seem to have increased. Increased melting probably would cause accelerated downslope ice movement and (or) increased flows in streams still draining Mount St. Helens' glaciers, but neither effect has been seen so far.

A controversy has developed between people who think that the timber downed by the May 18 blast should be left as a testament to the awesome force of the volcano and those who believe that the timber should be salvaged. Foresters point out that downed ash-coated timber is likely to be a threat to nearby healthy forests because it increases the risk of fire, tree disease, and insect infestation. Private timber companies plan to begin removing all salvageable trees from their lands soon. Forest Service official Norman Anderson said that it probably will take several months to work out plans for salvaging downed timber on national forest lands without jeopardizing adequate scientific study of the eruption aftermath. Some areas of blown-down forest probably will be left for public exhibit.

Wednesday, June 25
E Day Plus 38

The volcano continued to expel plumes of steam, which occasionally contained light ash, several thousand feet above the crater rim. The ash barely tinged the white of last night's snow on the upper part of the mountain.

Seismic activity increased again today; two small earthquakes (magnitudes 2 and 2.5) occurred, as did more harmonic tremor. The University of Washington seismology center reports that this morning's earthquakes were centered about 7 miles southeast of

Mount St. Helens. The quakes were not of volcanic origin but were perhaps the result of a crustal adjustment to recent volcanic and seismic activity at Mount St. Helens. Soon after the earthquakes were recorded, "sustained harmonic tremor" began.

Scientists cannot tell how the latest harmonic tremor may relate to conditions in the volcano's crater because poor weather and dense clouds of steam and fumes have prevented observations of the crater floor and dome for the past several days.

Thursday, June 26
E Day Plus 39

Harmonic tremor occurred early this morning (3:30 a.m.) but ended about 9:00 a.m. No earthquakes were recorded, and no unusual eruption plumes were seen.

Airborne observers got a brief look at the dome inside the crater, but they were unable to see well enough to judge whether the dome has grown during the past week.

Forest Service biologist William Ruediger reports finding some encouraging signs of wildlife in the generally bleak areas covered by Mount St. Helens ash. Eggshells from hatched eggs have been discovered, an indication that some birds stayed with their eggs during the ashfall. Native rainbow trout also have been found "surviving remarkably well." Conversely, cutthroat trout appear thin, sick, and less likely to survive.

In Japan, according to the Associated Press, geophysicist Motokazu Hirono reportedly has measured microscopic particles, which he ascribes to ash from the May 18 eruption of Mount St. Helens, at an altitude of about 11 miles in concentrations that might block sunlight and lower the Earth's temperature. Hirono cites the example of the stratospheric ash band from the 1883 eruption of Mount Krakatoa in Indonesia (see fig. 62), which caused record low temperatures and severe crop damage in Japan and elsewhere the following year. Scientists from the National Weather Service and the University of Washington, however, dispute Hirono's evidence for that much Mount St. Helens ash in the stratosphere and, especially, his comparison to the Indonesian eruption. Krakatoa blew a volume of ash into the stratosphere much larger than the entire mass of material blown out of Mount St. Helens so far this year. "Comparing Krakatoa to [Mount] St. Helens is like an elephant versus a gnat," says one scientist.

Friday, June 27
E Day Plus 40

The 100th day of activity at Mount St. Helens showed evidence that magma is still moving beneath the volcano. Harmonic tremor, which preceded the last two major eruptions, was recorded again today. Seismologists at the University of Washington said that, although today's harmonic tremor was the strongest since June 12, it had only about one-fourth the amplitude of the tremor preceding the June 12 eruption. Seismologists also reported a small (magnitude 2–2.5) earthquake that seemed to be centered about 7 miles north of the volcano.

The volcano continued to vent steam to an altitude of 11,000 feet today, but airborne observers were able to see into the yawning crater and reported that the dome of solidified lava looks no larger than it did when it was seen last. It was previously measured from photographs as about 1,200 feet across and 200 feet high.

USGS geologist Tim Hait said that, if the dome has really stopped growing, gases may be building up in the volcano. He repeated earlier warnings that the volcano could still explode without warning into further large eruptions of ash, along with pyroclastic flows of superheated gas and shattered rock. "It still is a mighty dangerous area," Hait said.

Water from the pond on Castle Creek (fig. 45), which was dammed by avalanche debris, has emerged from the debris deposits about 1 mile downstream from the pond after apparently seeping out along its buried channel deposits. The outflow is eroding a new creek channel through the valley-fill deposits. The debris dam, which contains timber debris as well as rock material, probably will not be undermined by outflow at the rate seen today. The water now is flowing into the next pond downstream, however, and may increase the danger of an outburst from that smaller pond.

The Corps of Engineers is moving a large dredge farther upstream (to river mile 6.3) in the Cowlitz River, which is still clogged by millions of cubic yards of volcanic flood debris. The dredge is intended to help clear a channel 25 miles long in the lower Cowlitz for flood passage and navigation. The dredge was moved from the mouth of the Cowlitz River, where it had been at work since June 10.

FIGURE 53.—Views of Mount St. Helens and Spirit Lake from the north-northeast before (top) and after (bottom) the eruptions of May and June 1980. The dashed outline in the bottom view shows how much of the original volcano cone was lost during the early part of the May 18 eruption. Spirit Lake (bottom view) now is more extensive and shallower, and its shoreline is about 200 feet higher than it was formerly. The lake now is choked with thousands of logs blown into it by the initial blast. (Paintings by Dee Molenaar, USGS.)

AT THE END OF THE FIRST 100 DAYS

Summary of Conditions

At the end of its first 100 days of 1980 activity, which began with the sudden earthquakes of March 20, Mount St. Helens is quiet, but it cannot be considered stable or safe.

Mount St. Helens has been called "a volcano in a hurry." In 11 weeks (March 27–June 13), the volcano has had three major eruptions of ash and pumice and related pyroclastic flows, as well as countless smaller eruptions involving only ash, steam, and other fumes. It has lost an estimated 3.4 billion cubic yards (0.63 cubic mile) of its cone (fig. 53) and has pulverized about 400 million cubic yards (0.07 cubic mile) of new magma; it has scattered volcanic ash and pumice over much of the Northwest and has begun to build a new dome inside its new crater. Volcanologists say that many volcanoes of this type require months or even years to complete these steps.

FIGURE 54.—Aerial view of Mount St. Helens from the southeast showing extensive mudflows on the eastern flanks. The larger mudflows originated from or near Shoestring Glacier, which now heads at the deeper notch in the crater rim. Many smaller mudflows cover the upper slopes on all sides of the mountain, but the dark areas seen here on the upper slopes are mostly ash that had been wetted by underlying snow or ice. The major streams shown here are the Muddy River, which leaves the photograph at the lower right, and Pine Creek, which leaves at bottom center. The pattern on the land to the left of Pine Creek is the result of logging before the eruptions. The haze in the picture is mainly from windborne volcanic ash, which is present near the volcano most of the time. (Photograph by Ralph Keuler, USGS, July 1, 1980.)

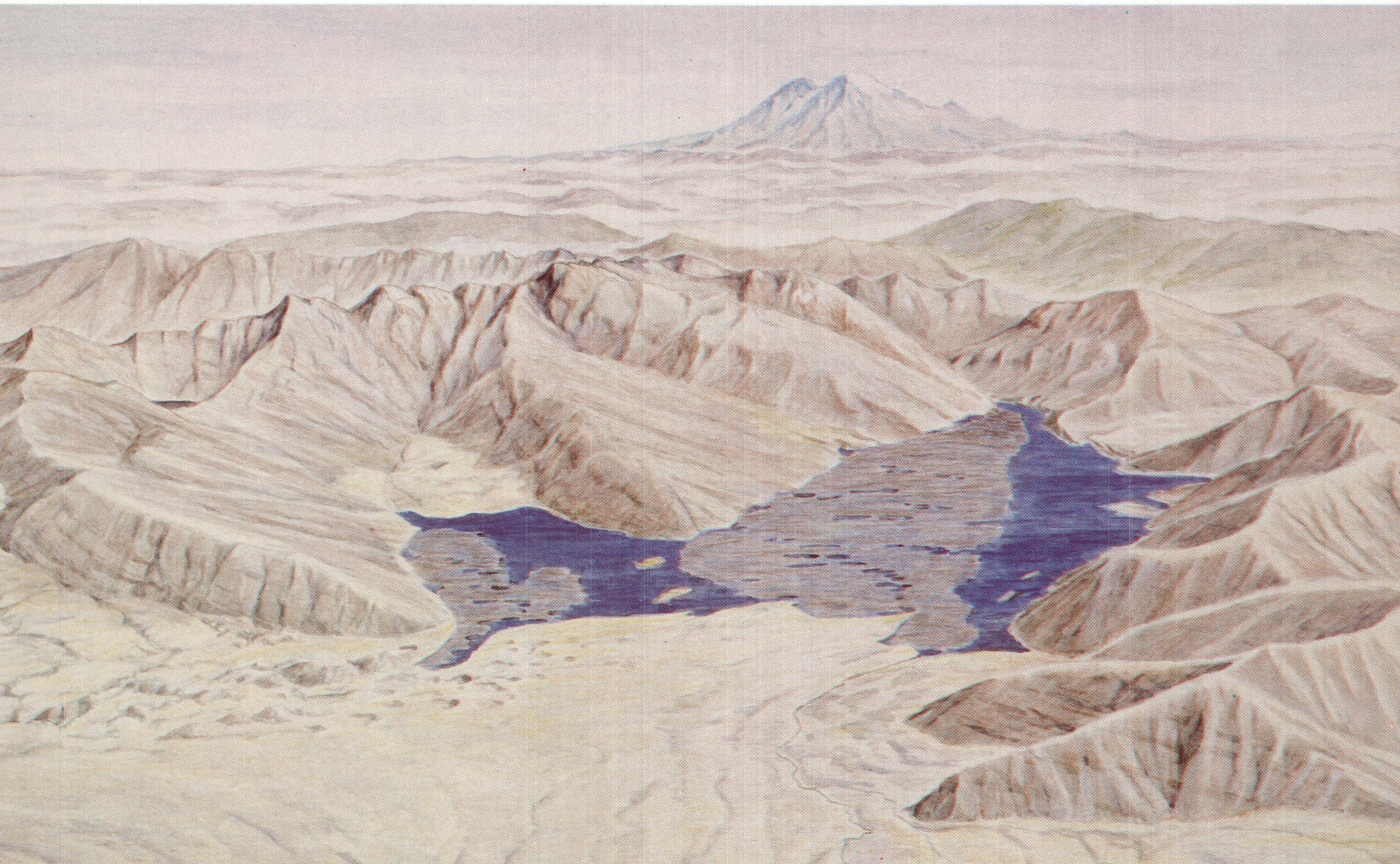
Above the timberline (on the sides of the volcano where timber still survives), the stubbed-off cone is ash gray streaked with brown from countless mudflows (fig. 54). Snow and ice remain on the upper slopes beneath the insulating blanket of ash but can be seen from the air only where the melt water has darkened the overlying ash or where steep ice faces have shed the ash. Many mudflows reach downslope into dusty timber, and the larger flows extend down the courses of preeruption streams. Tongues of mudflow deposits have killed some of the standing conifer trees and turned them brown.

Observations of the volcano, as well as general visibility in the area are often hampered by cloudy weather, by haze caused by blowing ash, and by smoke from hundreds of fires. These fires, which originally were started by lightning and hot pyroclastic material during the May 18 eruption, still smolder beneath the volcanic deposits. The fumaroles in the vicinity of Spirit Lake and the upper valley of the North Fork Toutle River that formerly were so effuse have dwindled greatly in their output.

The cratered cone yawns open to the north. The rampart on the northern side of the inner crater at its lowest point is now at an altitude of about 6,150, about 2,200 feet lower than the highest part (8,364 feet) of the sharp, jagged crater rim on the southwestern side. A broad ramp of avalanche debris and older rocks, somewhat smoothed by a mantle of pyroclastic deposits, descends northward from the rampart into the valley of the North Fork Toutle River and to the southern shore of the raised Spirit Lake (fig. 55). Avalanches frequently bring showers of rock and some blocks of glacier ice left at the crater rim down the inside crater walls. The horseshoe-shaped crater, which stretches about 7,000 feet (1.33 miles) from rim to rim in an east-west line, tapers to about half that width at its irregular inner floor, which, in places, is lower than the northside rampart by about 100 feet. North of the center of the inner crater floor is the roughly circular dome of gray, broken lava rock, surrounded by a "moat." Steam rises from the margin of the dome, but most of the steam now emanating from the volcano comes from a concentration of vents along the southern, or closed, part of the crater floor and the lower crater walls. During most of the period from June 15 to June 27, there was no running or standing water on the crater walls and floor; by June 28, however, a small pond had formed in the southwestern part of the crater floor.

The profile of the lava dome remains much as it was when it was first seen on June 19. The dome grew rapidly the first few days after its appearance, but its growth now seems to have slowed or stopped. No one knows what the final size of the dome will be (it is now roughly 24 acres in area) or what the volcano will do next. (This dome was almost completely blown away by an explosive eruption on July 22, 1980, which is shown in progress in figure 61*B*. Thereafter, dome building resumed.) USGS and State of Washington mapmakers are hoping that there will be no major changes in the

FIGURE 55.—Views from Mount St. Helens northeastward across Spirit Lake toward Mount Rainier before (top) and after (bottom) the eruptions of May and June 1980. Decades may pass before the barren ridges and log-choked Spirit Lake return to something like their former beauty. However, the coating of ash on Mount Rainier (bottom, background) was soon hidden beneath fresh snow. (Paintings by Dee Molenaar, USGS.)



landscape for a while, since they are busy preparing maps of the "new" Mount St. Helens and vicinity.

Sulfur dioxide emissions from the volcano were about the same at the end of June as they had been since mid-month—that is, about 1,200 tons a day. The presence of this gas proves that the volcanic fumes are coming from an underground source that remains very hot, and the rapid rate of emission makes Mount St. Helens the greatest point source of SO_2 air pollution in the Pacific Northwest.

The size of the area devastated by the May 18 lateral blast and the scale of the changes wrought by the eruption are often difficult to comprehend, especially from the air (fig. 56). Only when the view includes a familiar object such as a low-flying aircraft or when the observer is reminded that the tumbled mass of "matchsticks" may consist of trees 80 to 100 feet long does the immensity of the disaster become apparent.

On the ground, there is heartening evidence of the resurgence of vegetation and wildlife. A few green plants are emerging from the ash and blast deposits (fig. 57), and deer and other animals have been seen in the blast area. The restorative part of the cycle, repeated many times before at this volcano and others in the Cascade Range, has begun once more.

The Red Zone is still closed. Its boundary, established on June 2, remains at a distance of about 17 to 27 miles from the mountain (fig. 13). The Blue Zone boundary extends beyond that of the Red Zone to the east, south, and north. Individual entry into the Red Zone is by permit only; the only human activities legally allowed are logging, scientific studies, law enforcement, firefighting, and searching for those still missing and presumed dead. State officials are receiving requests to decrease the size of the restricted zone, despite the facts that the three major eruptions have spewed out hot pyroclastic flows and that no one can be sure if there are more eruptions to come.

Salvage of about a billion board-feet of blasted-down timber has begun slowly. Work is greatly hampered by a lack of access roads and even pathways between the large, tumbled trees and by the blinding, choking ash that rises in clouds at each disturbance. The ash affects machinery, as expected, by increasing wear and necessitating frequent maintenance. To humans working in ash areas, however, the ash is

FIGURE 56.—Aerial view of Mount St. Helens across the devastated area from about 13 miles to the north-northwest. The viewpoint is well within the area of blown-down trees. Elk Lake (lower center) and the quarter-mile-long Hanaford Lake (center) are among about 30 small lakes and ponds, formerly jewellike in forested settings, that were turned brown and desolate by blast and ashfall in a few minutes. Coldwater II observation station, where David Johnston was on duty at the time of the May 18 blast, is at right center. (Photograph by Austin Post, USGS, June 30, 1980.)

FIGURE 57.—Life returns to the vicinity of Mount St. Helens. *A*, Ferns and other small plants pushed up through a blanket of ash 4 inches thick on the southern flank, 3 weeks after the May 18 eruption. (Photograph by J. R. Stroh, U.S. Soil Conservation Service.) *B*, Avalanche lilies (*Erythronium montanum*) growing through blast deposits from the May 18 eruption, about 10 miles northwest of the volcano. (Photograph by Joseph G. Rosenbaum, USGS, June 8, 1980.)

proving to be even more troublesome. Some dust masks and respirators that are effective in filtering out the ash are unpleasant to wear and make strenuous labor difficult. Other masks leak, and some respirator filters are difficult to keep clean.

In the eastern part of the North Fork Toutle River valley, the debris avalanche has left a hummocky deposit (estimated volume, two-thirds of a cubic mile) that extends about 14 miles westward down the valley from the avalanche source on the flank of the volcano (fig. 47). The former valley floor is buried under more than 600 feet of avalanche debris directly north of the crater, but the debris deposit thins gradually in the downvalley direction. Farther west in the valley of the North Fork and also in the valley of the South Fork Toutle River, the former valley floors were buried by extensive but thinner mudflow deposits (fig. 31).

The valley of the main Toutle River, which is a scene of mud-plastered tree trunks, shattered buildings, missing bridges, and barren mudflow deposits, is slowly beginning to recover (fig. 58). The rebuilding of damaged or destroyed homes (fig. 32) has been slowed by the destruction of many access roads and driveways, by the widespread loss of income among loggers, farmers, and merchants, and by the threat of future floods.

Even the valleys of the North and South Forks of the Toutle River are coming back to life. At logging camps in both valleys, the chaos caused by the May 18 floods is beginning to be overcome. The tangled masses of logs and machinery are gone, and the logs have been restacked in neat storage piles. Logging trucks are moving along some roads again, trailing clouds of ash behind them.

FIGURE 58.—Effects of the Mount St. Helens eruptions in the upper valley of the South Fork Toutle River. *A*, Aerial photograph of mudflow deposits on the valley floor, looking east toward steaming Mount St. Helens and Mount Adams, in the distance. (Photograph by Austin Post, USGS, June 30, 1980.) *B*, A tongue of the hot lateral blast, which generally went to the north and east of this area, jumped across the ridge from the valley of the North Fork Toutle River and left an area of blown-down and scorched trees in the valley of the South Fork. The view here is to the northeast, at the point marked by the arrow in *A*. (Photograph by Edwin McGavock, USGS, May 20, 1980.)

The channels of Pine Creek, Muddy River, the Toutle River system, and the lower Cowlitz River are still largely choked with sediment and debris. Near the volcano, the streams are eroding new courses through the avalanche and mudflow deposits (fig. 59). Farther downstream, most original stream channels have been reoccupied by postflood streams, but they are obviously very shallow. Where former streams were deep and clear, many bars and shallows show through the muddy brown water. These channels probably will not enlarge much naturally before the period of increased runoff begins next autumn during the wet season.

Travelers along Interstate Highway 5 can easily see the effects of flooding at the bridge across the Toutle River and southward beyond Castle Rock. Most trees standing near the highway seem to have survived the flooding. Some leafy trees, however, are changing to their dormant coloring, giving the impression of an early autumn.

Farther downstream on the Cowlitz River, the Corps of Engineers is operating dredges to restore as much of the channel capacity as possible before the next wet-season floods begin (fig. 60). Off the mouth of the Cowlitz, dredging has restored the depth, if not the full width, of the Columbia River ship channel. As the dredges operate, areas of brown dredge spoil grow daily along the Cowlitz riverbanks and on the Columbia channel islands.

In the "ash belt" of eastern Washington, light-gray volcanic ash still borders the highways and blankets many uncultivated areas. Where the

ashfall was thick, workers in the fields (fig. 49) face the same kinds of problems with breathing protection and machinery wear and maintenance as the loggers near Mount St. Helens. The ash rises into the air at the slightest disturbance, unless it is wet. Fortunately, rainfall in the main ashfall areas during June 1980 was unusually frequent and abundant (20 to 25 percent greater than normal) and greatly alleviated the dust problem in the region. Ash is still being removed from highways in eastern Washington, and motorists may experience some delay during the upcoming Independence Day holiday.

Some insect populations in eastern Washington have been badly depleted by the ash, and other competing species have flourished as a result Many crops have suffered at least some damage, even if it is only stunted growth because the ash on leaves retarded photosynthesis this spring. Crops that still bear the persistent coating of fine ash bring lower prices on commodity markets.

In southwestern Washington and northwestern Oregon, evidence of the ash also persists, even in the cities of Portland and Vancouver, which received relatively light ashfalls and where cleanup efforts were extensive. However, by this time, little ash remains in the air, and deposits on buildings and streets are becoming less apparent.

Spokesmen for the tourist industry in Oregon and Washington are warning of dire impacts on that industry, which ranks third largest in both States. Ripple effects could be felt throughout local commercial structures unless the Northwest can manage to shed the "image of a hazardous volcanic disaster" and turn Mount St. Helens from a liability into a tourist attraction.

Economic losses in the State of Washington have been estimated officially at $860 million, down substantially from earlier estimates. The largest loss, reported to be $450 million, was standing timber in areas affected by the lateral blast and mudflows. Losses in agricultural output, which apparently are less than officials had expected, may range from $40 to $100 million. Except for losses in areas near the volcano, most economic damages were caused by ashfall. Notable exceptions are the flood damage along the Toutle and lower Cowlitz Rivers, the costs of dredging and levee building, and economic losses related to interrupted shipping

FIGURE 59.—Debris from the May 18 eruption in the valley of the North Fork Toutle River. *A*, View eastward up the debris-choked valley toward steaming Mount St. Helens (the edge of the crater mouth is barely visible). This area is near the southern fringe of the blast zone. (Photograph by Austin Post, USGS, June 30, 1980.) *B*, Stream eroding a new channel in avalanche and mudflow deposits in the valley of the North Fork Toutle River. This kind of erosion will go on for years, or even decades, until the stream network reestablishes itself into a new, stable system. (Photograph by Edwin McGavock, USGS, June 23, 1980.)

FIGURE 60.—One of several dredges that were clearing mudflow debris from the dangerously filled channel of the Cowlitz River during the summer of 1980. The floating pipeline carries dredge spoil (mud) to the dumping ground on the river flood plain. (Photograph copyright 1980 by Bud Kimball.)

on the Columbia River. The economic impacts on communities in the "ash belt" varied greatly, but, as a general rule, the greater the ashfall thickness, the greater the economic loss.

Oregon also has suffered economic losses, mostly because of ash effects and cleanup costs. A notable agricultural loss in northwestern Oregon (and also in southwestern Washington) occurred after the ashfall of June 12 and 13. Much of the strawberry crop rotted in the fields when ash-laden leaves pressed the fruit against the soil. Other losses to berry crops occurred because ash could not be washed from the fruit.

Most economic loss in the Portland-Vancouver metropolitan area has been related to ash cleanup, but a major loss also has resulted from the disruption of shipping on the lower Columbia River. For example, the Port of Portland reportedly expects to lose at least $5 million in revenues through the month of August 1980 because of closure of the Columbia River shipping channel. In addition, workers dependent on port business reportedly are losing about $4 million a month, and shipping firms also are suffering loss of business.

The number of victims stands at 25 dead and 37 missing and presumed dead as of late June. Searches for the missing now are being made only when there is evidence that can be used to pinpoint areas of search. Search dogs are often brought in by helicopter to help find human remains. Still, no trace of USGS volcanologist Johnston has been found.

How many lives were saved because essential information about the volcanic hazards was available and was used to reduce public risks? There will, of course, never be a precise answer, but estimates can be made. Forest Service records indicate that, during a nice spring weekend, as many as 2,000 visitors normally would have been in the Spirit Lake area. The added attraction of an active volcano might have brought as many as several thousand people into the area of destruction, had it not been for the designation and closure of the hazard zone.

Continuing Hazards

Potential hazards related to the Mount St. Helens eruptions have continued beyond the first 100 days. Information about these hazards comes from several sources. The discussion of hazards from ashfall, lateral blasts, pyroclastic flows, lava flows, and mudflows is taken mostly from an information bulletin (Federal Emergency Management Agency, 1980) prepared by Crandell. (Although he compiled that information before the June lava dome was seen, he anticipated its appearance.) Information on flood hazards is modified from a description prepared by USGS hydrologists to accompany a May 29 Hazards Watch update. Information on fire hazards comes from a variety of sources, including discussions with Forest Service officials. The following perceptions of hazards, as well as the hazardous conditions themselves, undoubtedly will change in the future.

ASHFALL

Because Mount St. Helens is still in an explosive eruptive phase, eruptions similar to those of May 25 and June 12 should be expected. Either a coarser grained pumice and ash eventually will erupt from the volcano, or else magma will form a dome within the present crater. The formation of a dome also could be accompanied by an eruption of ash, probably smaller than the eruptions of May 18 and 25. As of June 1980, it was not known whether such changes would take days or weeks.

If the maximum expectable eruption of pumice and ash were to occur, appreciable amounts could fall in any direction from the volcano but would be more likely in southeasterly, easterly, and northeasterly directions because of the most probable wind patterns. As the May 25 and June 12 ashfall patterns show, however, areas in other directions cannot be considered immune. The actual areas covered by future ashfalls would depend on the directions and strengths of winds at the altitudes reached by an ash column at the time of an eruption. The effects of the May 18 ashfall, bad as they were, would have been incalculably worse if the winds had carried the ash northward over the major cities of northwestern Washington.

Autopsies on people killed by the May 18 eruption indicate that the inhalation of hot ash was a major cause of death. Thus, hot ash clouds from the volcano, even from an eruption otherwise considered to be "light" or "moderate," can be an extreme hazard to humans and animals nearby.

LATERAL BLASTS

Present conditions at the volcano suggest that another lateral blast similar in force to the one of May 18 is unlikely unless a prolonged period of increasing seismicity and ground deformation occurs. However, the extrusion of a dome within the crater might be accompanied by lateral blasts that could carry rock debris outward at high velocity. The present shape of the crater suggests that lateral blasts from a growing dome most likely would be directed northward; blasts in other directions would tend to be deflected upward by the crater walls. If a dome were to grow to a height above the crater rim, however, lateral blasts also could affect the western, southern, or eastern sides of the volcano.

Magma could move into subsurface parts of the volcano at some point east, south, or west of the existing crater. Such movement probably would cause inflation that could be detected by surveys and perhaps also by visual observation, as the north-flank bulge of March 27 to May 18 was. Surveying and tiltmeter observations have been resumed, but, at the end of June 1980, no such bulge or other sign of instability had been detected on the other flanks.

LAVA FLOWS

Explosive eruptions of dacite, like those of May 18 and 25 and June 12, typically are not accompanied by lava flows. Molten dacite is relatively viscous and would tend to pile up around a vent and form a dome rather than a lava flow. The past history of the volcano suggests that, as this eruption progresses, magma of a more fluid type could be extruded and might form lava flows. Flows, however, are not anticipated in the near future.

PYROCLASTIC FLOWS

Pyroclastic flows can form during an eruption of pumice and ash. The largest and longest pyroclastic flows, which could be expected during an eruption of coarse pumice, would occur as a large eruption column was rising above the volcano. Pyroclastic flows of this kind most probably would follow the valleys of the North Fork Toutle River, Muddy River, and Pine Creek because the present northward opening of the crater rim and the notch in the southeastern wall of the crater would direct them toward these valleys. They are less likely, although possible, on all other sides of the volcano.

Pyroclastic flows probably would occur also during the eruption of a large dome. Such flows could be formed as the steep and unstable flanks of the dome crumbled and avalanched or as they were disrupted by earthquakes and volcanic explosions. Pyroclastic flows of this type probably would not extend into the North Fork Toutle River valley more than 10 miles from the dome, and they would not occur at all in the other valleys as long as the crater rim retained its present shape.

MUDFLOWS

The debris-avalanche deposit that now forms the floor of the upper North Fork Toutle River valley appears to be stable in the opinion of soil-mechanics experts who have examined it. The possibilities of piping (erosion along subsurface water conduits) or of sudden liquefaction of the deposit during a strong earthquake appear to be negligible in view of the fairly gradual general slope of the deposit and its poorly sorted texture. Mudflows may occur as streams cut down through the debris-flow deposit, but they probably would be small in volume in the immediate future and would not reach the heights or distances of the May 18 and 19 mudflows. Probably the greatest potential for major mudflows lies in the possibility that water in ponds behind the debris dams blocking tributary streams along the valley of the North Fork Toutle River could break out. A sudden outburst of this impounded water, especially from the largest pond at the mouth of Coldwater Creek (fig. 45), could rush down the valley of the North Fork, increasing in volume as it mixes with the easily erodible mudflow deposits, and might become large enough to inflict damage in the main Toutle River valley. The effects of such an outburst, if it were to occur, would be intensified by the diminished capacities of the stream channels. The principal danger zone of such mudflows would be in the North Fork Toutle River valley. Ample warning of any such outburst mudflow probably can be assured by continuous monitoring of water levels in the ponds.

Mudflows could also be caused by pyroclastic flows occurring during heavy rainfall or moving across snow-covered flanks of the volcano. Although this type of mudflow could occur in any valley that heads at the volcano, it would be most likely in the valleys of the North and South Forks of the Toutle River, Pine Creek, and Muddy River, which are the most probable routes for pyroclastic flows. Mudflow hazard zones should be regarded as extending up to and onto the flanks of the volcano.

In the long run, increased discharge into Spirit Lake by streams in its drainage basin could occur during periods of heavy precipitation and (or) rapid snowmelt. Although the lake currently has no surface outlet, water from the lake is seeping into and through the debris flow. During times of rapid inflow into the lake, water could enter the lake faster than seepage through the debris flow could carry it away. In such a situation, the lake water might rise to the top of the valley fill west of the lake, spill over, and begin to erode a new outlet channel. If the rate of spillover from the lake were adequate and if water were available from other sources, such as ponds behind debris dams at the mouths of tributaries, mudflows could form in the North Fork Toutle River valley. USGS hydrologists are studying this situation.

FLOODS

Sediment and debris in the channels of the Toutle and Cowlitz Rivers have increased greatly the short-term flooding hazard posed by even relatively small storms. Moreover, the threat of flooding in the Toutle River valley and along the Cowlitz River from the mouth of the Toutle downstream to the Columbia River may remain one of the greatest residual hazards associated with the volcanic activity.

The Cowlitz channel was filled as much as 15 feet above its normal depth. The flood-carrying capacity of the channel thus was reduced by about 85 percent, from a former ability to carry 76,000 cubic feet per second to a capacity of about 10,000 cubic feet per second. A flow of 10,000 cubic feet per second is about the average annual discharge of the river, and wet-season freshets often cause flows at several times that rate. Therefore, unless the channel can be restored and maintained at or near its former capacity, more frequent flooding seems inevitable.

Although dredging of the Cowlitz channel undoubtedly will help, at least

during the first major flood, the problem is complicated by the vast amount of easily erodible sediment in the Toutle drainage area. This sediment will move downstream, mostly during periods of high flow, and may occasionally add to the sediment "plug" in the Cowlitz channel.

FIRES

As of June 1980, hundreds of smoldering fires still were burning in the timber beneath the volcanic ash near Mount St. Helens. The danger of these fires breaking out and spreading to standing timber is greatest during the dry season and is a threat to timber on Federal, State, and private lands. Hot spots caused by the buried fires can be located by using infrared sensors carried on aircraft, but reaching and extinguishing the fires pose other problems. Firefighters are hampered by a lack of ready access, by the aggravating ash, and, most of all, by the need for heavy machinery to uncover and unpile the smoldering logs.

All or most of the fires still burning beneath the ash were set by the lightning and hot debris that fell during the May 18 eruption, and more fires could be set by lightning accompanying future eruptions of ash and ash avalanches. Many of the volcano's previous heavy eruptions of ash were accompanied by lightning, so it is reasonable to assume that future eruptions might bring ash-generated lightning into standing forests.

OUTLOOK FOR THE FUTURE

The question of greatest interest concerning the future of Mount St. Helens probably is, "Will Mount St. Helens continue to erupt?"

The answer is, "Yes." The volcano most probably will go through a period of repeated small- to moderate-scale eruptions producing ash, pyroclastic flows, and lava-dome growth. No one can predict how long that period will continue or how many such eruptions will take place. Less likely, but not impossible, is another large eruption among the expected smaller eruptions.

The natural evolution of Mount St. Helens and a few other Cascade Range volcanoes, as geologic evidence accumulated over the last several decades indicates, has included repeated explosive destruction of parts of the volcanic cones followed by generally longer periods of cone rebuilding. Both the destructive and the rebuilding phases have involved eruptions that could (and often did) damage the surrounding countryside. No one can be certain yet that Mount St. Helens is truly in a rebuilding phase; moreover, even if it is, the volcanic activity may take a different course this time. For example, the rebuilding may include long periods of nonexplosive lava eruptions, similar to those at Bezymianny, Siberia, in the U.S.S.R.(Gorshkov, 1959) (fig. 61*A*). Conversely, frequent explosive eruptions that remove accumulated lava might continue for years in the future (fig. 61*B*).

Seismologists at the University of Washington and USGS are cautiously optimistic that a pattern of preeruptive seismic activity at Mount St. Helens may provide advance warning of future eruptions. The key to forecasting volcanic activity may be the pattern of harmonic tremor. Before both the May 25 and the June 12 eruptions, the tremor built up steadily and then stopped for a time just before the explosive eruptions. The pattern must be used cautiously, however, because it was seen on June 2 and 3 as well, and no eruption occurred. If, however, the seismic pattern proves to be a useful predictive tool at Mount St. Helens, it may be useful for other volcanoes, as well. Some scientists believe that using this seismic clue to predict and assess volcanic activity could help save lives.

Other Cascade volcanoes also will erupt in the future, just as surely as they have erupted in the past. There is every reason to believe that the oceanic crustal plates will continue to thrust under the North American plate and generate magma to feed future eruptions (figs. 1 and 2). The rate of underthrusting is relatively slow, however—on the order of 1 inch a year—so, in the long run, Cascade volcanoes may be expected to erupt less frequently than some other groups of volcanoes around the Pacific Ocean's "Ring of Fire." The possibility still exists, however, that any volcano could erupt again at any time. Although scientists are not now capable of predicting which of the other Cascade volcanoes will be the next to erupt, the lessons learned from Mount St. Helens may allow them to forecast more accurately when a volcano is approaching eruption and to better anticipate when that eruption will occur. Volcanoes, however, are notoriously individualistic; therefore, much of what is learned by studying the activity at Mount St. Helens might not be valid if another Cascade volcano came to life.

The May 18 eruption of Mount St. Helens was not a large eruption by world historical standards or even among prior Cascade eruptions, although it was by far the most powerful of the year and, perhaps, of the last decade. Mount St. Helens is only one of perhaps 50 volcanoes worldwide that were active during 1980. As figure 62 shows, the amount of volcanic material thrown out of Mount St. Helens on May 18 (less than one-tenth cubic mile) was only about one-eightieth of the volume ejected during the 1815 eruption of Tambora volcano in Indonesia and less than one-hundreth of the estimated ***ejecta*** from

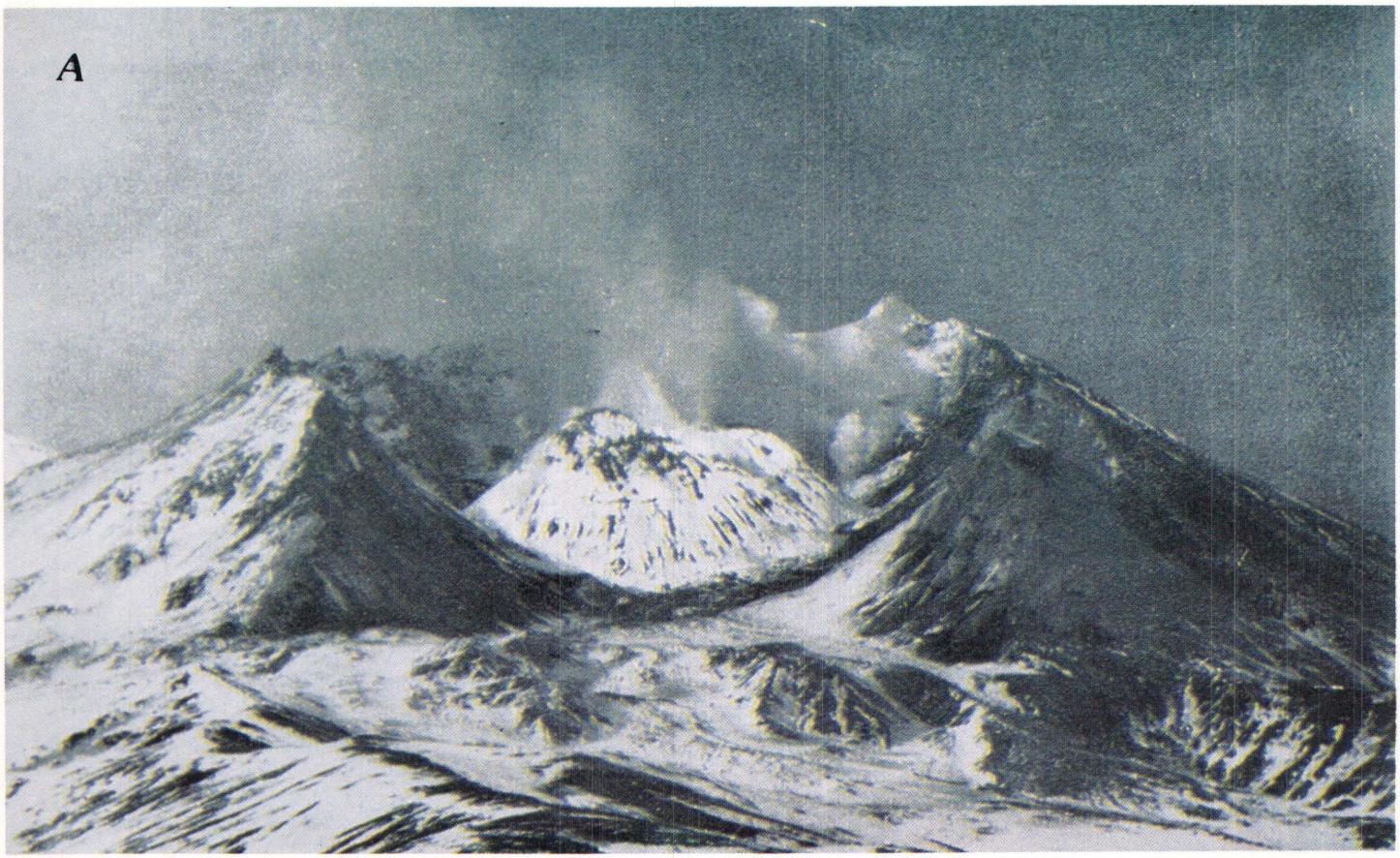


FIGURE 61.—Two possible futures for Mount St. Helens. *A*, The recent history of Bezymianny, Siberia, in the U.S.S.R., suggests one possible behavior pattern for Mount St. Helens in the near future. After exploding violently in March 1956 with a lateral blast that created an amphitheater crater similar to that of Mount St. Helens, Bezymianny has remained active; dome-building lava extrusions have dominated the volcanic activity. However, explosive eruptions also have occurred, the last in 1979. (Photograph by S. Gorshkov, May 1957, from *Bulletin Volcanologique*, 1959.) *B*, Mount St. Helens may continue in the near future having occasional explosive eruptions that remove accumulated lava. An eruption on July 22, 1980, shown here in progress, blew away nearly all of the June dome and thus confirmed the expectation of most volcanologists that explosive activity was not ended by the appearance of that dome. (Photograph copyright 1980 by J. Stewart Lowther, University of Puget Sound.)

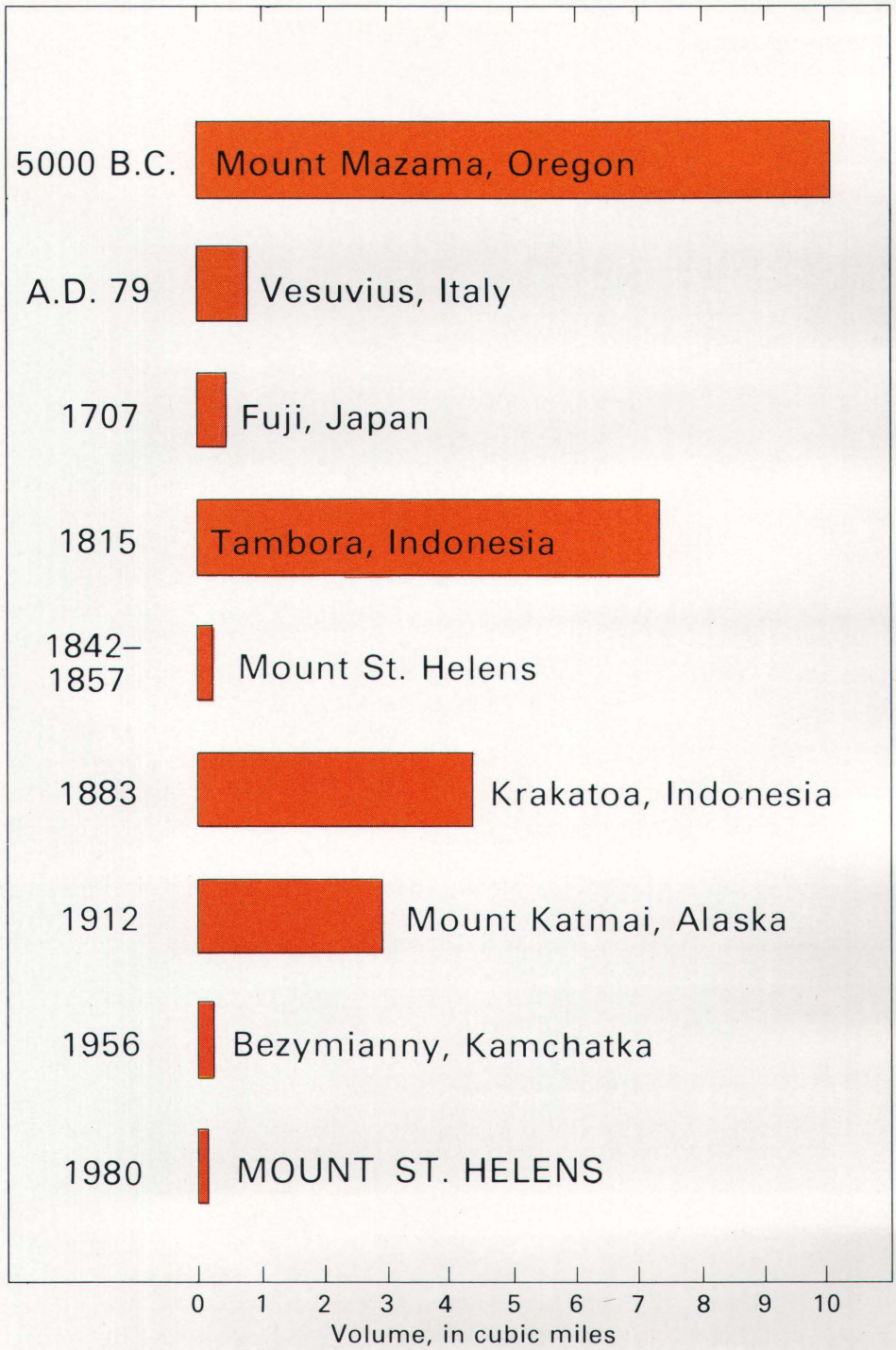


FIGURE 62.—Comparison of the volumes of ejecta thrown out by selected volcanoes during historic eruptions. The volume of ejecta from the May 18 eruption of Mount St. Helens (less than one-tenth of a cubic mile, not including avalanche or mudflow deposits) is relatively small in comparison with amounts from several earlier eruptions, including those from Mount Mazama (Crater Lake) in Oregon. (Data from Hédervári, 1963; Friedman and others, 1981; other USGS sources.)

Mount Mazama during the eruptive period that resulted in Crater Lake. Therefore, future eruptions of large Cascade volcanoes, including Mount St. Helens itself, might be even larger than the May 18 eruption.

So far as volcano experts know, the magma reservoirs deep beneath the Cascade volcanoes are not interconnected—at least not to the degree that an eruption at one volcano increases (or lessens) the chances of eruption at another. Nor are the region's earthquakes typically related to volcanic activity, except for the unusual shallow, frequent quakes ("swarms") of the kind that preceded the March 27 eruption of Mount St. Helens. The normal, deeper earthquakes are related to volcanic activity only indirectly—that is, only in the sense that earthquakes and volcanic activity all result from the same complex system of moving crustal plates (Hamilton, 1977).

Erosion of the volcano's deposits, as well as transport and deposition of the sediment derived from this erosion, will continue at a rate that is historically unprecedented in southwestern Washington. Moderate to intense rainstorms or even rapid melting of snow are now much more likely to cause flash floods and mudflows than they were before May 18, because little vegetation remains in the blast area to retard runoff and erosion and because all the volcano-related deposits are readily erodible. The erosion is most rapid on bare or ash-covered steep slopes, especially where avalanche debris and mudflow deposits have buried former stream channels at considerable depths. These deposits have disrupted greatly the natural stream gradients, which adjust automatically to the combination of sediment load, water available to carry the sediment, and differences in the altitudes of the headwaters of the channel system and of the stream mouth. Stream channels began adjusting (by erosion and sediment deposition) to the new volume of sediment supplied by the volcano during the floods of May 18 and 19 and will continue to do so for the fore-

seeable future—probably for several decades. Erosion occurs most rapidly during periods of high runoff and floodflows, and sediment is deposited largely as floods begin to subside. In western Washington, more than 90 percent of sediment transport by streams takes place during brief periods of high runoff from rainstorms and rapid snowmelt. The sediment loads carried by the Toutle River to the lower Cowlitz River and by the Cowlitz to the Columbia River also are greatest during these high-runoff periods, which usually occur during winter, spring, or late autumn.

Sediment transport from the Toutle River system will be an integral part of the stream-gradient readjustment; it is inevitable and will be largely uncontrollable by human intervention. Flood hazards along the lower Cowlitz River, however, can be reduced by dredging out previous flood deposits to increase channel capacity before the arrival of each succeeding flood and its new load of sediment.

Some areas that probably will be subject to a great deal of erosion or sediment deposition can be identified now; other areas where such changes may occur in the future will be found through studies now being conducted by the USGS and other organizations. After a few annual cycles of high and low streamflow, the patterns and trends of erosion, flooding, and sediment deposition will be more apparent than they are at present.

Revegetation is occurring in the blast-cleared areas, with and without human assistance. Surviving trees and other plants around the devastated area, especially the few small stands of remaining old-growth trees, would seem to be of critical importance in reestablishing the forest ecosystem. New vegetation eventually will slow erosion on the slopes but, in the short run, will have little effect on the readjustment of major stream channels themselves.

At times when the capacity of the lower Cowlitz River channel is substantially smaller than it was before May 18, the susceptibility of the lower Cowlitz to flooding may complicate the management and operation of hydropower reservoirs upstream. The reservoirs upstream from the Toutle River conceivably could be managed so that they provide more flood control than they have in the past. That is, reservoir levels could be controlled so that there would be storage volume available to retain peak flows from the upper Cowlitz basin when floodflows of the Toutle River (or other downstream tributaries) threaten to exceed the limited channel capacity of the lower Cowlitz. Operating those reservoirs to increase their flood-controlling capacity, however, might reduce the amount of electrical power that they can provide.

The low-level flows of streams that drain the flanks of the volcano and that are sustained largely by melt water from glaciers and snowfields on the mountain will be reduced to some extent because much glacial ice was lost on May 18. How the remaining glaciers will adjust and what the effects of this adjustment on the flows of the various streams are likely to be are now being studied by USGS hydrologists and glaciologists. If eruptions were to become less frequent and the volcano were to cool and stabilize in its present form, year-round snowfields or even a glacier might grow inside the largely shaded amphitheater. A crater lake also might form; if it did, it probably would act like a reservoir for a stream (or streams) draining from it, presumably to the North Fork Toutle River.

The main uses of land on and near Mount St. Helens before the 1980 eruptions were generally well suited to an area of long-term volcanic hazards, and these uses probably will be resumed. Forestry, farming, recreation, and hydropower generation seem to have struck a reasonable balance between using the land productively and minimizing human risk. In view of the known volcanic mudflow deposits in the major river valleys (including the site of the town of Castle Rock) and the frequency of historical volcanic activity, human occupancy of the flood plains was probably a less appropriate use. As volcanic activity decreases in the future and as former land uses are resumed, new flood plains (mudflow deposits) can be used more appropriately for nonresidential purposes. These valley-floor areas, along with the areas near and north of the crater mouth, should be considered the most hazardous places, unless changes occur indicating increased volcanic activity or related hazards on other sides of the mountain, as well.

Human reactions to the hazards and to warnings about them are being studied, and the lessons learned from the first 100 days of Mount St. Helens' activity doubtlessly will be applied to future hazard warnings and responses of emergency-services agencies. Visitor information centers such as those already established near Interstate Highway 5 are of great benefit in informing the public about eruptions, about volcanic hazards, and about the natural-hazards warning procedures. An essential prelude to good education already has been achieved; Mount St. Helens' eruptions have increased the American public's awareness of and interest in volcanic activity in the Cascade Range and elsewhere in the world.

State of Washington officials, looking beyond the dampening effect that the eruptions have had on the State's important tourist industry, envision a future that includes a Mount St. Helens National Park (or Monument or Volcano Area); as many as 2 million visitors to the volcano each year; more motels, restaurants, and visitor centers near the mountain; and a resultant $150 million boost to the State economy.

Even President Carter, when he visited the devastated area, predicted that, "People will come from all over the world to observe—when it's safe. It will be a tourist attraction to equal the Grand Canyon."

Public tours of the volcano itself, however, may be a long time off.

Volcanologists warn that relatively small but dangerous eruptions might be expected for an indefinite time. Mount St. Helens' eruptive period during the mid-1800's apparently spanned at least 15 years.

How soon it will be "safe" to approach the volcano on its northern side, no one can answer simply. Part of the answer depends, as Mullineaux recently said, on "how much risk one is willing to assume" (fig. 63). Some difficult decisions will have to be made about when and where to open the restricted areas. For the foreseeable future, a continuing flow of sound scientific information will be needed to guide these decisions and others like them; the USGS intends to provide such geologic and hydrologic information as long as it is needed. If intermittent explosive eruptions and dome building continue as expected, the need for such information may extend for years or even decades.

FIGURE 63.—The June 1980 dome viewed though "the gun barrel," the north-sloping ramp bounded by sidewalls of the Mount St. Helens crater. This informal name, used by scientists and officials, acknowledges the continuing hazards of working in the area north of the crater mouth. This ramp, sculpted by the May 18 lateral blast, was the route taken by several later pyroclastic flows that would have cremated anyone caught in their paths. (Photograph copyright 1980 by Bud Kimball.)

GEOLOGIC HAZARD RESPONSIBILITIES

The broad responsibilities assigned to the USGS by the Organic Act of 1879 include collecting, analyzing, and disseminating information about the Earth, its processes, and its water and mineral resources. As part of its basic historical mission, the USGS has, for many decades, undertaken studies of earthquakes, volcanoes, and other natural hazards. In recent years, as knowledge of these phenomena and related geologic processes has increased, the USGS has developed capabilities for predicting some potentially hazardous events in certain areas. The USGS has an implicit obligation to inform civil authorities and the public of all such predictions.

The USGS mechanism for assuring that the public and its officials get needed information quickly and in a form suitable to their needs is the Hazards Warning and Preparedness Program, developed in 1976 in response to previous Federal legislation. Under the provisions of Public Law 93-288, the "Disaster Relief Act of 1974" (88 Stat. 143), and subsequent delegations of responsibility, the Director of the USGS is required to " . . . provide technical assistance to State and local governments to insure that timely and effective disaster warning is provided . . . for an earthquake, volcanic eruption, landslide, mudslide, or other geological catastrophe."

A USGS Hazards Information Coordinator receives information about a potential geologic hazard and then is responsible for obtaining expert review of the data and conclusions and for disseminating information to the public, government officials, and news agencies. The program's procedures, outlined in the *Federal Register* of April 12, 1977, define three levels of geologic-hazard information and notification:

- Notice of Potential Hazard—Information on the location and possible magnitude of a potentially hazardous geologic condition.
- Hazard Watch—Information, as it develops from monitoring or from observed precursors, that a potentially catastrophic event of a generally predictable magnitude may occur within an indefinite time (possibly months or years).
- Hazard Warning—Information (prediction) as to the time, location, and magnitude of a potentially disastrous geologic event.

Notices are then sent to appropriate local, State, and Federal agencies and, through the news services, to the public.

These procedures do not apply to flood warnings, even if the floods are related to volcanic activity. Flood warnings, as well as predictions about windborne ash distribution, are the responsibility of the National Weather Service of the National Oceanic and Atmospheric Administration.

Concern about potential hazards posed by Cascade Range volcanoes led the USGS to establish a Volcanic Hazards Project in 1967. This project is based on the concept that a volcano's behavior pattern can be determined by studying deposits formed by its past eruptions. This project assesses the potential threat of a volcano by a special kind of geologic "detective work." Such investigations involve determining (1) the ways in which various volcanic rock materials and deposits originated, (2) the order and sequence in which rock materials from the volcano and other deposits interbedded with them were deposited, (3) the timing of past volcanic events as indicated by the deposits that they produced, and (4) the various areas that received deposits from and, therefore, were affected by past eruptions. Modern eruptions of a volcano may not affect exactly the same areas exactly the way that a geologic study might indicate; such studies of areas affected in the past are, however, the best gage available and are used as a rough guide to the potential impacts of future eruptions.

GLOSSARY OF VOLCANIC AND RELATED TERMS

Active volcano: A volcano that is erupting. Also, a volcano that is not presently erupting but that has erupted within historical time and is considered likely to do so in the future (there is no distinction between "active " and "dormant" in this sense).

Andesite: Volcanic rock (or lava) characteristically medium dark in color and containing 54 to 62 percent silica and moderate amounts of iron and magnesium.

Ash (volcanic): Fine pyroclastic material in fragments less than 4.0 millimeters in diameter. "Ash" in this sense is quite distinct from the ash produced by common combustion because the rocks do not catch fire and burn during a volcanic event.

Ash cloud: Eruption cloud containing appreciable amounts of ash.

Ashfall (airfall): Volcanic ash that has fallen through the air from an eruption cloud. A deposit so formed is usually well sorted and layered.

Ash flow: A pyroclastic flow consisting predominantly of ash-sized (less

than 4 millimeters in diameter) particles. Also called a glowing avalanche if it is of very high temperature.

Avalanche: A large mass of material or mixtures of material falling or sliding rapidly under the force of gravity. Avalanches often are classified by their content, such as snow, ice, soil, or rock avalanches. A mixture of these materials is a debris avalanche. (See also ***Debris avalanche***.)

Basalt: Volcanic rock (or lava) that characteristically is dark in color, contains 45 to 54 percent silica, and generally is rich in iron and magnesium.

Crater: A steep-sided, usually circular depression formed by either explosion or collapse at a volcanic vent.

Dacite: Volcanic rock (or lava) that characteristically is light in color and contains 62 to 69 percent silica and moderate amounts of sodium and potassium.

Debris avalanche: A rapid and unusually sudden sliding or flowage of unsorted masses of rock and other material. As applied to the major avalanche involved in the eruption of Mount St. Helens, a rapid mass movement that included fragmented cold and hot volcanic rock, water, snow, glacier ice, trees, and some hot pyroclastic material. Most of the May 18 deposits in the upper valley of the North Fork Toutle River and in the vicinity of Spirit Lake are from the debris avalanche.

Dome: A steep-sided mass of viscous (doughy) lava extruded from a volcanic vent, often circular in plan view and spiny, rounded, or flat on top. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome.

Dormant volcano: A volcano that is not presently erupting but that is considered likely to erupt in the future. (See also ***Active volcano***.)

Ejecta: Material that is thrown out by a volcano, including ***pyroclastic*** material (***tephra***) and, from some volcanoes, ***lava*** bombs.

Extinct volcano: A volcano that is not presently erupting and is not likely to do so for a very long time in the future.

Fumarole: An opening at the Earth's surface from which water vapor and other gases are emitted, often at high temperature.

Graben: An elongate crustal block that is relatively depressed (downdropped) between two fault systems.

Harmonic tremor: A continuous release of seismic energy typically associated with the underground movement of magma. It contrasts distinctly with the sudden release and rapid decrease of seismic energy associated with the more common type of earthquake caused by slippage along a fault.

Lava: General term for magma (molten rock) that has been erupted onto the surface of the Earth.

Lava flow: An outpouring of lava onto the land surface from a vent or fissure. Also, a solidified tonguelike or sheetlike body formed by outpouring lava.

Magma: Molten rock beneath the surface of the Earth. (See also ***Lava***.)

Magnitude: A numerical expression of the amount of energy released by an earthquake, determined by measuring earthquake waves on standardized recording instruments (seismographs). The number scale for magnitudes is logarithmic rather than arithmetic; therefore, deflections on a seismograph for a magnitude 5 earthquake, for example, are 10 times greater than those for a magnitude 4 earthquake, 100 times greater than for a magnitude 3 earthquake, and so on.

Mudflow: A flowage of water-saturated earth material possessing a high degree of fluidity during movement. A less-saturated flowing mass is often called a debris flow. A mudflow originating on the flank of a volcano is properly called a lahar.

Phreatic eruption (explosion): An explosive volcanic eruption caused when water and heated volcanic rocks interact to produce a violent expulsion of steam and pulverized rocks. Magma is not involved.

Pumice: Light-colored, frothy volcanic rock, usually of dacite or rhyolite composition, formed by the expansion of gas in erupting lava. Commonly perceived as lumps or fragments of pea size and larger but can also occur abundantly as ash-sized particles.

Pyroclastic: Pertaining to fragmented (clastic) rock material formed by a volcanic explosion or ejection from a volcanic vent.

Pyroclastic flow: Lateral flowage of a turbulent mixture of hot gases and unsorted pyroclastic material (volcanic fragments, crystals, ash, pumice, and glass shards) that can move at high speed (50 to 100 miles an hour). The term also can refer to the deposit so formed.

Rhyolite: Volcanic rock (or lava) that characteristically is light in color, contains 69 percent silica or more, and is rich in potassium and sodium.

Tephra: Materials of all types and sizes that are erupted from a crater or volcanic vent and deposited from the air.

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UNIT CONVERSION

Quantitative information in this report is given in the traditional (English) units of measurement that are most familiar to the general population of the United States, the intended major readership for this report. This conversion table is for the convenience of those who prefer metric units.

Multiply inch-pound unit	By	To obtain SI unit
acre	4,047	square meter
	.4047	hectare
cubic yard	.7646	cubic meter
cubic feet per second	28.32	liters per second
	.02832	cubic meters per second
cubic mile	4.166	cubic kilometer
foot	.3048	meter
gallon	.003785	cubic meter
	3.785	liter
gallons per minute	.06309	liters per second
inch	2.540	centimeter
mile	1.609	kilometer
miles per hour	1.609	kilometers per hour
square mile	2.59	square kilometer
ton, short (2,000 pounds)	.9072	ton, metric
	907.1848	kilograms