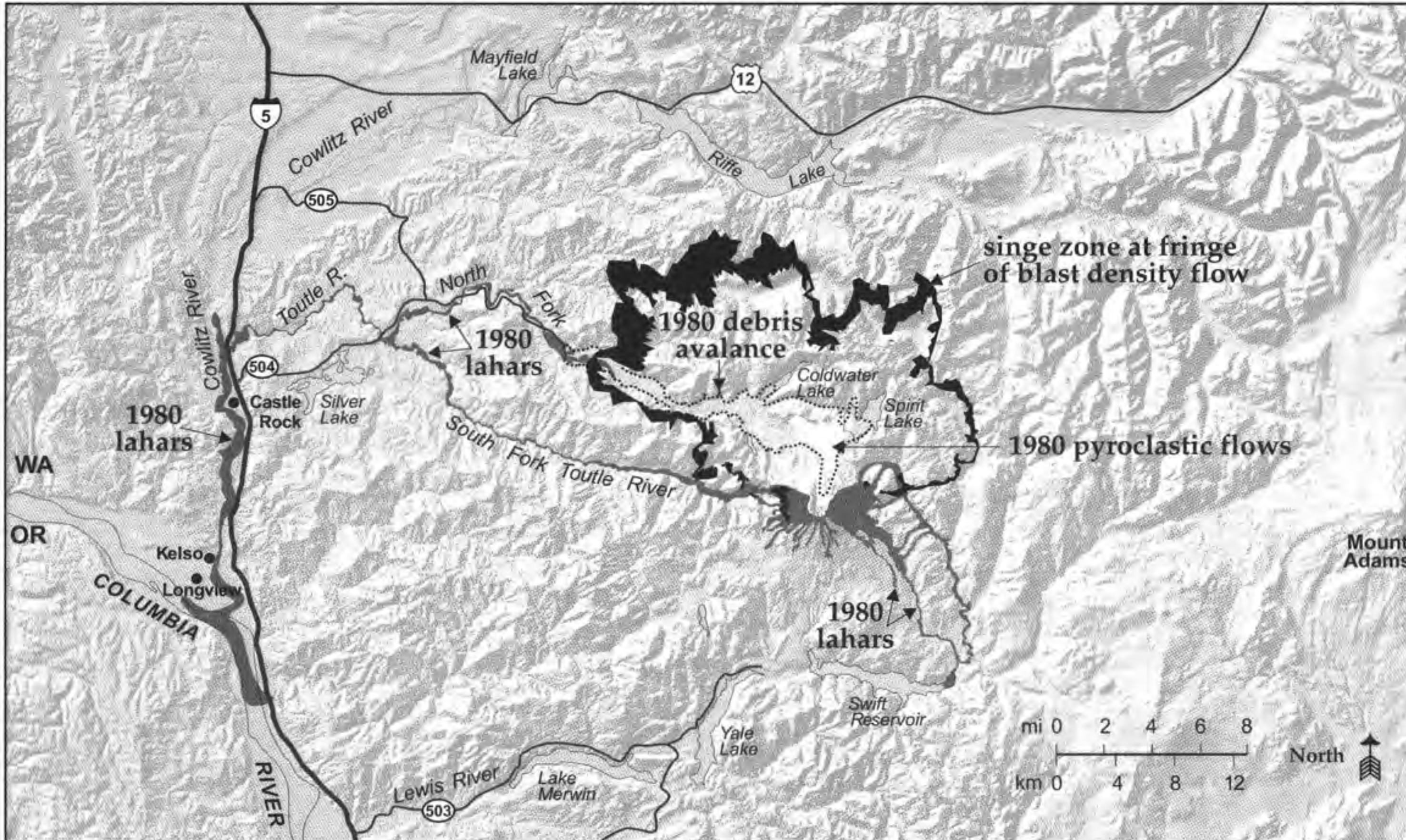
ROADSIDE GEOLOGY OF MOUNT ST. HELENS NATIONAL VOLCANIC MONUMENT AND VICINITY

by Patrick T. Pringle

WASHINGTON DEPARTMENT OF NATURAL RESOURCES
Division of Geology and Earth Resources Information Circular 88
1993 [Revised Edition 2002]



Shaded relief map of the Mount St. Helens area showing areas affected by1980 eruption processes. The image was created from 30 m digital elevation data.

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Natural Resources
Doug Sutherland - Commissioner of Public Lands

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Front Cover. Mount St. Helens from the north shore of Spirit Lake, about 7 mi (11 km) north-northeast of the crater. Photo taken in 1982 by Lyn Topinka, U.S. Geological Survey.

Back Cover. Mount St. Helens from the Longview "Y" Camp, circa 1937. Courtesy of the Washington State Historical Society; original photo by Claude Palmer of Photo Art Studios, Inc., Portland, Oregon.

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Dick Janda at the lahar source area on the debris avalanche on May 24, 1980. Photo by Barry Voight, Pennsylvania State University.

DEDICATION

To Richard "Dick" Janda (1939–1992). Dick's understanding of volcanic processes and hazards at Mount St. Helens was surpassed only by his spirited efforts to communicate his insights to public officials and the general public. He remains a great inspiration to friends and colleagues.

PREFACE

This guidebook is largely a compilation of research by many investigators who for decades have been examining the geologic history, structure, and processes of the Mount St. Helens area. I will acknowledge some of the principal sources of information below because I have included few references in the text in order to make it read more smoothly.

Much of the eruptive history of Mount St. Helens has been taken from the reports of U.S. Geological Survey (USGS) geologists Dwight Crandell, Donal Mullineaux, and Jack Hyde (deceased); Cliff Hopson (Univ. of Calif. at Santa Barbara) also contributed many details. Post-1980 erosion exposed previously unstudied deposits. Examination of those rocks, combined with new understanding and technological advances, has resulted in refinement of the eruptive history. USGS geologists Kevin Scott and Jon Major expanded the history of lahars in the Toutle–Cowlitz and Lewis River drainages. Brian Hausback (Calif. State Univ. at Sacramento) and Don Swanson (USGS) discovered ancient debris-avalanche deposits exposed in gullies cut after 1980, and Chris Newhall (USGS) identified similar deposits south of the volcano. The interdisciplinary collaborations of Rick Hoblitt, John Pallister, Dwight Crandell, and Donal Mullineaux (all USGS) with dendrochronologist

David Yamaguchi and botanist Donald Lawrence (Univ. of Minn., deceased) have resulted in a much improved and amazingly detailed history of the two eruptive periods that preceded the modern eruption. The history of Tertiary rocks in the area has been updated by new or recently published mapping by Russ Evarts, Roger Ashley, and Don Swanson (all USGS), Paul Hammond (Portland State Univ.), and Tim Walsh, Bill Phillips, Josh Logan, Hank Schasse, and Mike Korosec (all Wash. Dept. of Natural Resources, Divn. of Geology and Earth Resources).

Interpretations of the eruptive events and eruptive processes of May 18, 1980, and later eruptions have been compiled from USGS Professional Paper 1250 and other reports too numerous to mention. Tom Pierson, Kevin Scott, Dick Janda, and Ken Cameron (all USGS), as well as Lee Fairchild and Mark Wigmosta (both Univ. of Wash.), are among those who studied lahar processes in detail. For discussions of the blast density flow, I borrowed heavily from the publications of Richard Fisher (Univ. of Calif. at Santa Barbara), Tim Druitt (Univ. of Wales), and USGS geologists Rick Hoblitt, Richard Waitt, Dan Miller, Susan Kieffer, Steve Brantley, and Harry Glicken (deceased), and others whose investigations have provided many new insights about this unprecedented event at the volcano. Glicken's ideas, as well as those of Barry Voight (Penn. State Univ.) and Dick Janda, were the basis for much of my discussion of the debris avalanche. He described the geology of the debris-avalanche deposit in great detail in his Ph.D. dissertation and in several papers. Eliott Endo and Craig Weaver (both USGS), Steve Malone (Univ. of Wash.), and others have greatly improved the understanding of the seismicity and subsurface structure of the volcano. Don Swanson, Tom Casadevall, Christina Heliker, Bill Chadwick, Dan Dzurisin, John Ewert, Tom Murray, Robin Holcomb, Don Peterson, Jim Moore, Norm MacCloud, and Gene Iwatsuba (all USGS), Mac Rutherford (Brown Univ.), Katharine Cashman (Univ. of Ore.), Steven Carey and Haraldur Sigurdsson (Univ. of R.I.), Bill Criswell (Univ. of N.Mex.), Cathie Hickson (Geological Survey of Canada), and many others have added to our understanding of eruptive processes at Mount St. Helens since 1980. Tom Dunne and Brian Collins (both Univ. of Wash.), Dick Janda, Dave Meyer, and Holly Martinson (all USGS), Fred Swanson (U.S. Forest Service), Hugh Mills (Tenn. Tech. Univ.), and others have written extensively about post-eruption erosion and deposition. Ed Wolfe and Mike Clynne (USGS) continue to investigate and map the pre-eruption history of Mount St. Helens.

Finally, I thank the following reviewers for their critical, thoughtful, and inspiring comments on the text: Don Swanson, Richard Waitt, Russ Evarts, Steve Brantley, Peter Frenzen, Ken and Ellen Cameron, Kitty Reed, Bill Phillips, Eric Schuster, and Tim Walsh. Jari Roloff edited the text, designed and laid out the pages, and had numerous helpful review suggestions. Former State Geologist Ray Lasmanis supported this project from its earliest stages. Nancy Eberle designed the front and back covers and collaborated on the design and illustrations. Keith Ikerd prepared overlays for the photographs. Keith Ronnholm, Barry Voight, Rick Hoblitt, Charlie Larson, Lyn Topinka, Jon Major, the Washington State Historical Society, and Photo Art Studios, Inc., kindly allowed me to use their photographs. Dave Wieprecht and Dave Hirst (USGS) provided agency photos. My wife Leslie contributed valuable field assistance and moral support during this project. All figures and photographs are by the author unless otherwise noted.

I am grateful to the staff of the U.S. Forest Service at Mount St. Helens National Volcanic Monument for assistance and partial funding for this project through a challenge cost-share agreement.

Pat Pringle
May 2002

CONTENTS

INTRODUCTION

Welcome to the Mount St. Helens National Volcanic Monument, which was established by Congress in 1982 and is managed by the U.S. Forest Service. The monument was created to protect the unique environment formed by the 1980 eruptions of Mount St. Helens.

This road guide describes and interprets geologic features at diverse sites in the monument and surrounding area. It complements other published natural history and geologic guidebooks and can be used in conjunction with maps of the Mount St. Helens National Volcanic Monument available at the Mount St. Helens Visitor Center at Silver Lake on State Route (SR) 504 and at information stations along roads leading to the monument.

This booklet examines five aspects of Mount St. Helens geology: (1) pre-Mount St. Helens rocks and their history, (2) glacial history and glacial deposits of the area, (3) pre-1980 history and activity of Mount St. Helens volcano, (4) post-1980 eruptions and deposits, and (5) ongoing processes of erosion and landscape modification.

HOW TO USE THIS GUIDE

The text consists of four parts: Part I is an introduction to the geologic history of the Mount St. Helens area and a summary of the 1980–1986 eruptions; Part II is a road guide to the geology of Mount St. Helens and vicinity; Part III explains geologic processes and terminology; and Part IV contains a list of references cited, plus selected references for further reading, followed by a glossary.

The road guide provides general descriptions of the rocks and geologic history of specific areas, as well as more detailed explanations of features at roadside stopping points. It follows several major routes (Fig. 1) to the volcano: **(A)** the western approach along the Toutle River valley on the new Spirit Lake Memorial Highway, SR 504; **(B)** the southern approach along the lower Lewis River valley and the south flanks of the mountain via SR 503 and Forest Road (FR) 83; **(C)** the eastern approach, which includes stops along FRs 90, 25, and 99; **(D)** FR 99 to Windy Ridge; **(E)** the northern approach along the Cowlitz River valley via U.S. Highway 12, SR 131, FR 25, and FR 99; **(F)** the alternate northern approach via FR 26; and **(G)** the alternate southern loop on FR 81.

Units of measure: Measurements throughout the text are given in standard English units (feet, miles) followed by metric units (meters, kilometers) in parentheses (Table 1).

Units of geologic time: Geologists use some compact abbreviations to express geologic time. For example, Ma stands for mega-annum or million years. Points in

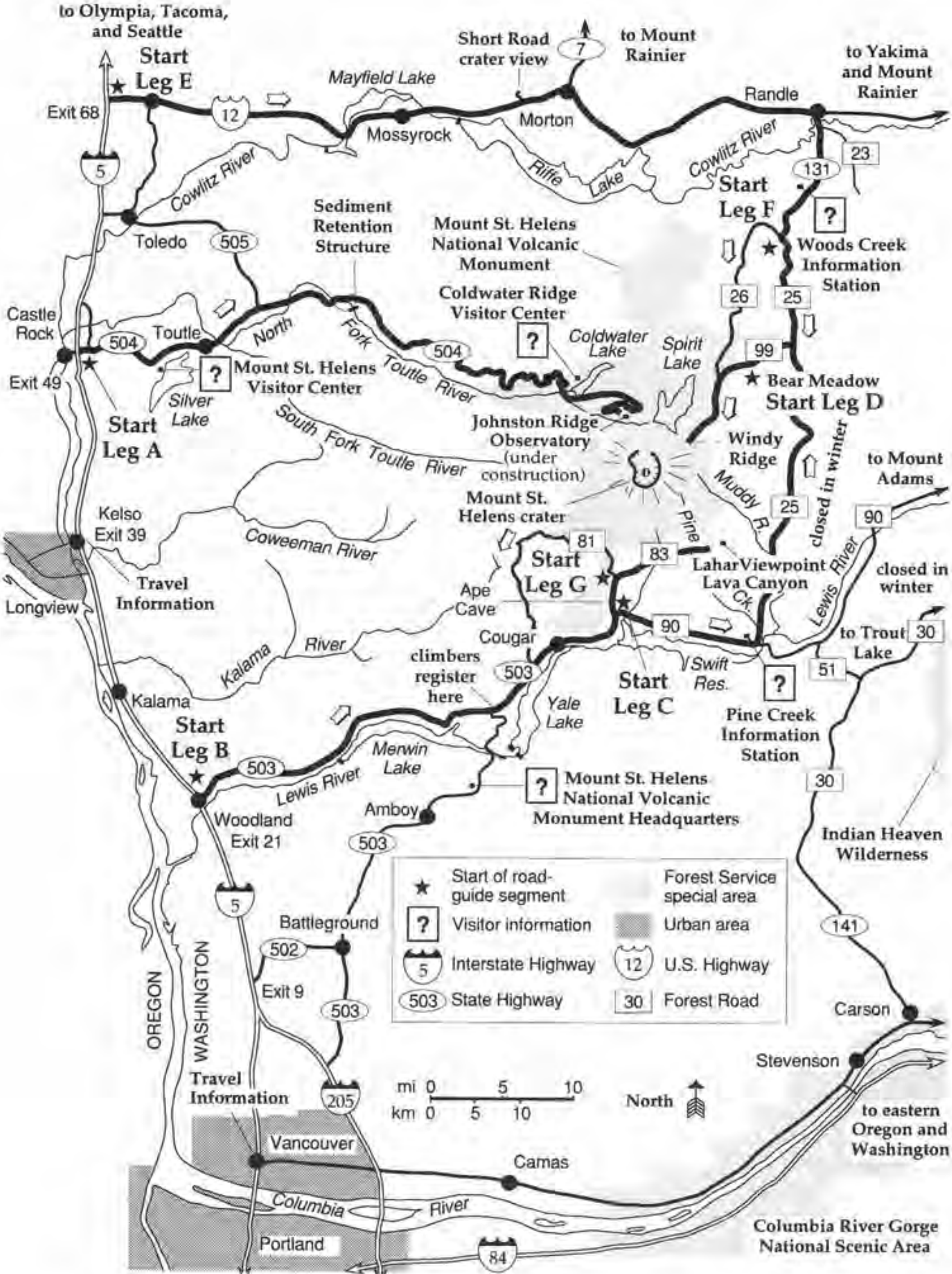


Figure 1. Location map of the Mount St. Helens area showing the national monument, major rivers, and various routes of the road guide. Symbols shown here are those used on maps throughout this guide.

Table 1. Metric equivalents for English units. To get the number of metric units, multiply the number of English units by the metric equivalent

English unit	Metric equivalent
1 inch	2.540 centimeters
1 foot	0.305 meter
1 yard	0.914 meter
1 $yard^3$	0.765 $meter^3$
1 mile	1.609 kilometers
1 $mile^2$	2.590 $kilometers^2$
1 $mile^3$	4.168 $kilometers^3$
1 ton, short	0.907 tonne

geologic time, such as the upper and lower age limits of the Oligocene Epoch, are written as 22.7 Ma and 36.6 Ma, meaning 22,700,000 years and 36,600,000 years. Or a bed deposited in the Pliocene might have an age of 3.4 Ma. Time spans, however, are indicated by the abbreviation m.y., again meaning million years. The Oligocene Epoch lasted about 14 m.y. For ages expressed in thousands of years, the abbreviation ka, for kilo-annum, is used. Thus, a certain glacial deposit has an age of 140 ka, indicating 140,000 years. Time intervals are simply expressed as thousands of years; there is no handy abbreviation like m.y. You will see these conventions used throughout this book. Table 2 is a quick reference for these and other abbreviations used in the text.

Radiocarbon dates: Age estimates for geologic units less than about 40,000 years old that have been derived by radiocarbon (^{14}C) dating methods are given as "yr B.P.", meaning "radiocarbon years before present" where the "present" is A.D. 1950. Radiocarbon years can differ slightly from calendar years because of variations in the carbon isotope content of atmospheric carbon dioxide through time. Tree ring data have been used to recalibrate these ages back to about 11,000 years ago. However, for the sake of simplicity, raw radiocarbon ages are used in this guide. However, tree-ring dates for Mount St. Helens deposits laid down since A.D. 1480 are given in calendar years.

Glossary: A glossary of geologic terms is provided at the end of Part IV. Glossary entries are italicized the first time they appear in each section.

A few words about safety: If you are driving alone and using this guidebook, please do not try to read it and drive at the same time. Instead, pull off the road into a designated turnout or parking area, then find the information you need. Better yet, share the field trip with a friend or friends, and let them do the navigating and reading while you drive. Rubbernecking to look at geologic features can

Table 2. Abbreviations used in text

A.D.	anno Domini (year of [our] Lord)	m	meter(s)
cm	centimeter(s)	mm	millimeter(s)
ft	foot, feet	Ma	mega-annum or million years
FR	Forest Road	mi	mile(s)
Gl.	glacier	m.y.	million years (time span)
hr	hour(s)	s	second(s)
I-	Interstate Highway	SR	State Route
in.	inch(es)	US	U.S. Highway
ka	kilo-annum or thousand years	yd	yard(s)
km	kilometer(s)	yr B.P.	radiocarbon years before present

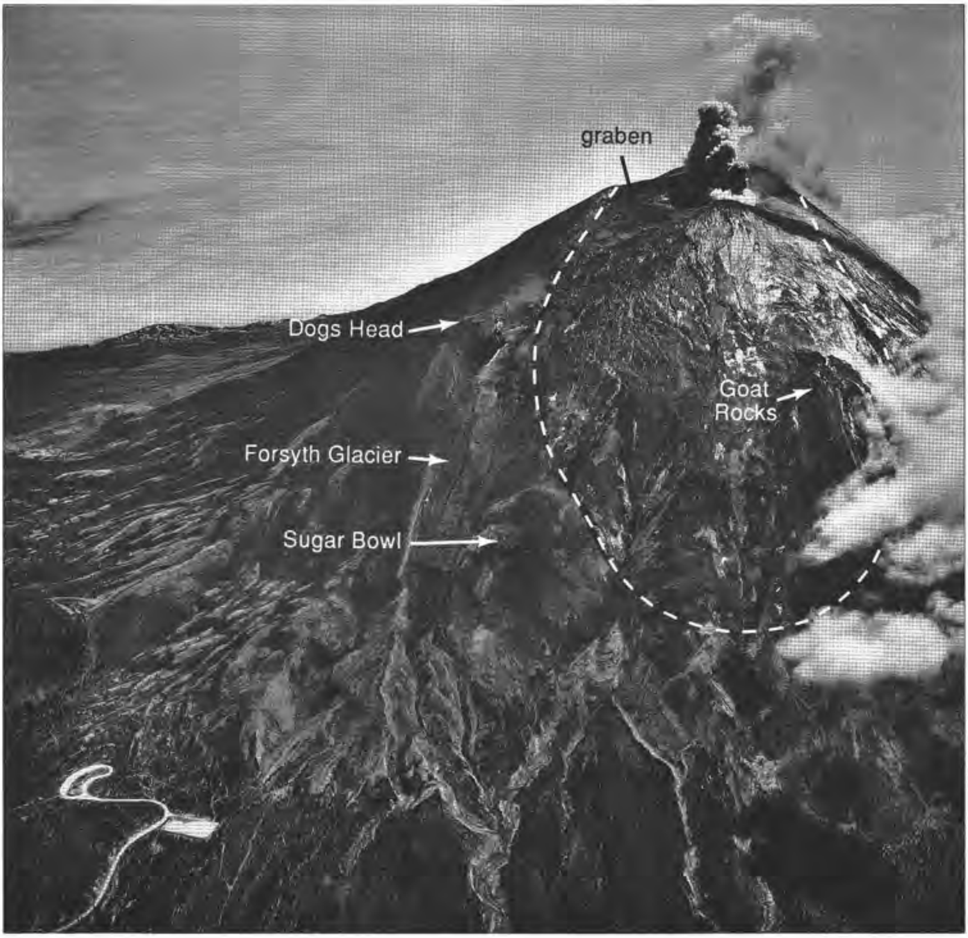


Figure 2. Small phreatic eruption at Mount St. Helens on May 11, 1980. Dashed line shows the approximate outline of the bulge. The graben, a down-dropped block, formed as the bulge was pushed outward by the rising magma. View is to the south and shows the Dogs Head, Sugar Bowl, and Goat Rocks dacite domes. Photo by Robert Krimmel, U.S. Geological Survey.

be dangerous on the narrow, winding roads that lead to and traverse the national monument.

Note: Gas stations are sparse in this area, so it advisable to plan ahead.

Etiquette for visitors in the Mount St. Helens National Volcanic Monument: The monument is a natural laboratory. Scientists (both professional and amateur) are studying geologic deposits, ongoing volcanic processes, and recovery of the landscape and its inhabitants. Please respect this landscape and any scientific plots, equipment, or experiments you may come across in your explorations. Please stay on designated trails and refrain from taking *pumice*, *ash*, rock, or plant

Figure 3. View to the north-northwest of the Plinian eruption column of Mount St. Helens during the early afternoon of May 18, 1980. Note the trace of the pyroclastic surge and lahar on Muddy fan downslope from Shoestring Glacier (lower right). Photo by Robert Krimmel, U.S. Geological Survey.

samples from inside the boundaries of the national monument. And always pack your litter out!

SUMMARY OF RECENT ERUPTIVE ACTIVITY AND HAZARDS

Mount St. Helens awakened with earthquakes on March 20, 1980, after 123 years of dormancy. The volcano produced a *phreatic* or steam eruption on March 27. After two more months of activity, including numerous earthquakes and relatively mild steam eruptions (Fig. 2), Mount St. Helens erupted cataclysmically on May 18, 1980, at 8:32 A.M. This large eruption was characterized by a huge landslide (*debris avalanche*), an explosive *lateral blast*, numerous *pyroclastic flows*, devastating volcanic *debris flows* and mudflows (called *lahars*) that flowed down river valleys originating on the volcano, and a tremendous *tephra* plume that injected ash into

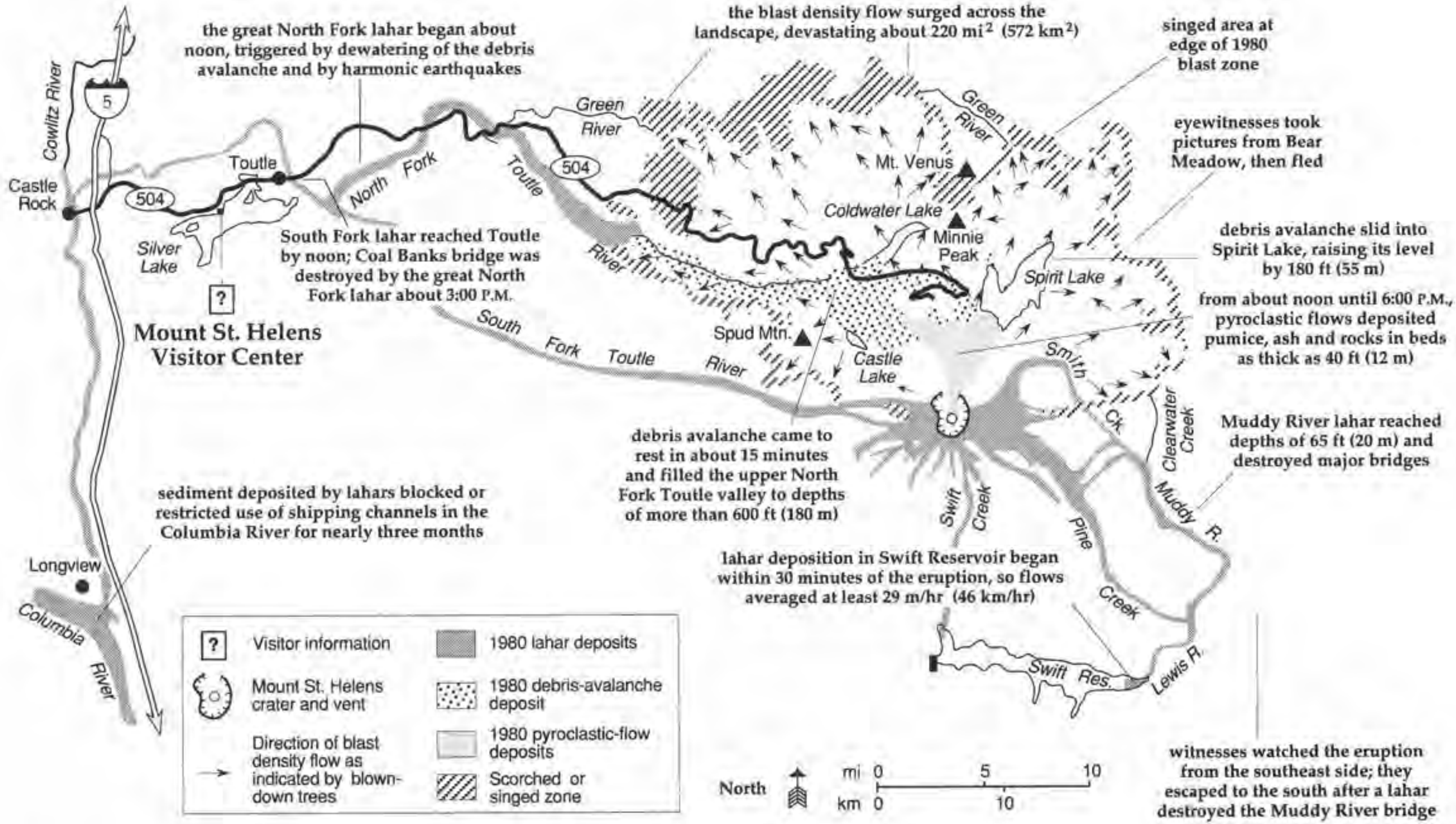


Figure 4. Generalized diagram showing the devastation caused by the climactic eruption of Mount St. Helens on May 18, 1980. The singe zone is at the periphery of the area affected by the blast. Other symbols used are identified in Figure 1. Modified from Lipman and Mullineaux (1981).

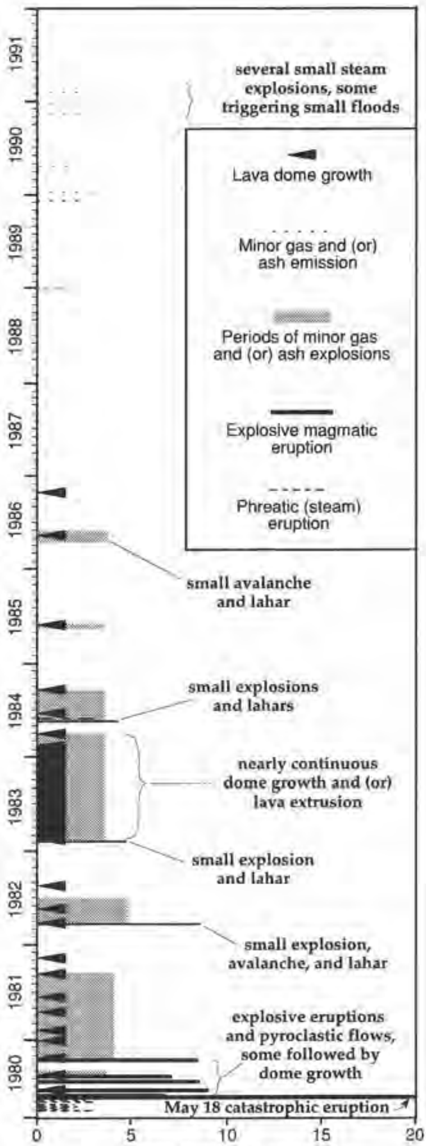


Figure 5. Diagrammatic summary of Mount St. Helens eruptive activity from 1980 to 1992. Modified from Tilling and others (1984).

the stratosphere for more than 9 hours (Figs. 3 and 4). The 1979 summit elevation of Mount St. Helens was 9,677 ft (2,951 m). It was reduced to 8,365 ft (2,551 m) and 0.6 mi^3 (2.5 km^3) of material was removed by the May 18 eruption. (For a discussion of volcanic processes, see p. 103 and Table 9.)

The May 18 event ranks as one of the most significant natural disasters in the United States this century. Some aspects of this eruption, like its tremendous lateral blast, were unprecedented in scale at Mount St. Helens and had never been witnessed or documented elsewhere from such close range. The debris avalanche was the largest landslide in recorded history. Intensive study of these volcanic events and their deposits and close observation of the volcano during its recent eruptive activity have led to far-reaching advances in volcanology (the science of volcanic studies) and to increased international cooperation in the study of volcanic hazards and the development of volcano monitoring technology (see p. 33).

Five additional explosive eruptions followed during the summer and fall of 1980. Each of those events produced plumes of ash that reached altitudes of 4 to 8 mi (6–13 km) and numerous pyroclastic flows. For all except the October eruption, small *domes* grew following the explosive event and then were blown away by subsequent eruptions.

Between late 1980 and 1986, 17 distinct eruptive episodes (Fig. 5) constructed a 876-ft (267 m) -tall *lava* dome. This dome is a large mound of viscous lava that cooled as it piled up over the vent area in the center of the gaping 1-mi (1.6 km) -wide crater created on May 18, 1980. Each of these dome-growth episodes produced between 3 million and 10 million yd^3 (2 million and 8 million m^3) of lava. On several occasions, small explosions accompanied the build-up of pressure preceding the eruption.

Typically, thousands of *volcanic earthquakes* precede the eruption of lava at Mount St. Helens by a few weeks or months. These earthquakes are caused as the viscous *magma* forces its way through brittle rocks to the surface. When the mag-

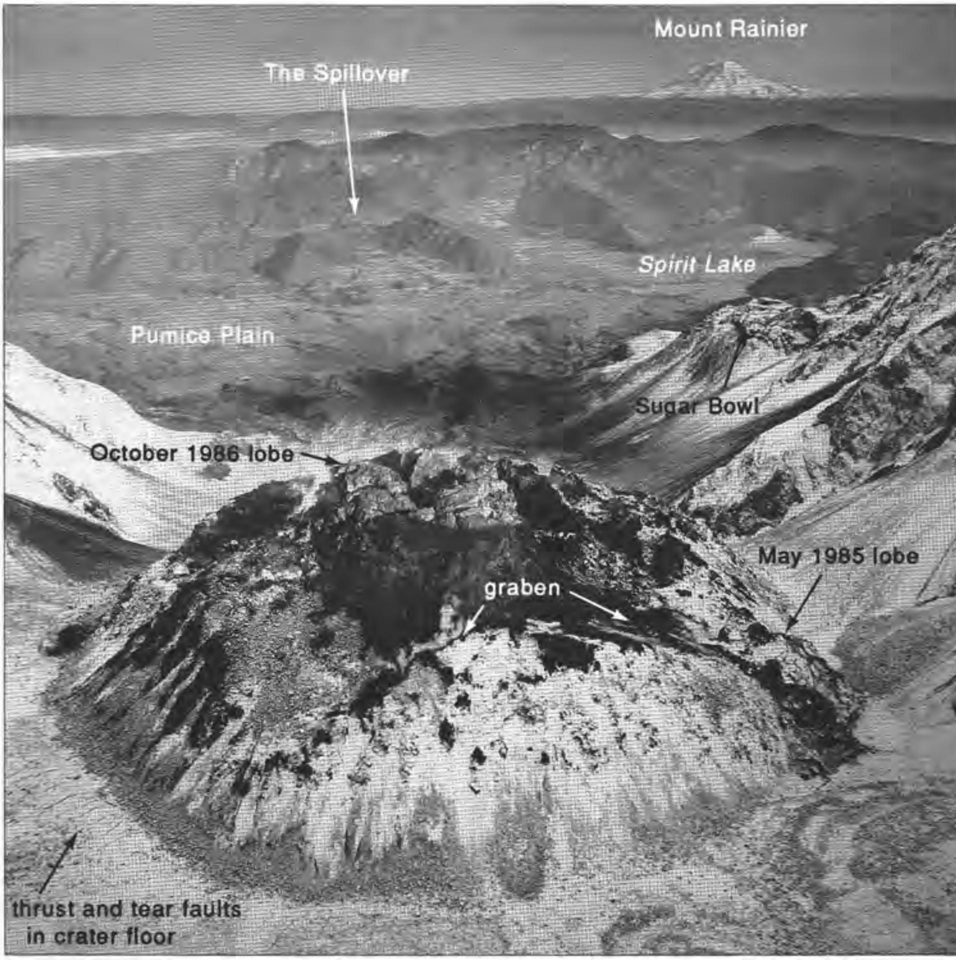


Figure 6. Lava Dome as seen from the south, showing the lobe of lava extruded on October 21 and 22, 1986. The thin lines in the snow on the west crater floor are thrust and tear faults that developed before this extrusion. Thrust faults are parallel to the perimeter of the dome, and tear faults are radial to it. Rubbly remnants of other lobes are visible on the dome surface. Also shown are the graben formed during the May 1985 eruption and The Spillover, where the 1980 debris avalanche spilled over Johnston Ridge. Note the east-dipping beds of Tertiary rocks north of the volcano. Photo by Lyn Topinka, U.S. Geological Survey.

ma finally pushes into the dome and leaks to the surface as lava, it adds to the dome's height and width. The most recent dome growth episode occurred in October of 1986 (Fig. 6).

Since 1986, the volcano has been quiet except for occasional explosions and ash plumes reaching altitudes as high as 3.5 mi (5.6 km) above sea level. These explosions have thrown rocks more than 1,000 yd (1 km) from the dome, formed small pyroclastic flows in the crater, and have generated small lahars that flowed more than 10 mi (16 km) from the volcano down its north flank. Although they have generated widespread public interest, these recent explosions have been confined to the crater and nearby areas.

Inside the crater, rockfalls are common, and these remain significant hazards to researchers who enter the crater between October and May. In winter, snow avalanches off the Lava Dome and from the crater walls have been large enough to flow out of the crater.

Geologists have found evidence suggesting that the reservoir of magma that fed the 1980 to 1986 eruptions is much larger than the volume of material erupted during that time. Therefore, there is plenty of magma remaining to supply future eruptions. The top of the magma chamber is about 4 mi (7 km) below the surface (Fig. 7). The magma in the narrow conduit beneath the Lava Dome has probably cooled and become solid, so future additions to the dome will likely be preceded by explosive activity as the volcano clears its throat and the magma forces its way through this crystallized plug to the surface.

Scientists expect major volcanic eruptions at Mount St. Helens to be preceded by days, weeks, or months of earthquake activity. During a major eruptive event, hazards would include tephra falls, explosive ejections of rocks, pyroclastic flows and surges, lava flows, lahars, and floods and would definitely extend outside the crater. Figure 8 is a preliminary hazards map showing the areas most likely to be affected. However, small explosions can occur in the crater without warning and might not be associated with an impending eruption. (A more detailed discussion of volcanic hazards is found on p. 35.)

The U.S. Geological Survey (USGS) maintains a network of monitoring devices and keeps the Forest Service and other public agencies informed about conditions at the volcano, including any significant changes in its activity. In the meantime, the biggest hazard to visitors in the Mount St. Helens National Volcanic Monument is the routine danger of traffic mishaps.

PHYSIOGRAPHY OF THE SOUTHERN WASHINGTON CASCADES

Mount St. Helens is a young addition to the landscape. The volcano sits on a glaciated and eroded mostly volcanic terrain composed of *faulted*, gently *folded Tertiary* bedrock. (The Tertiary Period lasted from about 65 Ma to 1.6 Ma.)

Resistant granitic rocks and the recrystallized (*hornfelsed*) rocks bordering them compose the high peaks north of the volcano. These mountains were the source areas of large *glaciers* that occupied several river valleys in this part of Washington during glacial episodes that preceded the birth of Mount St. Helens a little more than 40,000 years ago. Most older peaks in the monument reach elevations between 4,000 and 6,000 ft (1,200 and 1,800 m), and valley bottoms are at 1,000 to 3,000 ft (300–900 m).

Three river systems drain the volcano. Swift and Pine Creeks, along with the Smith Creek–Muddy River system, drain into the west-flowing Lewis River south of Mount St. Helens (see Fig. 1). The North and South Fork Toutle Rivers, which drain the north and west sides of the mountain, join to form the Toutle River, a tributary to the Cowlitz River. The Kalama River drains the southwest flank of Mount St. Helens and flows into the Columbia River north of Kalama. The Lewis River, which drains the south and east flanks, joins the Columbia slightly south of Woodland, WA, and the Cowlitz flows into the Columbia at Longview. All these valleys have been affected by eruptions from Mount St. Helens over its more-than-

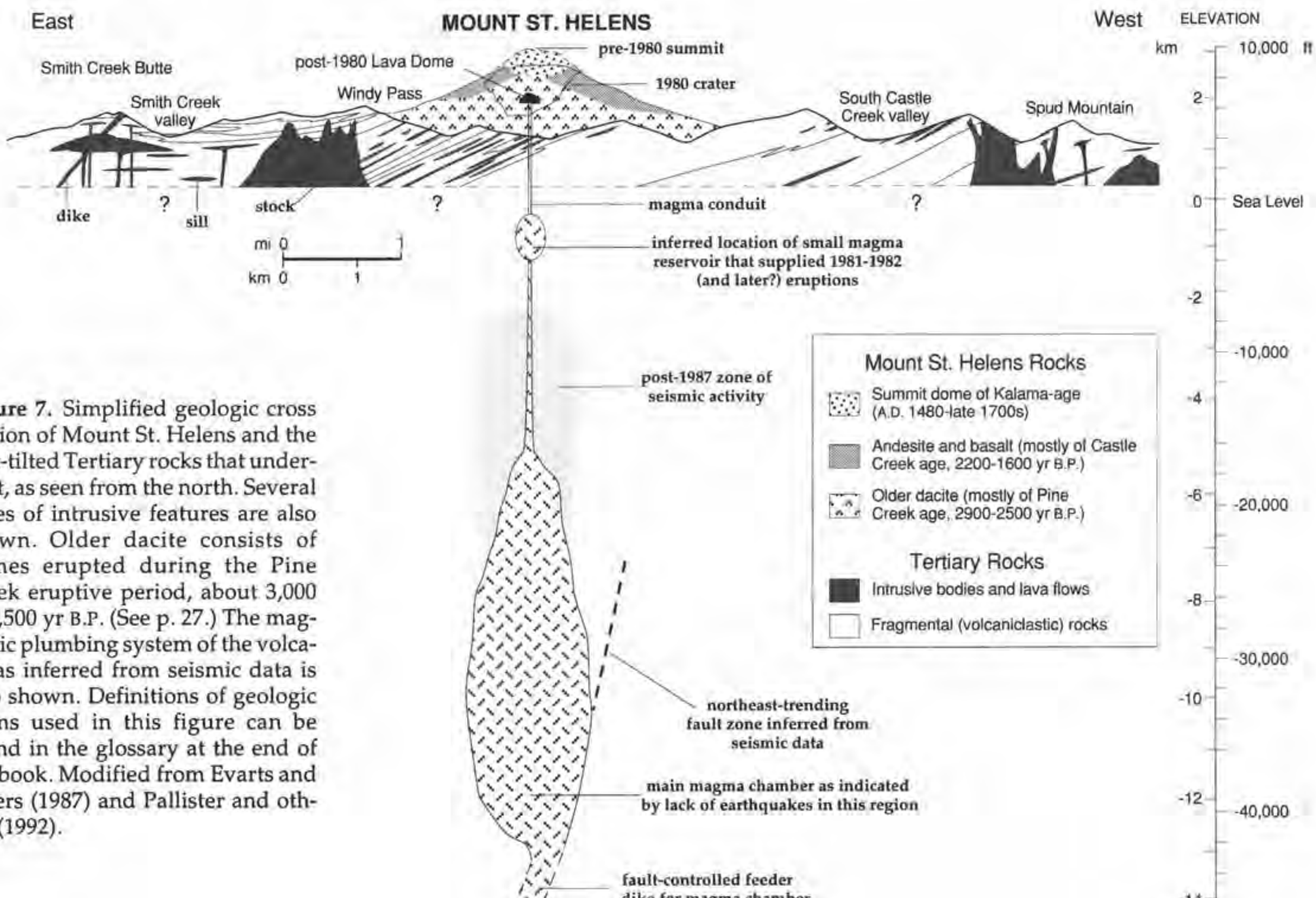


Figure 7. Simplified geologic cross section of Mount St. Helens and the east-tilted Tertiary rocks that underlie it, as seen from the north. Several types of intrusive features are also shown. Older dacite consists of domes erupted during the Pine Creek eruptive period, about 3,000 to 2,500 yr B.P. (See p. 27.) The magmatic plumbing system of the volcano as inferred from seismic data is also shown. Definitions of geologic terms used in this figure can be found in the glossary at the end of the book. Modified from Evarts and others (1987) and Pallister and others (1992).

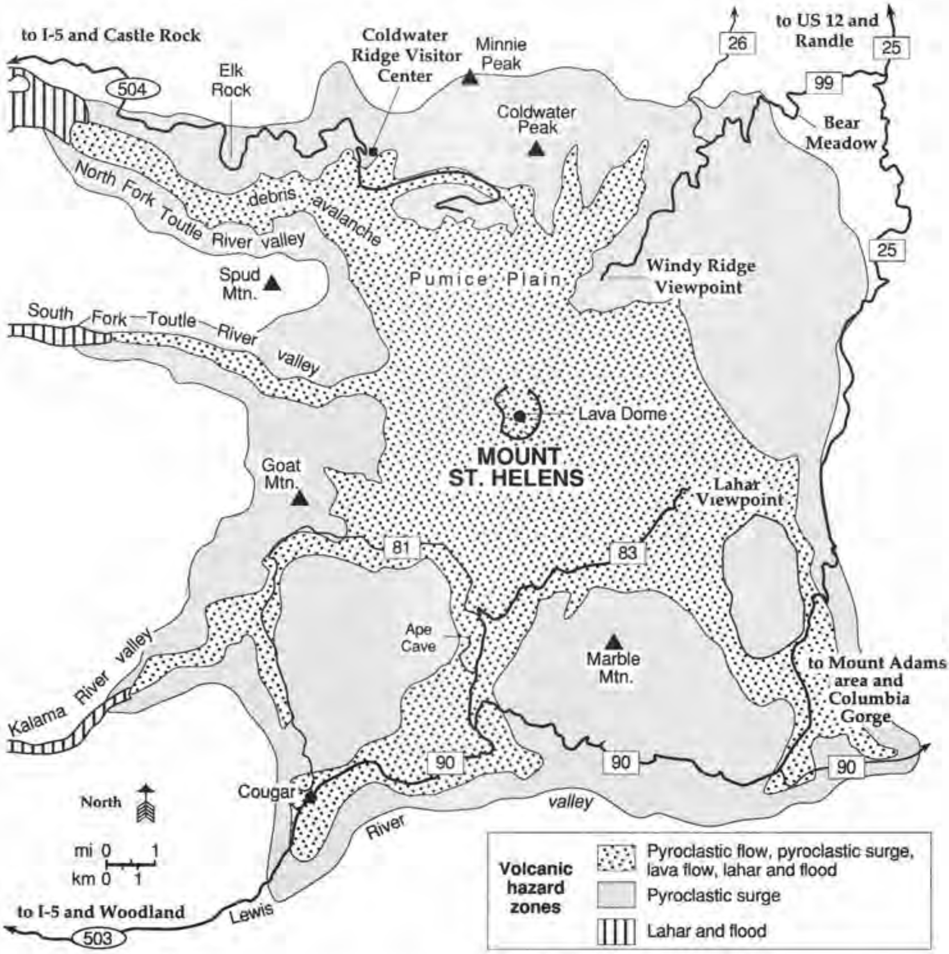


Figure 8. This preliminary volcanic hazards map, redrawn from one prepared by the U.S. Geological Survey (U.S. Forest Service, 1992), shows hazard zones close to the volcano that could be at great risk in the event of a major eruption. These areas would be evacuated and closed to the public. Such eruptive activity is typically preceded by a systematic increase in seismic activity that would give adequate warning. Symbols used are identified in Figure 1.

40,000-year history, and volcanic debris reaches thicknesses of hundreds of yards or meters in the upper reaches of these valleys.

Most of the modern Mount St. Helens edifice was formed within the last 3,000 years (Fig. 7). Younger deposits sit on top of older dacite that Jean Verhoogen (1937, p. 19) called "old Mount St. Helens". (A detailed summary of the volcano's history can be found on p. 24.)

PART I: HISTORY OF THE MOUNT ST. HELENS AREA

EARLY ACCOUNTS AND EXPLORATION OF THE AREA

"I was suddenly awakened by my mother, who called out to me that the world was falling to pieces. I then heard a great noise of thunder overhead and all the people crying in terror. Something was falling very thick, which we first took to be snow but proved to be ashes, which fell to a depth of six inches."

from an interview of Cornelius or Bighead
(chief of the Spokane Tribe, whose
Indian name was Silimxnotylmilakabok)
taken from an account of the 1800 eruption
by Charles Pickering (Wilkes, 1845)

"The clearness of the atmosphere enabled us to see the high round snowy mountain....I have distinguished by the name Mount St. Helens, in honor of his Britannic Majesty's ambassador at the Court of Madrid [Alleyne Fitzherbert, the Lord of St. Helens]."

Master George Vancouver,
October 20, 1792 (Vancouver, 1929)

"It is emensely high and covered with snow." "...a kind of cone in the form of a Sugar lofe...the most noble looking object of its kind in nature."

Lt. William Clark,
Nov. 4, 1805, and March 30, 1806,
near Vancouver, WA (Thwaites, 1959)

American Indians, Explorers, and Pioneers

Native cultures in the Pacific Northwest, such as the Salish and Klickitat Indians, called Mount St. Helens Loo-Wit Lat-kla or Louwala-Clough (fire mountain or smoking mountain). In their legends, a female spirit (Mount St. Helens) tried to make peace between two sons (Mounts Adams and Hood) of the Great Spirit who fought over her, throwing fiery rocks at each other and causing earthquakes. The warring of the sons destroyed the Bridge of the Gods that once crossed the Columbia River. These legends are undoubtedly referring to volcanic eruptions and earthquakes that both frightened and awed the area's early inhabitants.

The first documented observation of Mount St. Helens by Europeans was by George Vancouver on May 19, 1792, as he was charting the inlets of Puget Sound at Point Lawton, near present-day Seattle. Vancouver did not name the mountain until October 20, 1792, when it came into view as his ship passed the mouth of the Columbia River.

Figure 9. An eruption from the Goat Rocks dome on the north flank of Mount St. Helens painted by Canadian artist Paul Kane in 1847. The view is to the east, apparently from the Columbia or Cowlitz River. Photo courtesy of the Royal Ontario Museum.

A few years later, Mount St. Helens experienced a major eruption. Explorers, traders, missionaries, and ethnologists heard reports of the event from various peoples, including the Sanpoil Indians of eastern Washington and a Spokane chief who told of the effects of ash fallout. Later studies determined that the eruption occurred in 1800.

The Lewis and Clark expedition sighted the mountain from the Columbia River in 1805 and 1806 but reported no eruptive events or evidence of recent volcanism. However, their graphic descriptions of the quicksand and channel conditions at the mouth of the Sandy River near Portland, Oregon, suggest that Mount Hood had erupted within a couple decades prior to their arrival.

Meredith Gairdner, a physician at Fort Vancouver, wrote of darkness and haze during possible eruptive activity at Mount St. Helens in 1831 and 1835. He reported seeing what he called lava flows, although it is more likely he would have seen mudflows or perhaps small pyroclastic flows of incandescent rocks.

On November 22, 1842, Reverend Josiah Parrish, while in Champoeg, OR, (about 80 mi or 130 km south-southwest of the volcano), witnessed Mount St. Helens in eruption. Ash fallout from this event evidently reached The Dalles, OR (48 mi or 80 km southeast of the volcano). Missionaries at The Dalles corroborated Parrish's account. Captain J. C. Fremont recounts the report of a clergyman named Brewer, who gave him a sample of the ash a year later (Wilkes, 1845):

> "On the 23rd day of the preceding November, St. Helens had scattered its ashes, like a light fall of snow, over the Dalles of the Columbia."

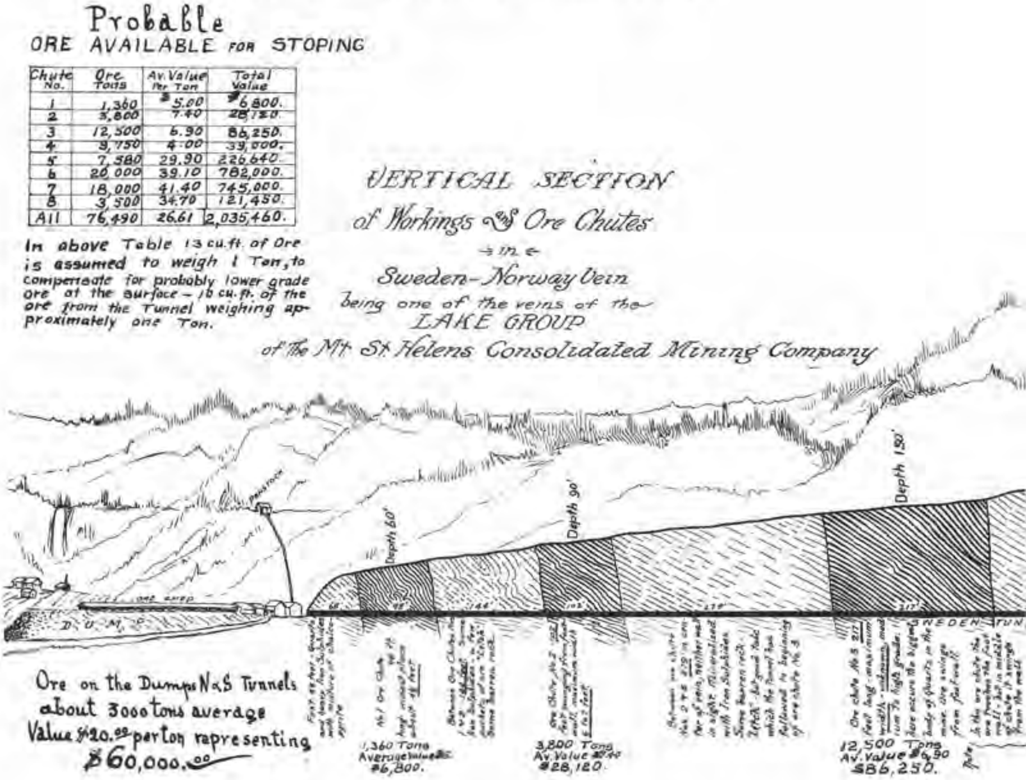


Figure 10. Diagrammatic cross section of the Sweden and Norway mines from a 1910 report by Prof. Barker of Eugene University. Areas of darker lines are ore chutes.

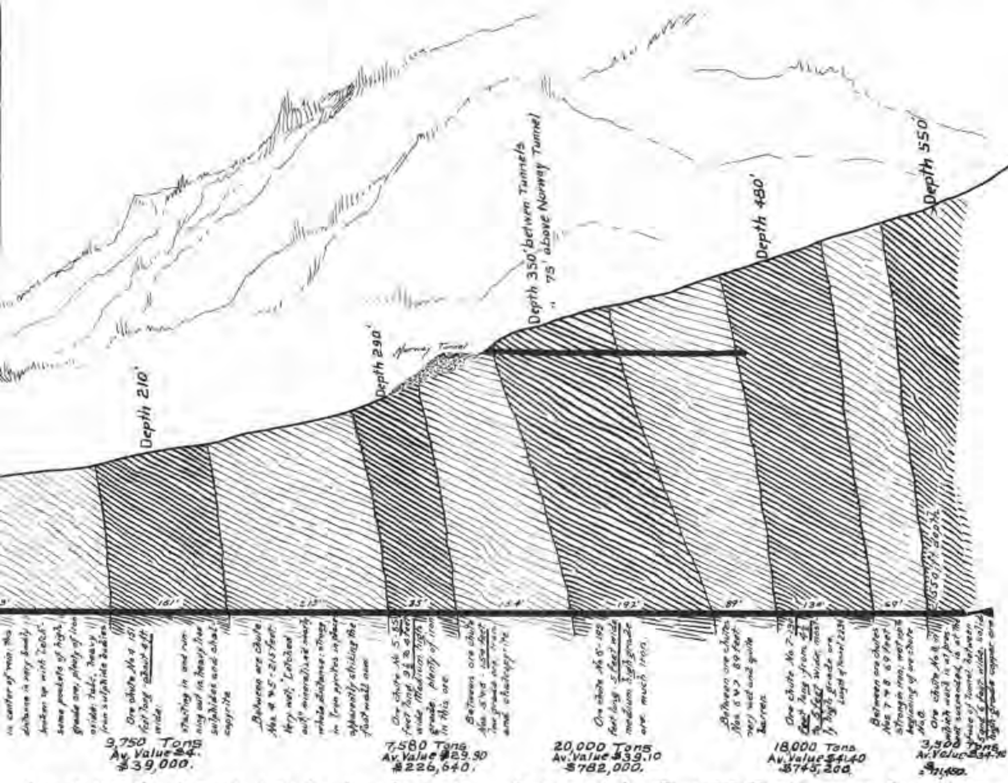
Other accounts of the same ashfall note that it was "like fine sand", its color "appeared like ashes", and the odor was "that of sulphur" (Majors, 1980).

Contemporary sketches and paintings by Paul Kane (Fig. 9) suggest the mountain was probably erupting at a point halfway down the north slope before or during 1847. The vent was apparently the Goat Rocks dome (Fig. 2), which was removed by the 1980 eruption. On the basis of these and other observations, scientists think eruptive activity may have continued intermittently until 1857.

Small eruptions were reported in 1898, 1903, and 1921, but these events were not independently confirmed, nor have their deposits been identified. Judging by the nature of the post-May 18, 1980, activity at Mount St. Helens, it is likely that these events were steam emissions, small explosions, or large rockfalls.

Mining

The first technical investigations of the geology near and at Mount St. Helens resulted from an interest in metallic minerals. Mining claims for copper, gold, and silver were staked in the St. Helens mining district north of the volcano as early as 1892. During trips to the area, hunters and fishermen had discovered sulfide minerals such as pyrite, chalcopyrite, arsenopyrite, galena, sphalerite, and other vein



Length, Width and Depth of Chutes traced according to Report by Prof. F.L. Barker July 28th 1910.

These zones of hydrothermal alteration contained vein minerals, such as the sulfides pyrite and chalcopyrite. The Sweden tunnel was about 2,200 ft long.

alteration minerals, including specular hematite, magnetite, and tourmaline. These minerals occur in a *porphyry copper deposit* associated with the Spirit Lake pluton. (See p. 19 for more information about the Spirit Lake *pluton* and the age of the mineral deposits associated with it.)

Mining fever broke out about 1900, and hundreds of claims were staked in the Spirit Lake area as prospectors sought high-grade vein deposits. About 14 tons of copper ore from the Sweden mine (Fig. 10) were hauled to a Tacoma smelter in 1905 and used to cast the bronze statue of Sacajawea for the Lewis and Clark Exposition held in Portland, Oregon, which commemorated the 100th anniversary of their expedition. The challenge of transporting this ore is suggested in a 1910 report by Professor F. L. Barker of Eugene University (now the University of Oregon):

> "The Sweden is reached by Northern Pacific Railroad to Castle Rock, Wash., thence by excellent mountain wagon road forty eight miles to Spirit Lake, then by boat across the lake two and one half miles to the landing of the Sweden...or the trip around the lake may be made by land about four miles."

Other mines in the area included the Margaret (Earl) group. Although thousands of prospect pits and more than 11,000 ft (3,355 m) of underground workings were dug, the veins proved difficult to work and contained only modest amounts of gold and silver. By 1929, most of the mines had been abandoned, although exploratory work continued sporadically until the eruption of 1980.

Geologic Studies of Mount St. Helens

> "The water of the...[North Fork] Toutle rises on the side of the cone of Mount St. Helens and is filled with a fine gray sediment which makes this fork look like a stream of milk."
> Zapffe (1912)

The first technical geologic description of the area near Mount St. Helens was published by Carl Zapffe in 1912. He provided an overview of the geology of the St. Helens mining district and brief descriptions of Mount St. Helens ("an extinct volcano") and local glacial features such as *cirques* and *striations* on rock surfaces.

In 1937, Jean Verhoogen completed the first detailed geologic study of Mount St. Helens. He compiled a history of the volcano and recognized its youth and wide variety of lava types. About that same time, botanist Donald B. Lawrence began a series of investigations here and at neighboring Mounts Adams and Hood. During his 1939 field work, he noticed anomalous tree ring patterns in areas where Mount St. Helens *tephra* deposits were particularly thick. He reasoned that "the fall of these rough abrasive particles through the tree crowns must have resulted in great mechanical injury to the needles, twigs, and branches" (Lawrence, 1938, p. 53). He further noted that the eruption must be recorded by "a series of very narrow rings starting about the year 1802 or '03" (Lawrence, 1939, p. 51). He used similar logic to estimate the time of eruption for the Floating Island lava flow. David Yamaguchi of the University of Washington later reinterpreted the timing of both events and the eruption of the Goat Rocks dome by using *cross-dating* techniques. (See p. 29 and 97.)

In 1946, Ward Carithers of the Washington Division of Mines and Geology (now the Division of Geology and Earth Resources) described two pumice deposits from Mount St. Helens in his report on the *pumice* and pumicite occurrences of Washington. This report was prepared because of commercial interest in pumice for making abrasives.

Detailed work on the eruptive history of Mount St. Helens began in the late 1950s. Dwight R. Crandell and Donal R. Mullineaux of the USGS discovered that the volcano was relatively young, perhaps only slightly more than 40,000 years old. They divided its history into four stages of activity, each of which was punctuated by intermittent eruptive periods. The volcano was apparently dormant for thousands of years between these stages. They described Mount St. Helens as the youngest and most active volcano in the Cascade Range, and although the mountain had been quiet since about 1857, they warned of the likelihood and hazards of future eruptions, on the basis of the frequency and style of past eruptions. Remarkably, the mountain erupted in 1980, only 2 years after the publication of their report (Crandell and Mullineaux, 1978). The history of the volcano (based on their work and the research of others) is described in more detail starting on page 24.

The intensive research conducted at Mount St. Helens since the 1980 eruption is summarized in "What have scientists learned from Mount St. Helens?" (p. 33) and the following section (p. 37).

GEOLOGIC HISTORY OF THE MOUNT ST. HELENS AREA

Pre-Mount St. Helens Rocks: 40 Million Years of Volcanic Activity

A generalized geologic history (Fig. 11) of the Mount St. Helens area can be interpreted as follows:

55 Ma to 43 Ma (middle Eocene time)

Basalt rocks (known as the Siletzia and Crescent *terranes*) that were originally part of the oceanic plate were wedged against and became part of the North American plate during this interval, in a process geologists call *accretion* (see p. 97 and Fig. 59).

Before the formation of the Cascades, rivers draining a granitic highland to the east and northeast flowed westward across a landscape of low relief and emptied into the sea. The rivers deposited sediments in two large marine basins, now preserved as the sedimentary rocks of the Cowlitz Formation and the Puget Group. The shoreline was near the route of Interstate Highway 5 (I-5) or slightly to the west. Throughout western Washington, *coal* deposits formed in a coastal lowland during this time. Sedimentary deposits covered the accreted oceanic basalt during the latter half of this interval. A chain of volcanoes (*volcanic arc*) was located several hundred miles (kilometers) to the east (Idaho and eastern Washington) at this time—it later migrated west.

42 Ma to about 37 Ma (late Eocene time)

The earliest Cascade Range volcanoes probably erupted in an environment like that of present day Fuego Volcano in the Pacific coastal plain of western Guatemala. Throughout most of western Washington, these volcanoes produced fairly high-silica eruptive products, including some rhyolites and much fragmental material. (See p. 96 and 106). However, west of the present location of Mount St. Helens, *shield volcanoes* erupted basaltic lavas that became interbedded with the *alluvium* of the river system. Later, *andesite* lavas were erupted, including minor amounts of fragmental volcanic debris. A small group of peaks called the Rockies, about 10 mi (16 km) northwest of Morton and almost due north of Mount St. Helens, are an erosional remnant of this volcanic system; the deposits are called the Northcraft Formation.

37 Ma to about 17 Ma (late Eocene, Oligocene, and earliest Miocene time)

At the start of this interval, a large pulse of volcanism apparently interrupted the streamflow and blocked off sediment carried from eastern sources. The new volcanic arc, slightly farther east than the Northcraft volcanoes, extended from near the Canada–United States boundary southward into California. These early Cascade Range volcanoes produced lava at a rapid rate. In southwest Washington, the Hatchet Mountain and Goble volcanic rocks were erupted during this time, as was an overlying volcanic sequence that is exposed near Spirit Lake. Some of these rocks are similar in age to the voluminous Ohanapecosh Formation volcanic rocks near Mount Rainier. Ultimately this pile of lava and volcanic debris attained a thickness of nearly 6 mi (10 km) at the present latitude of Mount St. Helens.

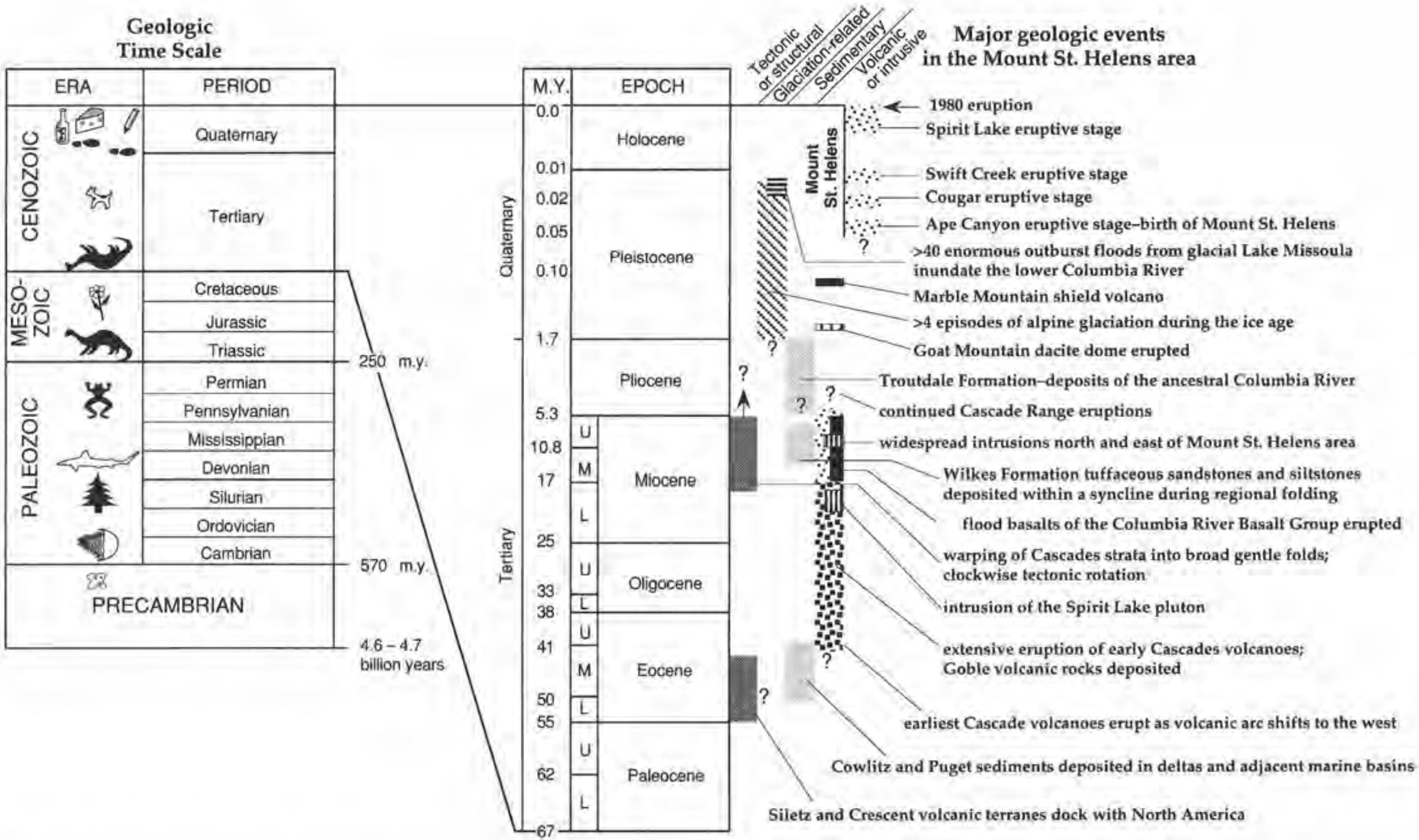


Figure 11. Simplified version of the geologic time scale (not to scale) showing major geologic events in the southwest Washington Cascades. U, upper; M, middle, L, lower; m.y., million years. The time scale is developed from those of Salvador (1985) and Aguirre and Pasini (1985). See Tables 3 and 4, p. 25 and 28, for more detailed information on the geologic history of Mount St. Helens.

Known volcanic centers in the immediate area were at or near Spud and Bismarck Mountains; other centers may have been buried or eroded away. During this time, the silica content of the lavas near Mount St. Helens gradually increased; basalt and basaltic andesite gave way to andesite and *dacite* (see Table 6, p. 94). The corresponding increase in the *viscosity* of the lava caused more explosive eruptions. Therefore, production of fragmental volcanic deposits increased and lava flows decreased. The deposits and erosional remnants of these volcanoes or their "plumbing systems" are visible throughout the area and are noted in the road guide.

The Spirit Lake pluton intruded surrounding rocks and possibly fed a volcanic system near the end of this interval. Other intrusions in the region have been dated at 22 Ma to 18 Ma. Gentle folding of the Cascades probably began after 21 Ma and before 18 Ma (Evarts and others, 1987).

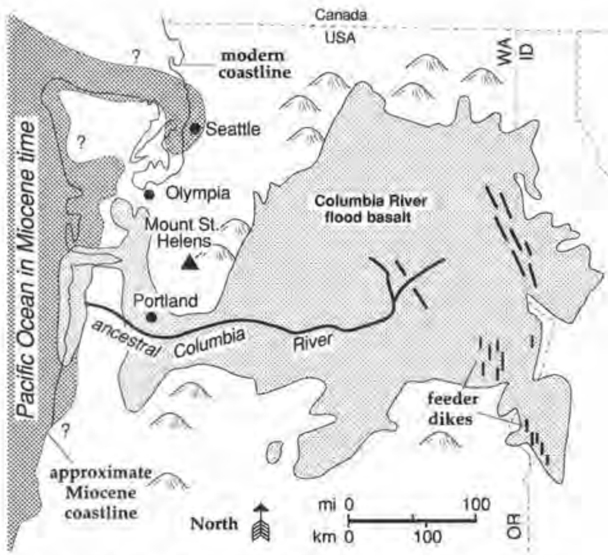


Figure 12. Miocene geography of the Pacific Northwest, showing the present location of Mount St. Helens; redrawn from Allen (1979). About 42,000 mi^3 (175,000 m^3) of lava was erupted between about 17 Ma and 6 Ma, most of it within the first several million years. During this time, more than 100 major eruptions of the Columbia River basalt inundated more than 63,000 mi^2 (163,000 km^2). Data from Tolan and others (1989).

17 Ma to about 12 Ma (middle Miocene)

During this period, volcanism apparently slowed down in the Cascades. However, because the area was being tectonically lifted, much evidence of the volcanoes of this age and their deposits has been eroded away. This prevents us from getting a representative glimpse of Cascade Range volcanic activity during this time. Miocene *intrusive* features such as *dikes* and *sills*, many of which may have fueled volcanic eruptions, are fairly common.

Between 17.5 Ma and 6 Ma, huge volumes of lava called *flood basalt* (*Columbia River Basalt Group*) erupted from feeder dikes (vents) in eastern Washington, eastern Oregon, and Idaho (Figs. 11 and 12). A few of the flows evidently traveled hundreds of miles west along part of the course of ancestral Columbia River to reach the coast over a period of several weeks or months. Because the Columbia River basalt flows were so extensive, they can be used as an indicator of the amount of uplift and folding of rocks that has occurred since then. For example, after their eruption about 16.5 Ma, rocks of the Grande Ronde Basalt in the Cascades north of Mount Adams were uplifted at least 0.6 mi (1 km) in comparison with rocks of the same basalt flow in eastern Washington. Grande Ronde Basalt, one of several formations of the Columbia River Basalt Group, is exposed in a quarry that is visible from I-5, high on the valley wall east of the Lewis River, about 0.6 mi (1 km) south of Woodland (see Leg B, p. 61).

12 Ma to about 10 Ma (late Miocene)

Numerous dikes and sills were intruded north and east of Mount St. Helens during this time. Volcanic products that correlate with the intrusions have not been identified, however. Gentle uplift and folding of the rocks continued.

5 Ma to Holocene (Pliocene through Pleistocene)

Volcanism in the Cascades picked up again at about 5 Ma. However, not much evidence for it is found near Mount St. Helens. The first eruptions in the Indian Heaven volcanic field to the southeast were produced slightly before 0.73 Ma, although some older basalt in that area has been dated at 3.7 Ma, 3.0 Ma, and 1.7 Ma. Goat Rocks volcano, 39 mi (65 km) to the northeast, was active between about 3.2 Ma and 1.0 Ma. Ages of 3.0 Ma, 1.0 Ma, and 0.74 Ma have been obtained for Goat Mountain plug dome, southwest of Mount St. Helens. Marble Mountain shield volcano was erupted sometime prior to 160 ka (see Fig. 44).

During the Pleistocene, glaciers covered much of the area near Mount St. Helens (Fig. 13). At least two and probably as many as four major episodes of alpine glaciation are recorded in the southern Washington Cascades, although the number of major glacial advances during the Pleistocene was probably more than ten. Eruptions and growth of Mount St. Helens started about 40 ka.

Huge *outburst floods* from glacial Lake Missoula repeatedly coursed down the Columbia River between 15,300 and 12,700 yr B.P. In the Portland basin near where the Trojan nuclear plant is now, these floods were hydraulically dammed and formed a temporary lake 400 ft deep. They also left slackwater deposits along the lower reaches of the Cowlitz and Lewis Rivers. More than 80 individual outburst floods have been documented east of the Cascades. Tephra deposits of Swift Creek-age (about 13,000 yr B.P.) from Mount St. Helens that are interbedded with the flood deposits in eastern Washington have helped date the flood events.

Glacial Deposits and Glaciation in the Mount St. Helens Area: Dramatic Alterations of the Landscape

During the Pleistocene, glaciers repeatedly spread over much of the Cascade Range and down onto parts of the adjoining lowlands. These alpine glaciers originated in the highlands near Mounts Rainier, Adams, and St. Helens. They evidently coalesced when these glaciers were at their maximum extent and created an ice cap over much of the crest of the Cascades. During each glacial episode, the glaciers radically modified the terrain by stripping off tens of yards or meters of rock, carving cirques and large U-shaped valleys, depositing glacial debris, and, when they melted, scouring the landscape with huge quantities of sediment-laden meltwater.

Rocks in *till* show that the alpine glaciers that predate Mount St. Helens had their source in the granitic highlands north of Spirit Lake. Abundant glacial deposits, including till, *outwash*, and *moraines*, record the glacial advances (see p. 108).

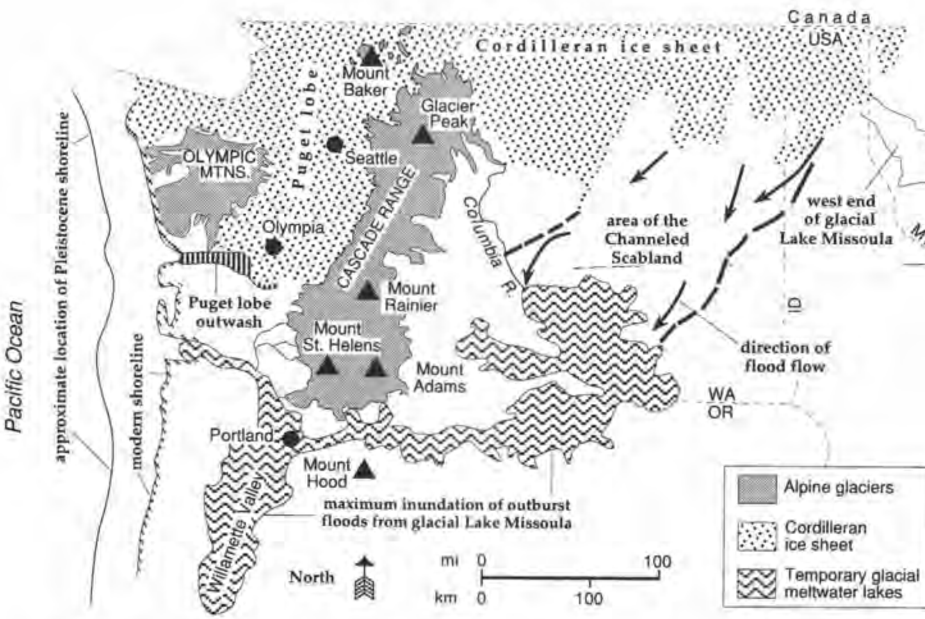


Figure 13. Diagrammatic sketch showing the approximate maximum extent of Pleistocene continental and alpine glaciers in Washington. Also shown are areas that were inundated by numerous outburst floods from glacial Lake Missoula, which filled a large valley in western Montana. The Channeled Scablands were created where these enormous floods stripped off soil and quarried and carved channels known as coulees in the underlying basalt. Ice caps and alpine glaciers not shown for the Oregon Cascades. Diagram modified from Waitt (1985) and Hammond (1989).

Hayden Creek glaciation (about 140 ka)

Much erosion can be attributed to the extensive Hayden Creek alpine glaciation. During this episode (and probably earlier ones), ice caps almost completely covered higher areas. The presence and configuration of U-shaped valleys show that these ice caps fed large *valley glaciers* that moved down the Clearwater, Smith–Muddy–Lewis, Toutle, and Green River drainages. A valley glacier of Hayden Creek age extended down the Cowlitz River for 63 mi (105 km) from Mount Rainier. The glacier in the Lewis River valley extended to within about 5 mi (8 km) of the location of I-5. This glacier dammed tributary valleys like those of Siouxon and Canyon Creeks (west and south of Yale Lake) to form meltwater lakes. Deposits in Cow, Maratta, and Hoffstadt Creeks (tributaries to North Fork Toutle River) indicate there were *proglacial* lakes in these valleys as well. Tens of feet of *varves*, or layered clays and silts, were deposited in these lakes (Fig. 14). These very fine lake sediments are generally unstable when saturated, and their location and extent greatly affects road building and other activities in the area.

Evans Creek glaciers (22,000 to 11,000 yr B.P.)

Evans Creek, the most recent alpine glaciation, was a substage of the latest major regional glaciation. It lasted from about 22,000 to 11,000 yr B.P. in the Mount St.

Helens area. During this period, icecaps were limited. A valley glacier from an icecap at Mount Rainier extended down the Cowlitz River 38 mi (64 km) and valley glaciers from near Mount St. Helens extended west for about 19 mi (31 km) down the North Fork Toutle valley and about 10 mi (16 km) to the south (Crandell, 1987).

The floors of *cirques*, small bowl-shaped glacial valleys, carved during Evans Creek time are found as low as 2,700 ft (824 m) elevation near Mount St. Helens. Some of the cirques are now occupied by lakes known as *tarns*; St. Helens, Grizzly, Venus, Shovel, Fawn, and Meta Lakes are good examples (see Fig. 64).

Figure 14. Annual layers of accumulated sediment (varves) deposited about 140 ka in a glacial lake of Hayden Creek age in Canyon Creek valley south of Mount St. Helens.

Neoglacial Advances

Two minor advances of the glaciers have been recorded within the last 10,000 years; we call these the neoglacial advances. The first of these episodes peaked between 2,800 and 2,600 yr B.P. The second episode, often called the "Little Ice Age", has been documented both by historic accounts and by tree-ring analysis of trees growing on, or adjacent to, moraines. The Little Ice Age lasted from about A.D. 1250 until the mid-1800s and reached a peak in the 15th and 16th centuries. Judging by moraines left by these advances, the glaciers at Mount St. Helens were larger and somewhat longer than they were before the mountain erupted in 1980. Neoglacial ice extended nearly a kilometer farther down the mountain. Even these more robust glaciers of the neoglacial advances, however, were puny versions of the huge and extensive Pleistocene glaciers.

The May 18, 1980, eruption removed all of Loowit and Leschi Glaciers and parts of Shoestring, Forsyth, Wishbone, Ape, Toutle, Swift, and Nelson Glaciers—in all, more than 70 percent of the pre-eruption ice volume (Fig. 15). Erosion and melting by the blast and later *pyroclastic flows* (both of which were hot, turbulent mixtures of gas and rocks) stripped much of the ice and snow pack from the mountain in the early moments of the eruption. Only two unnamed glaciers on the south side suffered no net volume loss during the eruption.

The Shoestring and Forsyth Glaciers lost about 75 and 90 percent of their volumes respectively when their zones of snow accumulation were removed by the eruption. Post-eruption changes in the Shoestring Glacier have been carefully documented to see how rapidly and how much the glacier has shrunk because of this loss. (See "The Shoestring Glacier Story", p. 70.)

The presence of *crevasses* and flow features in a snow-and-rock field now growing against the south crater wall indicates that a new glacier is forming inside

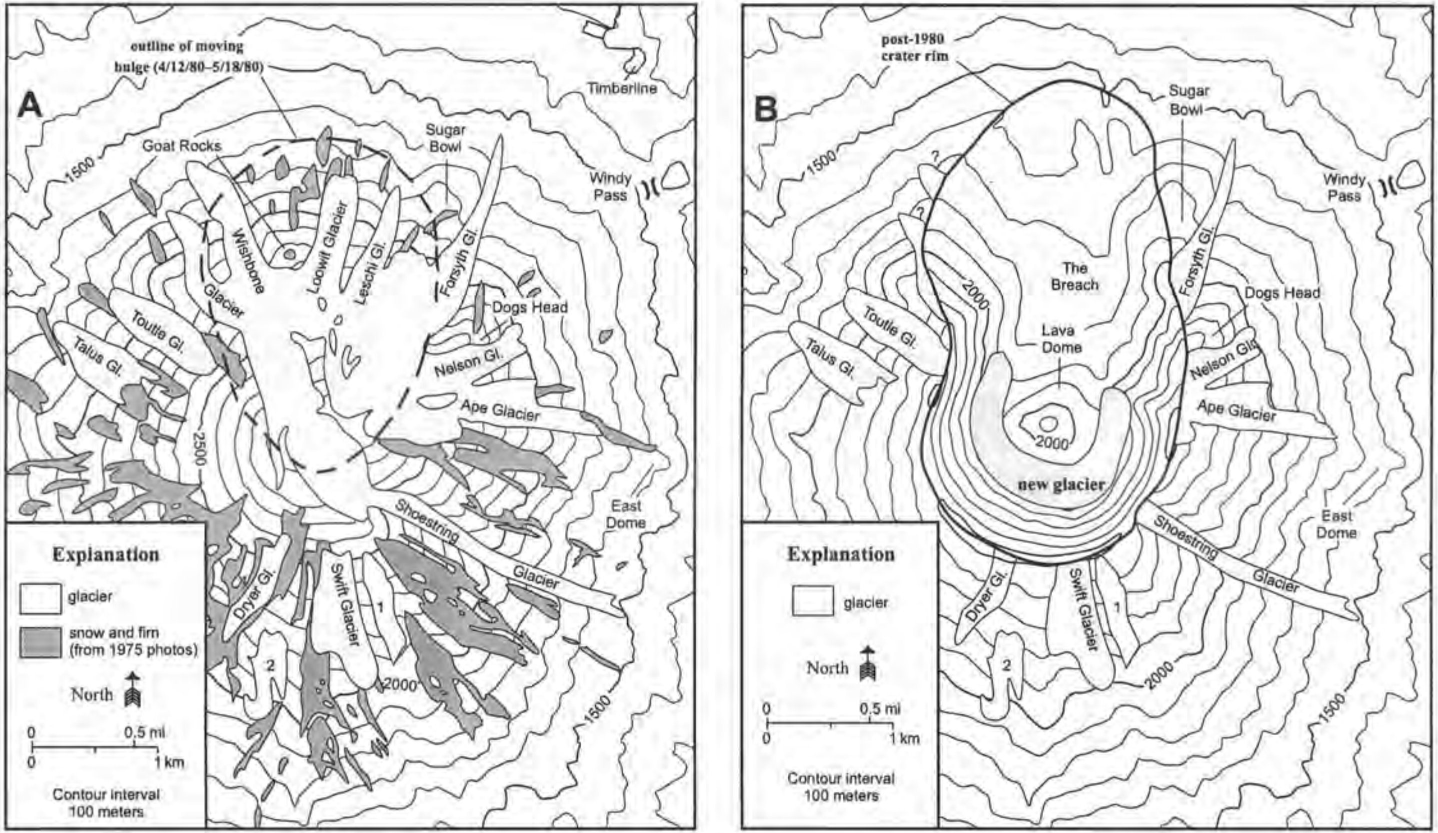


Figure 15. Glaciers of Mount St. Helens before and after the May 18, 1980, eruption. In **A**, the dashed line shows the outline of the bulge that developed on the volcano's north flank prior to the eruption. In **B**, the heavy solid line outlines the post-May 18 crater. The eruption removed more than 70 percent of the snow and ice volume from the volcano. A new glacier has grown between the south crater wall and the dome (see Update, p. 123. Unnamed glaciers are numbered 1 and 2. Redrawn from Brugman and Post (1981).

the crater. This glacier probably contains a large amount of rock debris because rock constantly falls from the crater wall and the Lava Dome (Fig. 16).

Lavas, Deposits, and Geologic History of Mount St. Helens: A Youthful Volcano with a Tumultuous Disposition

Mount St. Helens has erupted intermittently for at least the last 40,000 years. Four major stages of activity during that time have been outlined by USGS geologist Dwight Crandell (1987). Dormant intervals (periods during which little or no tephra was produced) separated the eruptive stages (Table 3). Eruptive periods lasting a few years to possibly centuries make up each eruptive stage, although only those eruptive periods that have occurred within the most recent (Spirit Lake) eruptive stage are named. The timing of the eruptive events has been established by a thorough study of the tephra and *lahar* deposits around the volcano.

Different tephra layers are identified by the *heavy-mineral* content of pumice fragments and are distinguished in the field by these heavy minerals which include crystals of *pyroxene, amphibole,* and *biotite*. Because tephra layers represent events that lasted very short times and are widespread, they provide excellent stratigraphic markers and have been used to establish relative ages for events far removed from the volcano. Layers produced since A.D. 1480 have been more precisely dated by tree-ring methods.

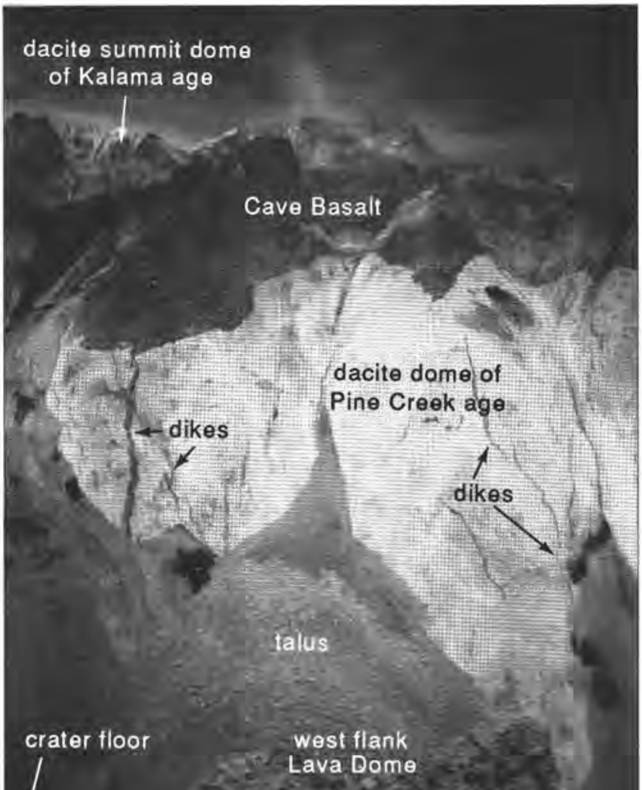


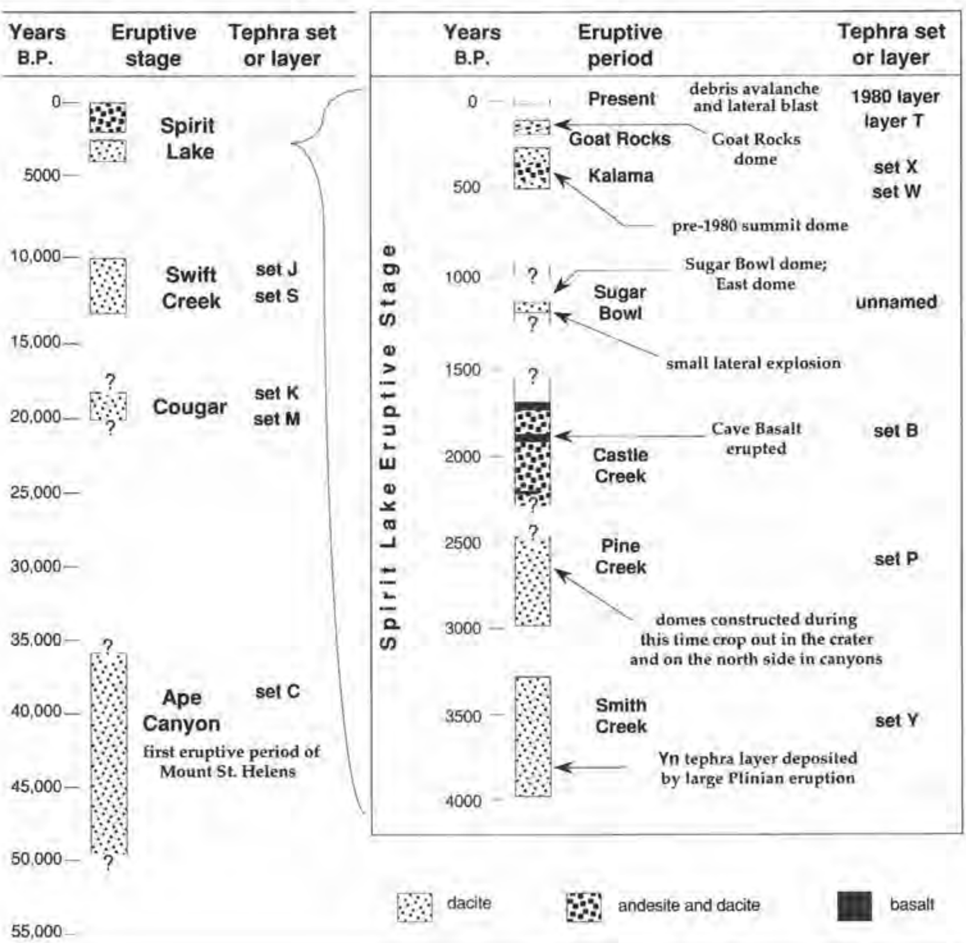
Figure 16. Wide-angle photo of the west crater wall taken from the west top of the Lava Dome. Note the dikes that intruded a dome of Pine Creek age exposed in the crater wall. The distance from the crater floor to the crater rim is about 2,000 ft (600 m).

Ape Canyon Eruptive Stage (about 50 ka to 36,000 yr B.P.)

The deposits of this stage provide the first confirmed record of modern Mount St. Helens. These early deposits indicate that Mount St. Helens began its history with an explosive fury similar to, but even larger than, that shown in recent centuries. Products included large volumes of *pumice*-rich dacite fallout tephra (known as tephra set C), as well as pyroclastic flows and lahars.

USGS geologist Donal Mullineaux has found six distinct tephra layers from this stage and has observed that the presence of biotite crystals (*phenocrysts*) in clasts of the Ape Canyon stage is unique among the Mount St. Helens tephra deposits. Poorly developed soil layers between individual tephra units suggest that the Ape Canyon eruptive stage could have consisted of as many as four distinct eruptive episodes and that these episodes were spread over a period of perhaps 5,000 years. One study, which used a method called *thermoluminescence dating*, suggests that one of the set C tephra layers may be as old as 50 ka (Berger and

Table 3. Eruptive history of Mount St. Helens. Left columns show eruptive stages and dormant intervals; right columns show the eruptive periods and dormant intervals of the Spirit Lake eruptive stage. Only major tephra units are shown. Ash from possible earlier eruptions (100 ka–50 ka) has recently been discovered in eastern Washington (Busacca and others, 1992). Data in table from Mullineaux (1986) and Crandell (1987); redrawn from Hopson and Melson (1990)



Busacca, 1991). Researchers have found two still older tephra layers that are chemically similar to C tephra and thus may record even earlier eruptions from Mount St. Helens between 100 ka and 50 ka (Busacca and others, 1992). The Ape Canyon eruptive stage probably ended by about 36,000 yr B.P. It was followed by a lengthy dormant interval of at least 15,000 years.

Cougar Eruptive Stage (about 20,000 to 18,000 yr B.P.)

This eruptive stage began about 20,000 yr B.P. and continued for about 2,000 years. Identified deposits include a sequence of lahars, a debris avalanche south of the volcano, pyroclastic flows, and dacite tephras (sets M and K). (See Stop B-1, p. 63.) The lahars and pyroclastic flows are found mostly on the southeast, south, and west sides of the mountain. The only andesite lava flow of this stage is on the southeast flank. (Legs B and G of the road guide take you to these deposits.)

Erupted material filled the Lewis River valley with more than 375 ft (115 m) of debris. Some of this debris undoubtedly extended the length of the Lewis River to the Columbia, although much of it has been covered by later deposits. One of the lahar deposits contains abundant rounded cobbles and pebbles and large chunks of what appears to be a debris-avalanche deposit similar to that produced by the May 1980 eruption. This lahar might have been generated by the breakout of an ancient lake dammed by a debris-avalanche deposit of this age.

A lack of volcanic deposits from Mount St. Helens between about 18,000 and 13,000 yr B.P. suggests that the mountain was dormant during this interval.

Swift Creek Eruptive Stage (13,000 to 10,000 yr B.P.)

This eruptive stage was characterized by the eruption of large volumes of tephra (sets S and J) and pumiceous pyroclastic flows. After the eruption of tephra set S, numerous *lithic pyroclastic flows* were produced. These probably originated at a summit lava dome or domes. Thick sequences of lahars filled the valleys of Pine Creek, Swift Creek, the lower Lewis River, and the South Fork Toutle River. The summit of the volcano was probably flanked by thick fans of fragmental debris on the west, south, and east sides.

A dormant interval of more than 5,000 years preceded the beginning of the Spirit Lake eruptive stage.

Spirit Lake Eruptive Stage (3,900 yr B.P. to present)

This stage consists of seven eruptive periods that include the most recent eruption and all other eruptive activity of the past 3,900 *radiocarbon* years (4,500 calendar years). These periods, in decreasing order of age, are the Smith Creek, Pine Creek, Castle Creek, Sugar Bowl, Kalama, Goat Rocks, and modern eruptive periods. The first two periods are characterized by volcanic activity similar to that of the earlier Ape Canyon, Cougar, and Swift Creek eruptive stages mentioned in the preceding paragraphs. However, the third period, the Castle Creek eruptive period, marked a change in the eruptive style of Mount St. Helens. In this period, more viscous silicic lavas, such as dacite, alternate with more *mafic* lavas including basalt and andesite. Details of the modern eruptive period are covered in a separate section (p. 29).

Smith Creek Eruptive Period (3,900 to about 3,300 yr B.P.) About 3,900 yr B.P., explosive eruptions of the Smith Creek eruptive period ended the more-than-5,000-year hiatus in volcanic activity at Mount St. Helens. Later, shortly after 3,510 yr B.P., a massive eruption produced a widespread layer of tephra known as the Yn tephra. The volume of this tephra suggests that this is the largest eruption yet discovered from Mount St. Helens. The Yn eruption produced about 1 mi^3 (4 km^3) (solid rock equivalent) of pumice, ash, and rock, more than 13 times the amount produced in 1980 (Carey and others, 1989). The area covered by this deposit stretches nearly 540 mi (900 km) north-northeast into Canada. Geologists who have reconstructed the eruption based on its magnitude, chemistry, and the extent of its deposits have concluded that it must have been very similar to the tremendous eruption at Mount Vesuvius in Italy in A.D. 79. That famous eruption buried the towns of Pompeii and Herculaneum. The descriptions of its vertical column of ash by the Roman historian Pliny led to the term *Plinian column*. The May 18, 1980, eruption also produced a Plinian column (see Fig. 3).

At least four additional major tephra layers were produced during the Smith Creek eruptive period. The presence of lithic pyroclastic flows suggests that lava domes were being formed during this time as well. Almost all the Y tephras (as tephras from this period are known) can be distinguished from other Quaternary tephras from Cascade Range volcanoes by the presence of crystals of an amphibole mineral called cummingtonite.

Pyroclastic flows and lahars of the Smith Creek eruptive period traveled mainly down the east and north sides of the volcano. Deposits of Smith Creek lahars have been found as far as 30 mi (50 km) down the Toutle River. An ancestral Spirit Lake may have been born at this time when a debris avalanche or erupted material dammed the upper North Fork Toutle River.

Pine Creek Eruptive Period (about 2,900 to 2,500 yr B.P.) Intermittent eruptions occurred during this interval. A thick fan composed of lithic pyroclastic flows was constructed on the southeast side of the mountain. Some of these flows may have been produced by the domes whose remnants can now be seen in the crater walls exposed by the 1980 eruption. (See Fig. 16.) Tephra set P was produced during this time, but it does not have great volume or extent.

Silver Lake was formed about 2,500 yr B.P. when Outlet Creek was dammed by a series of enormous lahars generated by repeated breakouts of lakes upstream in the Toutle River drainage (Scott, 1988). Recently, geologists have discovered deposits of two ancient debris avalanches in the canyons of Step and Loowit creeks, which drain the crater of Mount St. Helens (Hausback and Swanson, 1990). These ancient debris avalanches may have created the dams that were breached.

Recognition of these enormous ancient lake-breakout lahars alerted scientists to the possibility of similar events being generated by an outburst flood from Spirit Lake. This concern led to the construction of facilities that could drain the lake—first a pipeline in 1982 and, later, the tunnel that presently drains lake water to South Coldwater Creek and the North Fork Toutle River.

Castle Creek Eruptive Period (about 2,200 to 1,600 yr B.P.) After an approximately 300-year dormant interval, the Castle Creek eruptive period began. This period marks a major change in the eruptive activity at Mount St. Helens. The volcano's lava composition began to alternate between higher and lower proportions of silica. Basalt, andesite, and dacite were produced during this period. The Cave Basalt, which formed Ape Cave, was produced about 1,900 yr B.P., as was the

Table 4. Mount St. Helens eruptive products of the past 500 years. PFs, pyroclastic flows. Precise ages for the events have been derived by tree-ring studies (Yamaguchi, 1983; Yamaguchi and others, 1990; Yamaguchi and Lawrence, 1993)

Eruptive period	Tephra	Volume (km^3)	Type of activity	Date	Silica (%)
1980 to ?	...	...	dome; PFs	1980 to 1986	61-63
	18 May	0.34	blast, PFs	1980	64-62
			— dormant for 123 years —		
Goat Rocks	...	...	Goat Rocks dome; PFs	1842 to 1857	63
	...	0.1	Floating Island lava flow	1800	60
	T	0.5	explosive eruption	1800	64
			— dormant for several decades —		
Kalama	...	...	dome; PFs	mid-1600s to late 1700s	61-64
	...	...	lava (Worm Flows); PFs	≈1505 to mid 1500s	57-58
	...	...	minor tephra	pre-1505	58
	X	...	explosive andesitic eruption	≈1500	58
	...	...	PFs; dome	1490s	65
	We	0.4	explosive dacitic eruption	1482	67
	Wn	2	explosive dacitic eruption	1480	68-65

basalt of Lava Canyon. The Dogs Head dacite dome (northwest flank of the mountain) was probably erupted during this time.

Geologists are not sure why Mount St. Helens began these unusual fluctuations in the composition of its lavas. The fluctuations may reflect the progressive tapping of deeper and deeper parts of a *stratified magma chamber*. The magma chamber may have developed this layering over many thousands of years as denser *mafic* lavas accumulated at the bottom of the chamber and *magma* containing more silica migrated to the top. By the end of the Castle Creek eruptive period, the volcano had become nearly as high as it was before the 1980 eruption.

Sugar Bowl Eruptive Period (age range uncertain) Events of this period produced the Sugar Bowl dome and possibly East Dome. Lahars, pyroclastic flows, and a small, northwest-directed lateral explosion were produced as well. The explosion deposit extends about 18 mi (30 km) from the volcano, but the maximum width of the deposit is only about 7 mi (12 km). A ^{14}C age estimated for the explosion is 1,150 yr B.P. No dates are available to bracket the beginning and end of the Sugar Bowl eruptive period, however.

Kalama Eruptive Period (A.D. 1480 to late 1700s) Tree-ring dating has clarified the timing of the Kalama eruptive events (Yamaguchi and others, 1990). (See also

p. 97.) The eruption in 1480, which produced the Wn tephra, began the Kalama eruptive period. The Wn layer has about six times the volume of the tephra produced in 1980 (Table 4). Even the smaller We tephra eruption of 1482 was about 20 percent larger than the 1980 eruption. These eruptions were followed by pyroclastic flows and formation of a lava dome during the 1490s and, in about 1500, by an explosive andesitic eruption that produced the X tephra.

Minor amounts of andesite tephra were deposited after the X tephra, and andesite lava and pyroclastic flows during the early to mid 1500s produced the sinuous Worm Flows on the south and southeast flanks of the cone (Fig 3). From the mid 1600s to late 1700s, the silica content of lavas increased while construction of the volcano's summit dome produced dacite pyroclastic flows. The volcano was dormant for only a few decades before the Goat Rocks eruptive period.

Goat Rocks Eruptive Period (A.D. 1800 to 1857) The Goat Rocks eruptive period commenced in 1800 with the eruption of the T tephra. Recent tree-ring studies indicate that the Floating Island lava flow (a high-silica andesite flow, now mantled by 1980 eruptive products) was extruded within a few months of this tephra eruption. Silica content of the magma increased again from 1842 to about 1857, while the Goat Rocks dacite dome was constructed. (See Fig. 9.) A dormant period of 123 years then preceded the most recent eruptive sequence.

Modern Eruptive Period (A.D. 1980 to ?) Geologists have noted that, as in the Kalama and Goat Rocks eruptive periods, the post-May 1980 eruptive products show a decrease in silica content and followed by an increase. They suggest that the 1980–1986 activity resembles the pattern of the Goat Rocks eruption and speculate that, if it follows the Goat Rocks cycle, we will have continued intermittent lava extrusion, possibly over the next 30 years or so (until early in the next century), and then a dormant period before yet another explosive eruption. Considering the explosive eruptions that have occurred at Mount St. Helens over the past 500 years, Crandell estimated a 10 percent probability per decade of similar eruptions in the future.

THE MODERN ERUPTIVE PERIOD, 1980–PRESENT

Pre-May 18 Warning Signs

The earthquakes that signaled movement of molten magma under the volcano (and a possible eruption) began on March 20, 1980, and on March 27, a phreatic eruption created a small summit crater. Although earthquakes, swelling, and disruption of the mountain and its glaciers continued, the phreatic activity occurred only intermittently over the next 7 weeks. Repeated surveys, initiated in mid April and continued during the next few weeks, showed that a large bulge had formed on the north flank of the mountain in response to the intrusion of magma. The bulge moved outward at an average rate of about 5 ft (1.5 m) per day—until May 18, when Mount St. Helens became the first Cascade Range volcano to erupt *juvenile material* since Mount Lassen's 1914 to 1921 activity.

The Catastrophic Eruption of May 18, 1980

On May 18, at 08:32 PDT, the catastrophic eruption began, apparently triggered by a *magnitude* 5.1 earthquake. The bulge collapsed in a series of three huge slide blocks (Figs. 17 and 18). This debris avalanche, the largest landslide in recorded

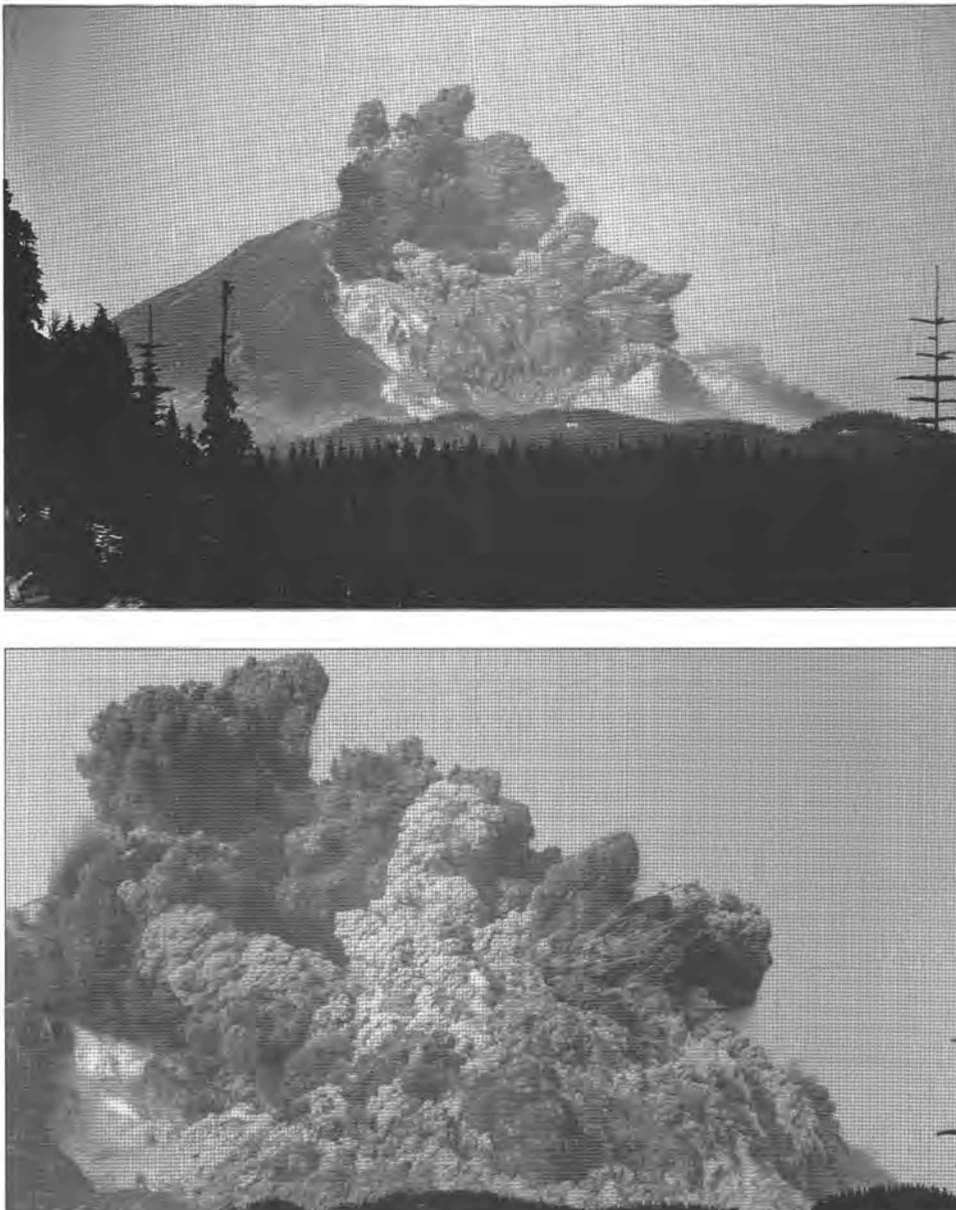


Figure 17. Initial moments of the May 18, 1980, eruption, as seen from Bear Meadow, 7 mi (11 km) northeast of the mountain. The top photo, taken about 14 seconds after the start of the eruption, shows the high-velocity cloud of the blast penetrating the second slide block of the debris avalanche and overtaking the first slide block. (Compare this photo with C in Fig. 18.) The bottom photo, taken with a telephoto lens about 7 seconds later, shows the expanding blast cloud continuing to blow through and engulf the debris avalanche as the crater expands. Note the projectiles indicated by the streaks near the right edge of the cloud. (Compare this photo with D in Fig. 18.) Photos by Keith Ronnholm, Remote Measurement Systems, Inc.

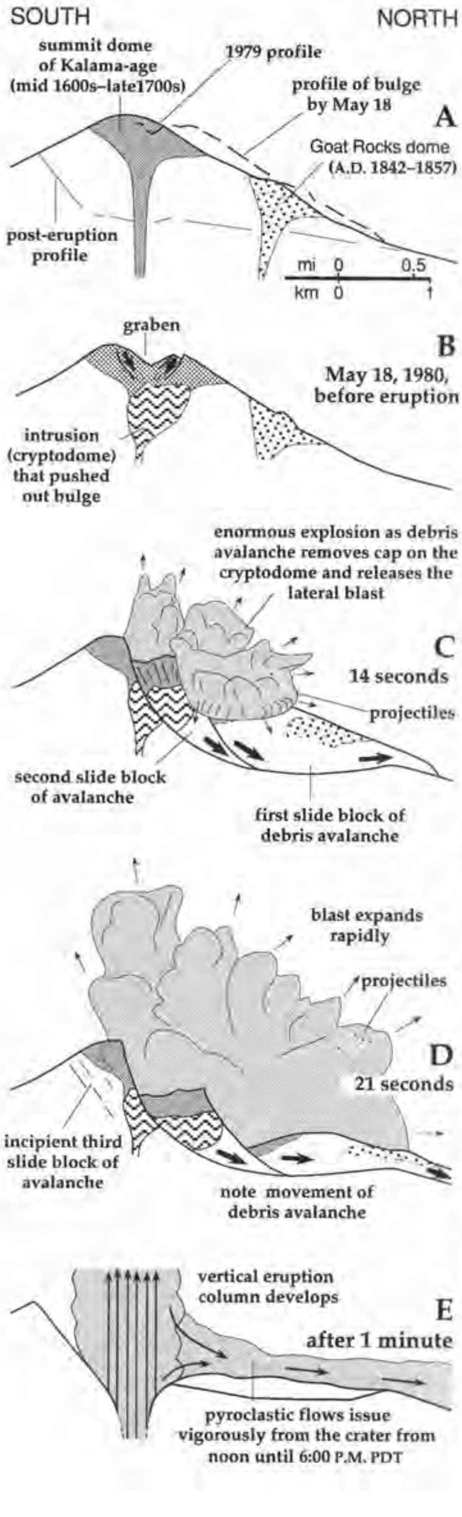


Figure 18. Diagram showing the intrusion of new magma into Mount St. Helens. The intrusion led to the formation of the bulge and disruption of the north flank of the mountain prior to the cataclysmic eruption of May 18. The failure of the individual slide blocks is discussed in the text. **A**, the configuration of the mountain before the 1980 eruptive events compared with the profile of the bulge on May 18; **B**, the volcano on May 18 just before the eruption; **C**, **D**, and **E** show the movement of the debris avalanche and the onset of the blast and vertical eruption column within the first minute after the collapse as confining pressure on the cryptodome is released. Compare C and D with Figure 17. Redrawn from Lipman and Mullineaux (1981).

history (0.6 mi^3 or 2.5 km^3 of material), traveled northward through Spirit Lake and swept over the top of Johnston Ridge (1,150 ft or 350 m high) into the Coldwater Creek drainage. (See p. 102 for more information about debris avalanches and other mass movement.) It also raced from the volcano westward 15 mi (25 km) down the North Fork Toutle River, reaching speeds greater than 60 mi/hr (27 m/s). Keith and Dorothy Stoffel, two geologists who saw the avalanche from an airplane, described it as "rippling and churning". The sudden removal of this immense volume of material from the mountain instantly reduced the pressure holding back the *hydrothermal* and magmatic system and released the laterally directed blast. This blast, a *pyroclastic density current* composed of large rocks, smaller particles, and gas, moved out across the landscape at more than 650 mi/hr (300 m/s), stripping off the soil layer in areas close to the volcano and leveling most vegetation within 12 mi (18 km) in a 180° arc north of the volcano. About 230 mi^2 or 600 km^2 were severely damaged by the blast. (See

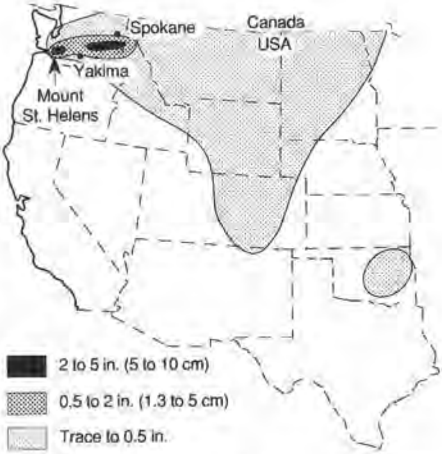


Figure 19. Extent of noticeable ash fallout from the May 18, 1980, tephra plume. Minor concentrations of ash from the same eruption traveled around the world in the stratosphere (above 36,000 ft or 11 km).

p. 105 for more information about pyroclastic density currents.)

Major lahars, started mainly where snow and ice were melted by the blast, traveled down the South Fork Toutle and Muddy Rivers, carrying boulders, logs, trucks, and even bridges with them. Smaller lahars flowed down channels on all sides of the mountain, some traveling only a few kilometers beyond its base. (See p. 107 for more information on lahars.)

The water-saturated debris-avalanche deposit in the North Fork Toutle River valley began to lose water almost immediately after it stopped moving. This water, together with the silt and clay it carried, gave birth to the largest and most destructive lahar of May 18 later in the day. Flowing at velocities of up to 27 mi/hr (12 m/s), this lahar reached the Columbia River just after midnight. There it dropped more than 45 million yd^3 (35 million m^3) of sediment, reducing the average channel depth from 39 ft (12 m) to about 12 ft (3.5 m). This plug of sediment blocked the shipping channel to ocean-going vessels for 13 days and disrupted shipping traffic for 3 months, costing ports millions of dollars. (See Fig. 4 for a map of the devastation caused by this eruption.)

An eruption of ash rose to more than 12 mi (20 km) within 10 minutes of the explosion and formed an enormous mushroom cloud 45 mi (75 km) across. Later, an eruption column jetted vertically for more than 9 hours. Fallout from the eruption, including particles ranging in size from boulders to ash (sand-sized), exceeded 0.2 mi^3 (1 km^3) and spread across Washington and Idaho and into Montana (Fig. 19). The ash disrupted human activities, especially transportation, and damaged civil works such as sewage- and water-treatment facilities. Within 2 weeks, airborne ash had drifted around the globe.

Starting about noon, pyroclastic flows accompanied the vertical column of ash. Some of the larger pyroclastic flows formed when material "boiled over" the rim of the crater; others were formed by the gravitational collapse of material from the vertical eruption column. The flows left a thick accumulation of ash, pumice, and rocks on the debris avalanche-deposit north of the volcano. These flow deposits are made up of numerous overlapping ash sheets and lobes of pumice. The Pumice Plain, north of Mount St. Helens, is composed of these deposits, which in some places are as much as 100 ft (30 m) thick. (See p. 105 for a discussion of pyroclastic density currents and pyroclastic flows.)

Fifty-seven people died as a result of the eruption, most from ash asphyxiation. The debris avalanche filled the upper North Fork Toutle River valley to depths of more than 600 ft (180 m) locally. More than 200 mi (320 km) of roads, 15 mi (24 km) of railways, at least 43 bridges (many of them wooden logging-road bridges), and about 200 homes were destroyed or severely damaged. Mount St. Helens was reduced in volume by about 0.6 mi^3 (2.5 km^3), a volume that would fill a football field to a height of more than 600 mi (960 km). The mountain lost more than 1,300 ft (396 m) off its summit.

Post-May 18 Volcanic Events

Five smaller explosive eruptions occurred later during 1980, each accompanied by pyroclastic flows and tephra. Small dacite lava domes, mounds of blocky gray lava, grew during and after three of these episodes and were blown apart by the July 22, August 7, and October 16, 1980, eruptions. From December 1980 until October 1986, 17 episodes of dome growth constructed the composite Lava Dome to a current height of 876 ft or 267 m (Fig. 6 and cover photo). The domes grew by a combination of inflation, as the lava pushed into the dome from below, and deposition of new lava as lava lobes protruded out onto the surface of the dome.

Minor explosions accompanied several of these episodes, and lahars that flowed at least 10 mi (15 km) from the crater were generated on two occasions (March 19, 1982, and May 14, 1984). Other, very minor explosions have occurred independent of eruptive activity, some with no warning. Some of these events occurred soon after storms, indicating that they are probably caused by geyser-like explosions resulting when water percolates down into the dome and contacts hot rock. The most recent dome-growth event (October 1986) increased the volume of the dome to 96 million yd^3 (74 million m^3), more than 40 times the volume of the Seattle Kingdome indoor stadium. Although this figure seems impressive, it amounts to only about 3 percent of what the mountain lost in the May 18 eruption.

WHAT HAVE SCIENTISTS LEARNED FROM MOUNT ST. HELENS?

Mount St. Helens is now the world's most closely studied *composite volcano*. As a result, our understanding of volcanic processes and deposits has greatly improved, as has public interest in volcanoes and volcanology. Volcano-monitoring techniques have been refined to the point that we can now confidently predict major eruptive events at Mount St. Helens. This has led to the application of similar monitoring techniques at other volcanoes around the world.

Volcano Monitoring: Listening for Signs of Restlessness

What is volcano monitoring? Just as an increased pulse rate or sudden change in weight are clues to our own health, so changes in a volcano's physical condition can presage a change in its eruptive status in the near future. In the early 1980s, monitoring efforts at the U.S. Geological Survey's Cascades Volcano Observatory in Vancouver, Wash., focused on earthquakes and on measuring movement along *thrust faults* and radial cracks in the crater floor with a carpenter's steel tape (Fig. 20). Increasing displacement rates on cracks and thrust faults indicated rising, swelling magma, and analysis of the rate of these changes allowed scientists to predict dome-building onsets (Swanson and others, 1983).

Monitoring the Lava Dome with surveying equipment such as electronic distance-measuring devices and theodolites began in 1981 and made possible more reliable prediction of eruptions. Geologists observed that rates of movement on dome features systematically increased before the extrusion of lava, reaching rates as high as 174 ft/day (53 m/day) or more than 0.5 in./s (1.3 cm/s)! When the

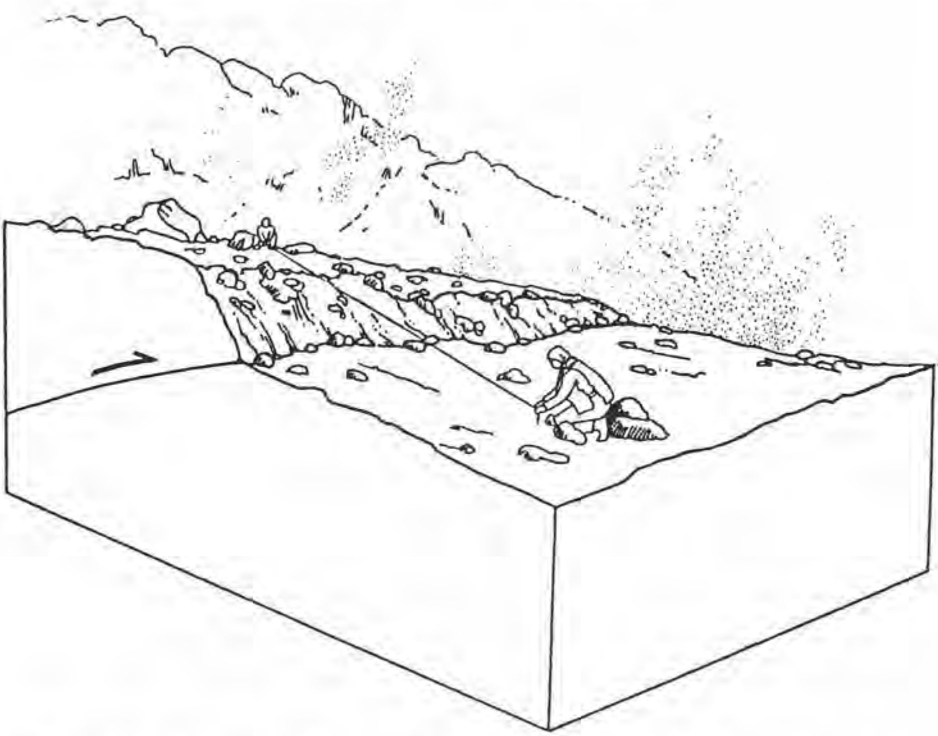


Figure 20. Measuring thrust fault motion on the crater floor adjacent to the lava dome. During 1980–1982, thrust faults were closely monitored on the crater floor. The upper block material (hanging wall, on the left part of diagram) is pushed over the lower block (foot wall) in response to magma intrusion into the dome. By measuring the distance between reference points on the blocks with a steel tape, the slope distance can be determined, and a rate of fault motion can be calculated from changes in that distance. An eruption is commonly preceded by accelerated shortening of the slope distance. Sketch by Bobbie Meyers, U.S. Geological Survey.

swelling rates increased beyond a given threshold, a "window" of time was predicted during which the eruption could be expected (Fig. 21).

Strainmeters and electronic tiltmeters placed on the Lava Dome now send data on dome growth to the Cascades Volcano Observatory and the University of Washington via radio telemetry. These instruments can take measurements continuously or at regular intervals even during bad weather and (or) at night and supplement field surveys by geologists.

The combined use of these prediction techniques was effective in all but one instance during the 1980–1986 dome-growth episodes. Only the explosion that occurred in May 1984 (and was followed by lava extrusion) was not predicted.

Thanks to a new computer-assisted monitoring system devised at the Cascades Volcano Observatory, most data can now be plotted automatically against other available monitoring information on a common time base (Fig. 21). For example, volcanic gas discharge, earthquake energy, surveyed deformation measurements, tilt, and ground temperature changes can be plotted simultaneously. Changes in seismic activity and atmospheric conditions, as well as instrument difficulties, can leave distinct patterns in the data record. This system has been useful in predicting the three latest dome-building episodes at Mount St. Helens, and it was successfully used during recent eruptions at Mount Spurr and Redoubt volcanoes in Alaska and at Mount Pinatubo in the Philippines.

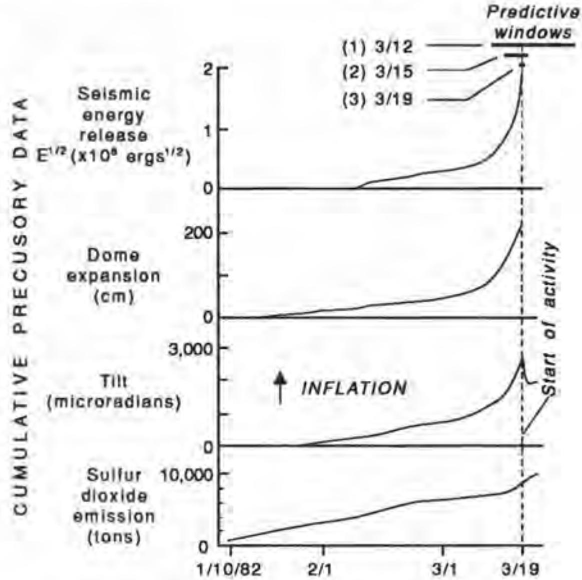


Figure 21. Increases in rates of precursory activity with time for the eruptive episode of March 19, 1982. Measurements showed simultaneous increases in several kinds of activity in the weeks preceding March 19. By relating the timing and rates of increase, scientists were able to predict the start of the eruption within smaller and smaller time intervals (predictive windows 1, 2, and 3). A predictive window is a period during which an eruptive event is thought to be most likely to occur.

Seismic monitoring remains the most effective tool for predicting volcanic activity. Seismologists at the University of Washington have made substantial progress in interpreting the wide variety of earthquakes that have occurred at Mount St. Helens. They have classified these earthquake characteristics in order to determine the type of volcanic activity and its location. This experience has helped scientists discriminate the recorded signals of and locate events such as debris flows at Mount St. Helens, as well as at Mounts Rainier, Adams, and Hood.

Volcanic Hazards Analysis: Forecasting and Planning for Future Activity

Volcanic hazards are destructive volcanic processes that have a high probability of occurring. (See also p. 106.) Risk, the magnitude of the potential loss, involves not only the geologic hazard, but also people, property, and livestock and their vulnerability to the hazard. As the population increases near a volcano, there is more at risk for a given hazard. Geologists, therefore, study natural hazards like earthquakes and volcanoes to define the nature, extent, and frequency of past volcanic processes so that risks can be minimized. It is almost always cheaper to plan for and (or) avoid disasters than it is to suffer them and rebuild afterward.

The main technique for evaluating hazards at a volcano is to study the history of its deposits, paying close attention to the frequency and nature of past eruptions and the extent of the resulting deposits. Eyewitness observations of Mount St. Helens eruptions and prompt investigation of the deposits have provided scientists with new insights about volcanic processes. As a result, geologists have developed new criteria for recognizing the deposits of debris avalanches and pyroclastic density currents, enabling them to reinterpret deposits at other volcanoes around the world. Hummocky deposits similar to those of the Mount St. Helens debris avalanche have been identified at Mount Shasta and at numerous volcanoes worldwide. Geologists now realize that this type of gigantic avalanche occurs more frequently than previously recognized and that events thought to be unprecedented in the geologic record, like the enormous 1980 blast at Mount St. Helens, have occurred before and must be considered in a volcanic hazards study.

Investigations at Mount St. Helens have also led to advances in understanding lahars and lahar-related flows and their deposits. On one occasion, geologists were able to witness a lahar generated by an explosion on the dome, sample the flow at a downstream locality as it passed, observe the lahar's impact on the stream channel during the event, and then study the deposits of the lahar as they became exposed by stream action over the next year. During this and other events, they observed the distinctive features and progressive textural changes of lahar and lahar-related deposits that could help them determine how a particular deposit had formed. This information has resulted in an improved classification scheme for lahar deposits. For example, the recognition of sandy *lahar-runout* deposits not previously correlated with lahars has resulted in more accurate reconstructions of the behavior, volume, stage height, and extent of these ancient sediment flows. The sedimentary characteristics of lahar deposits have important implications for the design of structures and civil works in river valleys surrounding volcanoes.

Secondary Effects of Eruptions

The secondary effects of the 1980 Mount St. Helens eruption serve as a reminder that hazards can linger long after the initial eruptive activity has ceased. At Mount St. Helens, dramatic post-eruption erosion and sedimentation and the ongoing potential of floods from lakes impounded by the debris avalanche have presented costly problems. Nearly $1 billion was spent during the first 10 years after the eruption to mitigate the flood hazards.

During the first 3 years after 1980, an estimated 8 million tons of tephra were washed off hillslopes into the Toutle River system. While hillslope erosion eased somewhat after 1983, erosion of the debris avalanche and the subsequent widening and incision of this drainage system by the development of a stream network resulted in a huge sediment *discharge* to downstream areas. (See p. 43.) The post-eruption Toutle River became one of the most sediment-laden rivers in the world. Downstream water quality and aquatic habitat severely deteriorated, and increased downstream flooding due to sediment-filled river channels jeopardized homes and roads built near the river.

Numerous natural dams were created by the debris avalanche in the North Fork Toutle River drainage. On at least five occasions during 1980 to 1982, the collapse of one of these dams released a small lake or pond adjacent to the debris avalanche and caused minor floods. (See Elk Rock Viewpoint, p. 49.) However, public concern focused on Spirit, Coldwater, and Castle Lakes, the three largest lakes impounded by the debris avalanche. Studies by geologists in the 1980s indicated that enormous floods had resulted from the breakouts of similar lakes in pre-historic times. The levels of Coldwater and Castle Creek were stabilized in 1981 by trench outlets. Pumping of Spirit Lake via a floating barge and outlet pipe began in November of 1982. A permanent outlet tunnel at Spirit Lake, completed by the U.S. Army Corps of Engineers in 1985, allows the lake to be lowered an additional 30 to 40 ft (9 to 12 m) for safety reasons.

Preparedness and Mitigation: Public Awareness of Volcanic Hazard

The 1980 events at Mount St. Helens have changed not only the way volcanic hazards are studied, but also public awareness of those hazards. The three most important aspects of volcanic hazards mitigation are: (1) communication of volcano-monitoring and volcanic-hazards information by geoscientists to the public, the media, and responsible agencies; (2) emergency preparedness by responsible agencies and officials; and (3) community and regional planning and land-use designations. All three aspects are interrelated. Successful mitigation depends on the timely communication of understandable scientific information about the current state of the volcano, as well as the nature, extent, implications, and likelihood of the variety of volcanic processes possible at that volcano.

Communication of scientific information about the status of a volcano (Table 5) has improved mainly because geologists have observed Mount St. Helens so closely. Public demand for prompt and comprehensible technical information and the experience of working with an accessible volcano, such as Mount St. Helens, have helped scientists refine the communication process. Geologists now use three types of public statements when describing volcanic activity:

- Factual statements provide information but do not anticipate future events.
- Forecasts are comparatively imprecise statements about the nature of expected activity (typically based on the past history and potential of a volcano and on geologic mapping).
- Predictions are relatively precise statements about the time, place, nature, and size of impending activity (usually based on measurements at the volcano).

Public statements about Mount St. Helens and other volcanoes from Alaska to the Philippines have been accepted by the media and the public because they define and translate scientific information and clarify public expectations and understanding of volcanic events and hazards. They also improve credibility and trust and can foster serious planning efforts (Swanson and others, 1985).

WHAT IS THE FUTURE OF MOUNT ST. HELENS?

Reconstructing the history of a volcano provides many clues to the kind of future activity we can expect, but history cannot be used to predict the exact timing and nature of a volcano's short-term activities. With new information and instrumentation, however, scientists have had great success predicting the behavior of Mount St. Helens days or weeks in advance.

As we have learned, the May 18, 1980, eruption was only one of five explosive eruptions in the last 500 years. Eruptive activity, including pyroclastic flows, lava flows, and lahars, usually continues for decades or centuries. If the volcano follows a pattern similar to that suggested by the geologic record, we can expect more activity in the near future, including more explosive eruptions. The Lava Dome may continue to grow and fill the existing crater...or it may stop growing if

Table 5. Types of volcanic hazards statements. The examples shown are taken from statements issued jointly by the U.S. Geological Survey (Cascades Volcano Observatory) and the University of Washington Geophysics Program. Similar hazard levels and types of statements would be used worldwide, based on United Nations standards

Hazard level	Type of statement	Purpose of statement, with example
1 (green)	Information Statement	Describes unusual events, typically short-lived, such as steam bursts, small avalanches or mudflows, rockfalls, thunder storms, or smoke plumes from fires. Can be the first statement issued when background conditions change and may be issued as a commentary to clarify a situation.
		"A period of sustained seismic activity on March 22 apparently was associated with a large snow and rock avalanche from the south crater wall."
2 (yellow)	Extended Outlook Advisory	Expresses concern about volcanic unrest or hydrologic conditions but does not imply an imminent hazard. Used when the USGS can first confirm changes that could lead to an eruption or hazardous hydrologic event.
		Thursday, October 16, 1986, 6:00 P.M. PDT – "Seismicity within the crater and deformation rates on parts of the dome are increasing slowly at Mount St. Helens. These changes are similar to those that preceded earlier episodes of rapid dome growth. If current trends continue, another episode is likely to begin within the next 3 weeks. As in previous episodes of dome growth, small explosions are possible but hazards will likely be confined to the crater."
3 (orange)	Volcano Advisory	Emphasizes heightened potential hazard when monitoring by the USGS indicates processes are under way that could culminate in eruptive activity. Does not imply evidence that a life- or property-threatening event is imminent.
		Sunday, October 19, 1986, 10:00 A.M. PDT – "Seismicity and deformation rates have continued to increase since the Extended Outlook Advisory of October 16. We now expect an episode of rapid dome growth to begin during the next 2 to 10 days. As in previous episodes, small explosions and ash plumes, with effects mostly confined to the crater, may accompany the dome growth."
4 (red)	Volcano Alert	Issued when USGS monitoring and evaluation indicate an escalation in precursory activity to the point where a volcanic and (or) hydrologic event threatening to life or property appears imminent or is under way.
		"Seismicity and rates of deformation in the crater have accelerated sharply....the expected eruption will probably begin within the next 24 hrs."

the volcano becomes dormant for an extended interval. As long as the volcano's magma chamber and dome core remain hot, small unanticipated steam explosions may occur.

In the meantime, the best way to get familiar with the volcano is to examine its effects and its deposits. They will give you a better understanding of the history, nature, and processes of this natural laboratory. The road guide in Part II will introduce you to many of the features used to decipher Mount St. Helens' past and to predict its future.

RECENT GEOMORPHIC EVOLUTION OF THE LANDSCAPE

Some of the biggest changes at the mountain since 1993 have been caused by erosion. On February 6–11, 1996, severe rainstorms caused major flooding and landslides throughout the Pacific Northwest. The sustained rainfall from a very warm, humid tropical air mass fell on a heavy snowpack and caused a "rain-on-snow" flood. The Spirit Lake instrument site recorded about 31 in. and the June Lake station recorded 36.5 in. of precipitation (including snow moisture) between February 5 and 10 of that year. Numerous landslides destroyed about $15 million of forest roads near Mount St. Helens, including areas along FR 26 (now open only as far north as Quartz Creek). Many of the landslides visible in the Clearwater valley were triggered by this storm.

On September 16, 1997, a heavy rainstorm eroded the crater floor and triggered a debris avalanche as much as 80 ft deep at Loowit Falls. A small debris flow and flood from this event reached Spirit Lake. The crater floor will no doubt continue to be sculpted by headward erosion during events such as this.

In the crater, a new glacier, perhaps composed of roughly equal parts ice and rock, is growing between the south crater walls and the Lava Dome. The top surface of this new glacier appears as north-sloping mass of snow that is slowly beginning to surround and overwhelm the Lava Dome. Growth of this glacier suggests that future eruptions will almost certainly be characterized by episodes of steam emissions or explosions and by interactions of hot rock debris with snow and ice.

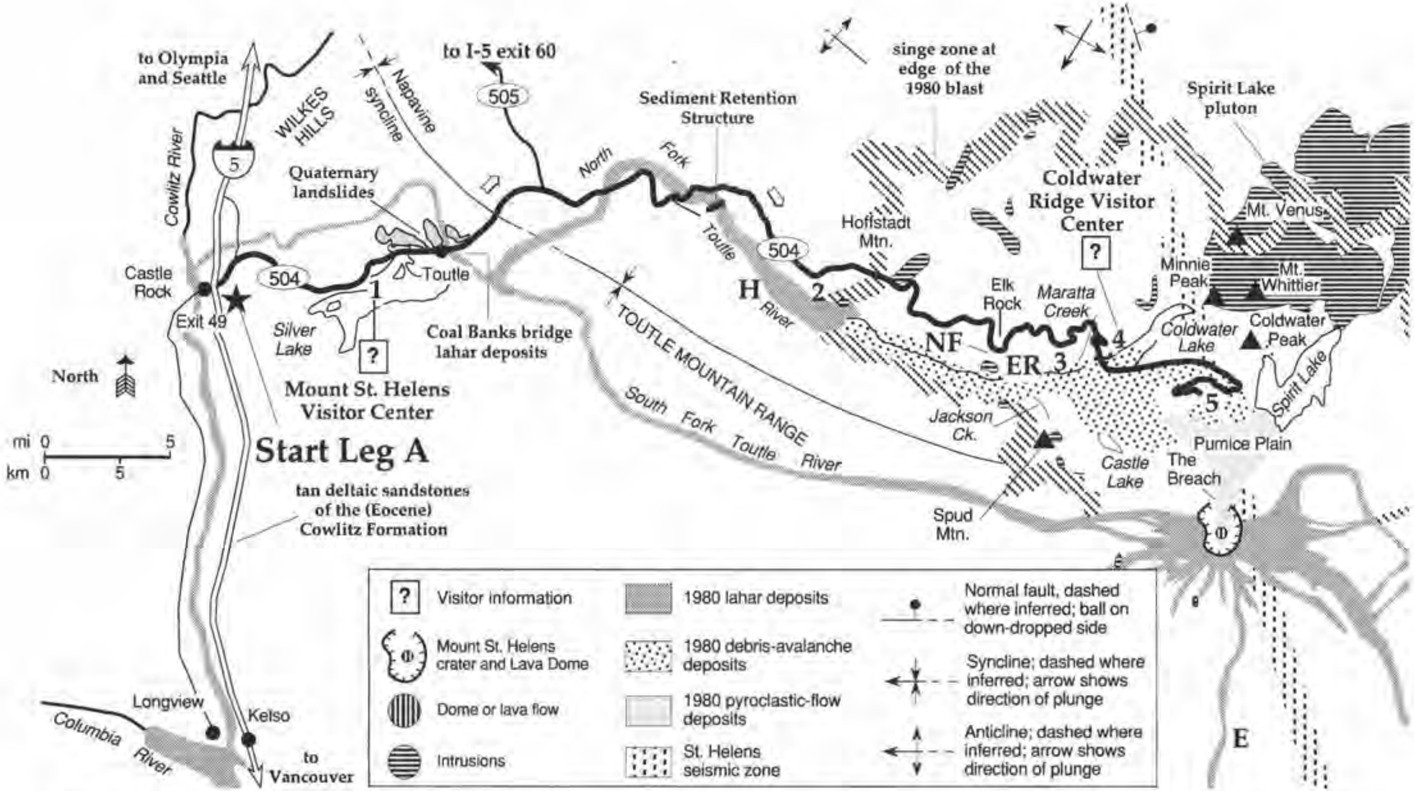


Figure 22. Sketch map for Leg A along SR 504, showing numbered road stops (referred to in text), geologic units, features, and structures, and May 18, 1980, Mount St. Helens deposits and generalized areas of devastation by the blast. E, approximate western and southern limits of glaciers of Evans Creek age (22,000–11,000 yr B.P.); ER, Elk Rock Viewpoint (monument entry); H, approximate western limit of glaciers of Hayden Creek age (140 ka); NF, North Fork Viewpoint. Road symbols are identified in Figure 1.

PART II: ROAD GUIDE TO THE GEOLOGY OF MOUNT ST. HELENS

LEG A: WESTERN APPROACH—TOUTLE RIVER VALLEY

Via State Route 504 (Spirit Lake Memorial Highway)

On this approach from the Cowlitz River valley, you proceed east toward Mount St. Helens, generally along the Toutle River valley (Fig. 22). En route, the highway crosses uplands of gently folded *Tertiary* sedimentary and volcanic rocks and passes through areas where these rocks are overlain by Quaternary glacial deposits, landslide deposits, and ancient deposits from Mount St. Helens. As the highway approaches the Coldwater Lake–Johnston Ridge area, the focus of the guide shifts to the deposits of the catastrophic May 18, 1980, eruption and the radically altered landscape created by the powerful *blast* and *debris avalanche*. This landscape is continually being modified by erosion. It is also being rapidly colonized by pioneer plant and animal species.

Distances along the route are given in miles, followed by kilometers in brackets. The mileage for this leg follows the posted road mileage, which starts at Castle Rock near Exit 49 from Interstate Highway 5 (I-5). It may differ slightly from actual road mileage.

Distance

0.0 [0.0] Drive east on State Route (SR) 504.

0.6 [1.0] The fairly flat surface within 0.6 mi of I-5 is underlain by pre-historic Mount St. Helens *lahar* deposits, possibly of Cougar age (20,000–18,000 yr B.P.). (See Table 3, p. 25.) These deposits are overlain by rhythmically bedded silts deposited by large floods from glacial Lake Missoula at the end of the last glaciation. (See p. 20.)

The route then takes you up the wall of the Cowlitz River valley and over sediments of the lower Pleistocene Logan Hill Formation. This formation does not crop out here, but it composes most of a high *terrace* underlying the road and visible south of the road near the top of hill. The Logan Hill Formation in this area is chiefly *outwash* sand and gravel from large *valley glaciers* that extended down the Cowlitz valley from Mount Rainier perhaps more than 1 Ma. This terrace is an erosional remnant of that valley fill.

2.0 [3.3] From about milepost 2 to Stop A-1, the road traverses rolling hills composed of Wilkes Formation sedimentary rocks and Goble Volcanics (both

Tertiary). A quarry on the north side of the road at milepost 3 exposes a *lava* flow in the Goble Volcanics.

5.3 [8.5] **STOP A-1: MOUNT ST. HELENS NATIONAL VOLCANIC MONUMENT VISITOR CENTER.** Operated by the U.S. Forest Service, the visitor center is an excellent orientation point for the western approach to Mount St. Helens. A variety of educational displays can be viewed, and maps, audiovisual materials, and books are available at the center. Movies and slide shows are generally scheduled on the half hour, punctuated occasionally by special presentations and lectures. Weather permitting, Mount St. Helens can be seen 30 mi (48 km) to the east across Silver Lake. The stone used to construct the center and the low walls around the building is a welded *tuff* quarried in the Oregon Cascades.

Silver Lake is shallow (maximum depth about 16 ft or 5 m) and was formed and is partially underlain by lahar deposits. About 2,500 years ago during the Pine Creek eruptive period, a series of very large lahars traveled down the Toutle River from Mount St. Helens. The lahars flowed into Outlet Creek (east of the lake) and dammed its valley to produce Silver Lake. These lahars were generated by the catastrophic draining of a lake (presumably an older Spirit Lake) or lakes that had been dammed by debris avalanches from Mount St. Helens. The level of Silver Lake is now controlled by a dam.

En route to Stop A-2. As you proceed east from the visitor center, you travel along the north shore of Silver Lake and then ascend the Toutle River valley, passing ancient landslides, pre-historic Mount St. Helens deposits, and local *outcrops* of bedrock, most of which are *basalt*, basaltic *andesite*, and andesite of the Goble Volcanics.

11.0 [17.6] Coal Banks bridge. Coal Banks bridge is the local name for the bridge that crosses the Toutle River about a mile (1.6 km) northeast of the town of Toutle (about 31 mi or 50 km downstream from the volcano). It was probably named for the lenses of soft *coal* that crop out slightly downstream in landslide blocks derived from the Toutle Formation (upper Eocene–Oligocene). This bridge is a short distance downstream of the confluence of the North Fork and South Fork Toutle Rivers. An earlier bridge here was destroyed by the 1980 North Fork Toutle lahar when logs jammed beneath it and it floated off its foundation. The bridge was rebuilt so that the roadway is higher than the previous bridge. This was accomplished by extending the original bridge piers, which survived passage of the lahar.

Deposits visible in the bluff upstream of the bridge include some of the lahar that plugged Outlet Creek to create Silver Lake. One of these layers lies 60 ft (18 m) above the river; the top of the layer corresponds roughly to the peak stage or inundation height of the lahar. Using this estimate of stage along with the valley cross-sectional area and lahar velocity estimates, geologists were able to estimate the magnitude of the flood wave from this ancient flow. This largest lahar during Pine Creek time evidently had a peak *discharge* similar to that of the Amazon River at flood stage, nearly 9 million ft^3 (260,000 m^3) per second of rocks, sand, mud, and water.

About one mile (1.6 km) past the Coal Banks bridge, the highway passes through the axis of the Napavine *syncline*, a broad, elongate depression of folded rocks that trends generally northwest (Fig. 22).

15.0 [24.0] The rocks that crop out along the highway in this area to 17.3 mi (27.7 km) are mainly lava of the Goble Volcanics. The platy andesite flow dips to the east. Rounded features are formed by spheroidal weathering. The lava flows are overlain by bouldery glacial outwash (Pleistocene).

17.3 [27.7] Kid Valley bridge over the Toutle River.

19.5 [31.2] Maple Flats area. This terrace was inundated by a lahar on May 18, 1980. It is underlain by ancient lahar deposits, also visible across the river.

20.5 [32.8] Tertiary bedrock stained orange by *hydrothermal alteration*.

21.1 [33.8] **OPTIONAL STOP: SEDIMENT RETENTION STRUCTURE**. The road to the right slightly before the Toutle River bridge leads to an overview of the Sediment Retention Structure (SRS), which was completed in 1989.

A serious side effect of the Mount St. Helens eruption has been the downstream movement of enormous amounts of sediment (*tephra*) eroded from hillslopes and from the debris-avalanche and *pyroclastic-flow* deposits in the upper reaches of the North Fork Toutle River (Fig. 23). The SRS was constructed to trap this sediment before it was carried farther downstream, where it could clog the river channel and exacerbate floods along the lower Toutle and Cowlitz Rivers. An overflow channel was added to divert lahars around the dam.

Before the 1980 eruption, the amount of suspended sediment transported downstream annually in the Toutle River would fill 520 railroad hopper cars (each 127 m^3). The average amount of suspended sediment transported during each of the first 5 years after the 1980 eruption would fill more than 75,000 hopper cars—

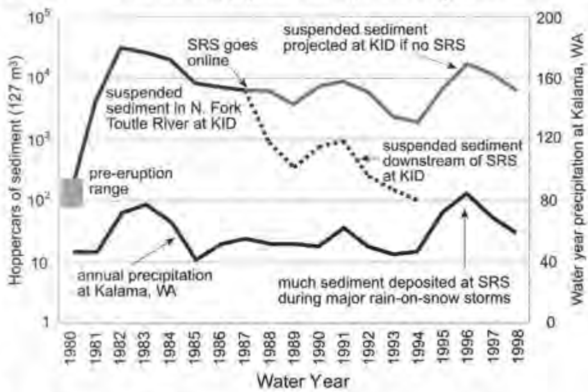


Figure 23. Graph showing the estimated suspended-sediment load in the Toutle River near Kid Valley (KID) for water years 1980 to 1998 plotted with annual precipitation measured at Kalama, Washington. (A water year begins on October 1 of the previous calendar year.) Kid Valley is about 27 mi (45 km) downstream of the crater and only 2.5 mi (4 km) downstream of the Sediment Retention Structure (SRS). Notice the dramatic reduction in suspended sediment beginning in 1988 when the SRS went online. Estimates do not include bed load, which could increase values by 15 to 40 percent. Data for the pre-eruption range are from Collins and Dunne (1988), for water year 1981 from Lehre and others (1983), and all other values from Major and others (2000).

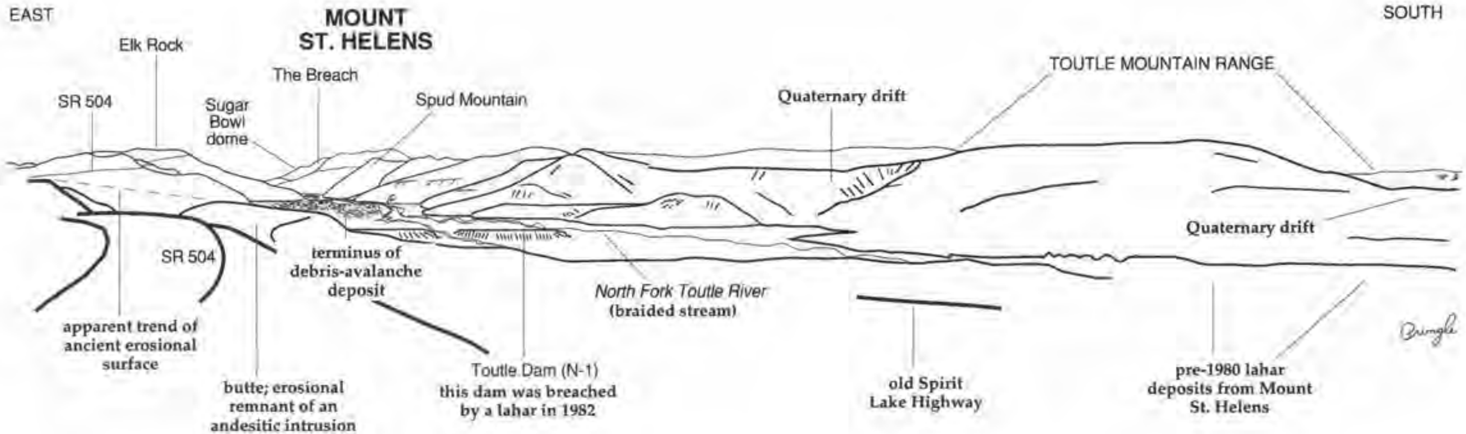


Figure 24. Panorama to the east and southeast from Hoffstadt Viewpoint, about 15 mi (25 km) from Mount St. Helens. The numerous hummocks of the 1980 debris-avalanche deposit dot the valley bottom of the North Fork Toutle River in the distance. Its terminus is slightly upstream of the N-1 dam. The dam was constructed to trap sediment, but was breached by a lahar on March 19, 1982, and further damaged by flooding later that year. Sugar Bowl is an ancient lava dome on the flank of Mount St. Helens. The Breach is a crater breach, an opening to the north in the crater wall that was created by the debris avalanche and blast of the 1980 eruption. (See Fig. 18.) Spud Mountain is the recrystallized remnant of a volcanic plumbing system. Resistant Elk Rock is composed of an altered Tertiary tuff that was locally recrystallized.

enough to create a train 800 mi (1,280 km) long and make the Toutle River one of the most sediment-laden rivers in the world. Sediment moving downstream (chiefly very fine material in suspension) has been reduced significantly by the SRS, and yet it is still several times the pre-1980 annual average.

The enormous amount of sediment transported after the eruption drastically degraded water quality and aquatic habitat. It also increased flood potential downstream and jeopardized homes and roads built on the flood plain and terraces adjacent to the Toutle River. As the lower Toutle and Cowlitz Rivers filled with sediment, their capacity to contain water during flood events was dramatically reduced. In addition, extreme sediment concentrations (both *suspended* and *bed load*) magnified flood volumes for given amounts of precipitation. Early mitigation efforts that preceded construction of the SRS included dredging the Cowlitz River and constructing temporary sediment dams in the upper North Fork Toutle River.

En route to Stop A-2. Continue east toward the volcano, passing outcrops of the Goble Volcanics. In this area, they consist mainly of basaltic andesite lava flows and *flow breccia*.

25.0 [40.0] At about milepost 25, west of Hoffstadt Mountain, bedded fragmental volcanic deposits of andesite and basalt are exposed. A series of lahar deposits and *ash* beds containing fossil wood are exposed here in a cliff on the north side of the road. There are a few *faults* cutting the outcrop, but the rocks are not as dramatically altered as they are at Spud Mountain and Elk Rock. (See Fig. 24 and p. 49.) Notice that the rocks are more brightly colored and are increasingly cut by *dikes* and *sills* as you drive east. (See Fig. 7 and the discussion of intrusive igneous rocks on p. 94.)

27.0 [43.2] **STOP A-2: HOFFSTADT VIEWPOINT**. This site, about 15 mi (25 km) northwest of Mount St. Helens, provides a panorama (Fig. 24) of Tertiary rocks, the remnants of an ancient erosional surface, and parts of an early sediment-retention dam (N-1) that was constructed at the far end of the May 18, 1980, debris-avalanche deposit.

Elk Rock and Spud Mountain to the southeast are made up of resistant rocks that constrict the valley of the North Fork Toutle River.

Glacial deposits of Hayden Creek age (140 ka) have been found on top of the butte-like erosional remnant of andesite shown in Figure 24. The elevation of the top of the butte seems to match that of some other erosional surfaces in the valley, and together they may delineate a former valley floor that was some 330 ft (100 m) higher than the modern valley bottom.

Upstream, remnants of the N-1 dam stretch north across the valley. Constructed in 1981, the dam was not large enough to hold the lahar of March 19, 1982, which flowed over the top of the dam and breached it. Further damage was inflicted by storms of November 1982 and by later floods. The failure of this dam indicated that a much larger structure would be needed to contain future lahars and to reduce the extreme sediment loads in the river. In response to this need, the U.S. Army Corps of Engineers constructed the SRS, located downstream.

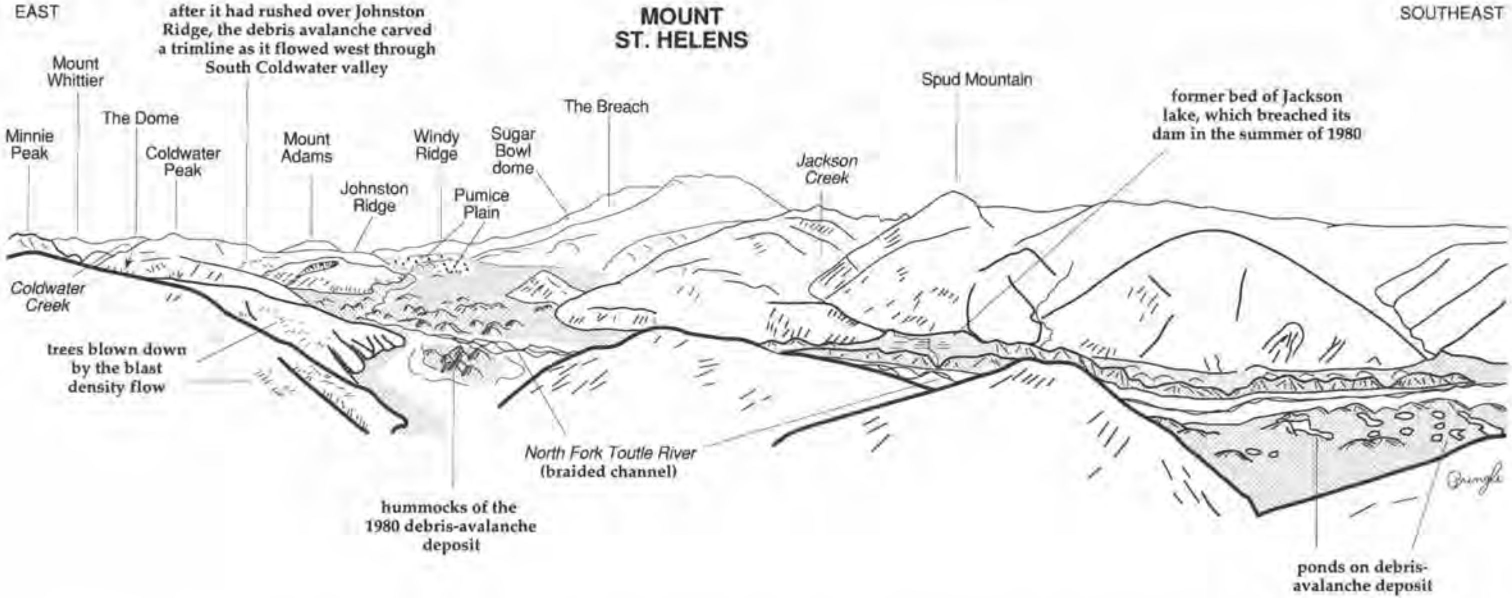


Figure 25. Panorama from Elk Rock Viewpoint, about 10 mi (15 km) from Mount St. Helens. The North Fork Toutle River has been incising and laterally eroding the hummocky 1980 debris-avalanche deposit. To the south, numerous ponds are visible on the surface of the avalanche. Jackson Creek was one of many tributary streams dammed by the debris-avalanche deposit. The Jackson lake bed is a remnant of the lake that formed behind the debris dam and breached it in 1980. Minnie Peak and Mount Whittier are composed of resistant granodiorite of the Spirit Lake pluton. The Dome, which is not a lava dome, and Coldwater Peak are composed of Tertiary volcanic rock, mostly fragmental debris.

Continue east around the south flank of Hoffstadt Mountain.

27.7 [44.3] Hoffstadt bluffs bridge. Just west of the bridge, the lack of *talus* at the base of the cliffs indicates that these cliffs are the scarp of a large landslide. The absence of vegetation on the scarp increases the potential for rockfalls and *debris flows*, which are most likely to occur during heavy rainfall. (See Mass Movement, p. 102.)

28.0 [44.8] Columnar *jointing* in an Oligocene basalt flow is visible on the left at the east end of the second small bridge after the Hoffstadt Viewpoint. Columns form as a result of contraction of the lava during cooling. (See Fig. 57.)

28.7 [45.9] Cow Creek bridge.

29.9 [47.8] Cross the high bridge spanning Hoffstadt Creek, 370 ft (113 m) below. This area is near the western limit of the zone affected by the 1980 blast. From here east, all but the strongest trees or those in the lee of ridges were blown down. Mounds composing the far end of the debris-avalanche deposit are visible to the south in the valley bottom. Several *moraines* have been mapped in this area. The road passes rubbly outcrops of *till* of Hayden Creek age. Lake deposits that crop out upstream in the valley of Hoffstadt Creek and at Cow Creek indicate that the valley was temporarily blocked by the glacier that occupied the North Fork Toutle River valley during the Hayden Creek glaciation and (or) by earlier glaciers. In the next few miles, the road ascends the south flank of a ridge. Tertiary dikes and fragmental volcanic deposits crop out. The road passes through more hills of Hayden Creek *drift* on the east side of the ridge.

32.3 [51.7] Beginning at 32.3 mi (51.7 km) and continuing for a little more than a mile (1.6 km), the road skirts precipitous Elk Rock, passing light-green dikes and multicolored Tertiary breccia and lava flows that were recrystallized or partially altered to clay minerals such as greenish chlorite.

33.3 [53.3] **OPTIONAL STOP: FOREST LEARNING CENTER**. At the museum you can see exhibits, such as salvaging and replanting forests leveled by the eruption. From here, you can look down on a broad reach of the North Fork Toutle River valley and the numerous hummocks of the 1980 debris-avalanche deposit. Since 1984, the North Fork Toutle River has remained on the south side of the valley. Erosion has deepened and widened its channel and removed much of the debris-avalanche material.

Hayden Creek glacial deposits are not present just upslope of this viewpoint, an indication of the maximum thickness (about 1,600 ft or 500 m) of alpine glacial ice that once occupied the North Fork Toutle valley. Seismic studies indicate as much as 200 ft (60 m) of valley fill in this area, so the terminal moraine for the Hayden Creek glacier may be buried (Burk and others, 1989).

37.0 [48.1] Near here dark-green (almost black) fine-grained rocks known as *hornfels* are cut by numerous dikes. These hornfelsed rocks have been totally recrystallized by the heat of the intrusions. Rock bolts and at least one concrete buttress placed by the Washington Department of Transportation secure rock masses along this stretch of highway.

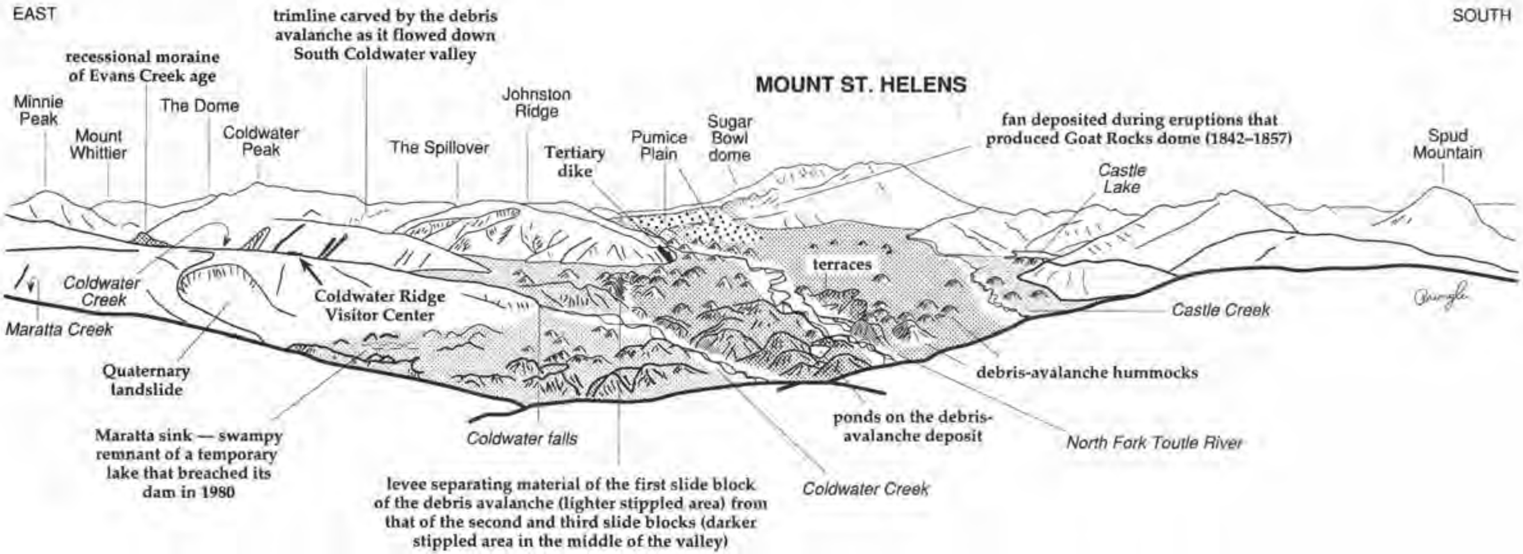


Figure 26. Panorama to the southeast from the Castle Lake Viewpoint, about 8 mi (13 km) from Mount St. Helens. This site presents a spectacular vista of the hummocky debris-avalanche deposit of May 18, 1980, and Mount St. Helens in the background. Sugar Bowl is an ancient lava dome. Goat Rocks fan is a debris fan deposited between 1842 and 1857 just downslope from Goat Rocks dome, which was removed by the May 18, 1980, eruption. Castle Lake was dammed by the debris-avalanche deposit, and Maratta sink is a remnant of Maratta lake, a dammed lake that breached in 1980. Coldwater Lake in Coldwater Canyon was stabilized by the U.S. Army Corps of Engineers at Coldwater Creek outlet. Notice the trimline on the wall of South Coldwater Creek valley cut by the debris avalanche after it had run up on, and spilled over, Johnston Ridge. A series of terraces in the North Fork Toutle River valley has resulted from both deposition by post-1980 lahars and floods and by erosion. A pronounced levee in the debris-avalanche deposit separates material deposited by the first slide block (lighter stippled area at valley margins) from that of the second and third slide blocks (darker stippled area in the medial part of the valley), which were deposited seconds later.

37.2 [59.5] **OPTIONAL STOP: ELK ROCK VIEWPOINT**. The road enters Mount St. Helens National Volcanic Monument. Effects of the May 18, 1980, blast become quite dramatic upstream from here (Fig. 25). Also notice that immediately upstream, the hummocky terrain of the debris-avalanche deposit has greater relief. The constriction in the Toutle River valley here helped to "pond" or hold back the debris avalanche as it flowed downstream. Debris dropped out of the avalanche here when its velocity decreased.

Mount Adams volcano is visible 30 mi (50 km) to the east. Elk Rock and Spud Mountain, to the southeast, are made up of hornfelsed and altered volcaniclastic rocks cut by intrusions of *diorite* and related rocks. The intrusions, in a radial pattern centered on Spud Mountain, probably represent the crystallized plumbing system of a small volcanic complex. The recrystallization has hardened the rocks and made them erosion resistant.

Using *fission-track dating*, the age of a crystal in one of the intrusions was estimated at about 31 Ma. The approximate age of the fragmental volcanic rocks cut by the intrusions is 32 Ma, as determined by *radiometric dating* techniques, so these rocks were probably baked and recrystallized by *contact metamorphism* not long (in geologic time) after their deposition. Although it is slightly older, an intrusion on Johnston Ridge is thought to be correlative.

Jackson Creek, the stream that drains Spud Mountain into the North Fork Toutle valley, was temporarily dammed by the 1980 debris avalanche, forming Jackson lake. The basin behind the blockage filled and breached its dam during the summer of 1980. The flat, swampy area between the debris-avalanche *levee* and the valley wall is what remains of the lake. The levee is a longitudinal ridge of material deposited at the edge of the debris avalanche as it flowed downvalley adjacent to the valley wall.

Continue around the south side of Elk Rock over a small bridge (Elk Creek).

37.8 [60.5] Elk Pass (elev. 3,800 ft or 1,159 m).

39.0 [62.4] The road enters a notch cut into Tertiary bedrock. Rocks exposed in the roadcut are altered to bright greens and pinks and cut by numerous dikes. The greenish rocks are an altered *pumice*ous tuff.

40.7 [65.1] **STOP A-3: CASTLE LAKE VIEWPOINT**. This stop provides a spectacular overview of the volcano and the debris-avalanche deposit, as well as the structure of neighboring bedrock valleys (Fig. 26). To the east is Coldwater falls where Coldwater Lake has cut its outlet down through the debris-avalanche dam to bedrock. The lake level was stabilized by the U.S. Army Corps of Engineers in 1981. Numerous erosional terraces are visible along the North Fork Toutle River and expose debris-avalanche, lahar, and fluvial deposits. Directly to the east, the North Fork Toutle River has eroded debris-avalanche deposits as it has shifted back and forth across a broad area of the valley floor.

Across the valley to the south is Castle Lake, which was born when its valley was dammed by the south levee of the debris avalanche. Engineers cut an outlet to keep the lake at a safe level. Wells drilled into the debris-avalanche

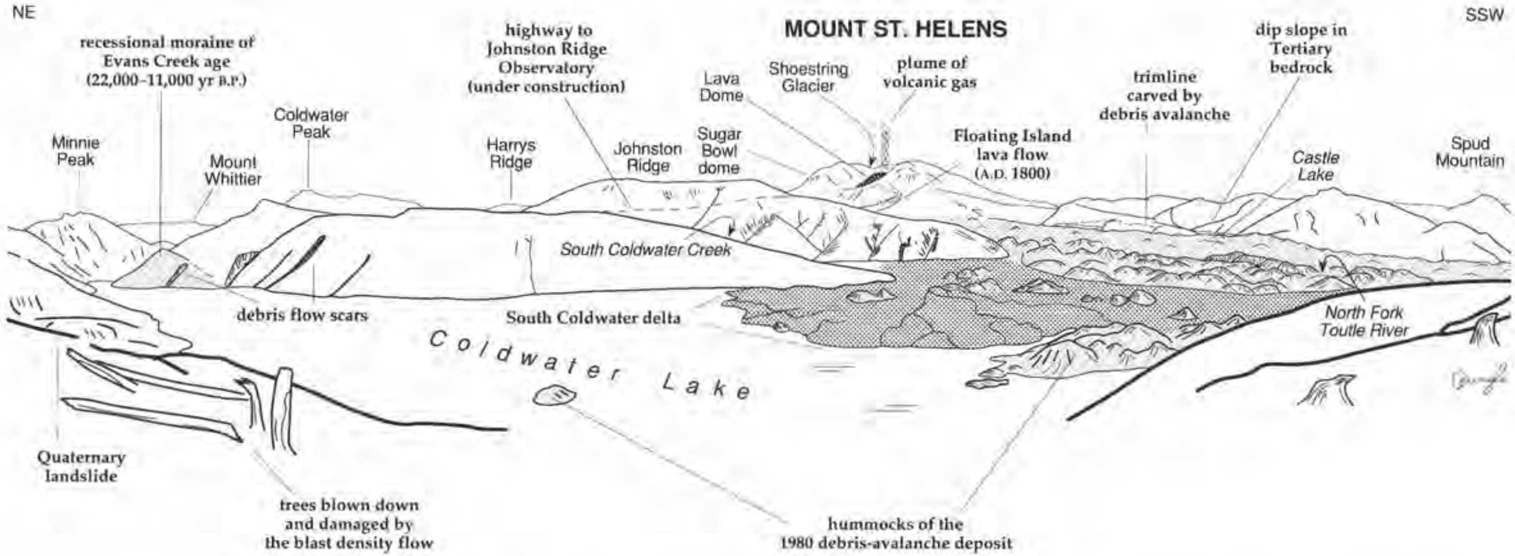


Figure 27. Panorama from the Coldwater Lake Visitor Center, about 7 mi (11 km) from Mount St. Helens. Coldwater Lake was created when Coldwater Creek was dammed by the 1980 debris-avalanche deposit. Most of the South Coldwater delta has been constructed since 1985, when a drainage tunnel through Harrys Ridge began to discharge water from Spirit Lake into the South Coldwater valley. Minnie Peak and Mount Whittier are composed of resistant granodiorite of the Spirit Lake pluton. Highlands composed of these resistant rocks were the sources of the Pleistocene glaciers that carved Coldwater valley and left the sharp recessional moraine visible on the east shore of the lake. The modern Lava Dome has been constructed since 1980 by 17 eruptive episodes during which the lava both squeezed into it and oozed out onto its surface. The debris flows that have scoured the hillslopes were likely triggered during rainstorms. The blast removed or killed the trees whose roots helped hold the soil together on the steep slopes.

blockage are monitored for changes in the ground-water flow or other factors that could signal reduced stability of the debris dam.

Continue to descend the long grade toward Stop A-4 at Coldwater Lake.

42.0 [67.2] Maratta Creek bridge. An area of swamps and small ponds north of the road is called the Maratta sink. Within a month after the debris avalanche was deposited in 1980, the irregular surface of the debris avalanche in this area was dotted with ponds that had collected runoff from neighboring slopes. Seepage from Maratta sink filled lakes downstream. On August 19, 1980, the Maratta sink debris-avalanche impoundment failed, and a flood of water drained into downstream lakes, which also overflowed. This and similar events helped carve an integrated channel system in parts of the debris-avalanche deposit during the next several years.

Till is visible in some roadcuts in this area. It is probably at least as old as the Hayden Creek deposits (about 140 ka); the age is estimated from weathering rind thicknesses of more than 3 or 4 mm. When a rock weathers, an oxidized outer layer or rind forms. The thickness of this layer is roughly proportional to amount of time the rock has been exposed to the atmosphere.

42.2 [67.5] A *normal fault* is exposed in Tertiary bedrock north of the road.

43.5 [69.6] **STOP A-4: COLDWATER RIDGE VISITOR CENTER.** The Coldwater Lake area is one of the best places to get views of the hummocky 1980 debris-avalanche deposit. The spectacular valley that extends to the north was carved by Pleistocene valley glaciers originating in the granitic highlands to the north (Fig. 27).

The generally east-dipping beds visible on the west side of Coldwater Lake are Oligocene basaltic and andesitic lava flows and fragmental volcanic deposits. The beds are part of the west limb of the broad Pole Patch syncline, a gentle fold in the crustal rocks whose axis is located about 15 mi (25 km) east of the Coldwater Ridge Visitor Center. (See Fig. 53.) The lava flows apparently lay on the flank of a nearby *shield volcano* and were later gently warped. Numerous dikes cutting Johnston Ridge were part of the vent system of the volcanic center at Spud Mountain, as indicated by a *radiometric age* of about 34 Ma for one of the dikes.

Minnie Peak (5,610 ft or 1,711 m) and distant Mount Whittier (5,819 ft or 1,775 m) are composed of resistant granodiorite of the Spirit Lake *pluton*. The pluton is a complex of once-molten rock that intruded the surrounding rocks between 23 and 20 Ma. It may have reached the surface to fuel volcanic eruptions, but no extrusive products have been firmly linked to the pluton.

The *St. Helens zone* of active seismicity passes north-northwest between the area of Oligocene lavas just mentioned and Minnie Peak. Although much evidence of faulting can be found in the rocks, geologists have found no surface breaks along this fault zone. Nevertheless, there is seismic activity along a linear zone stretching nearly 80 mi (130 km). (See p. 111.) Geologists have estimated that the seismic zone could produce an earthquake as large as *magni-*

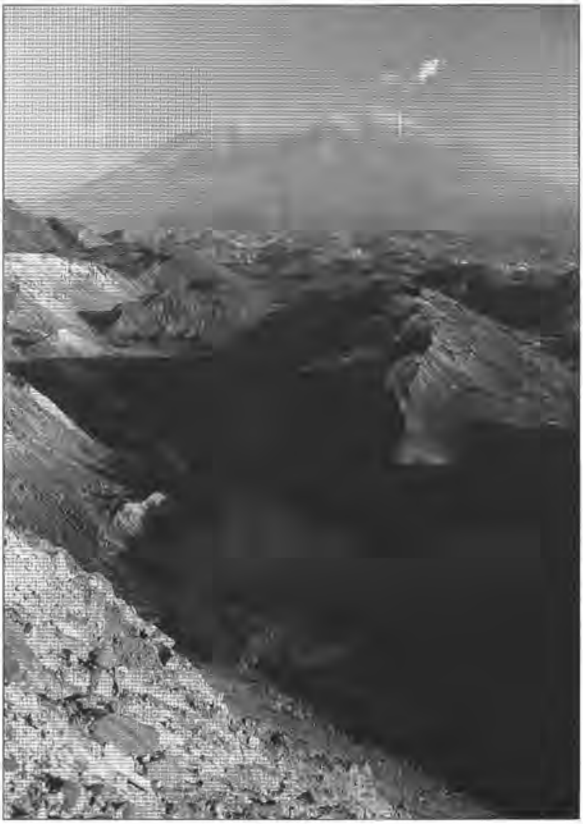


Figure 28. Debris-avalanche hummocks along the Hummocks Trail, Mount St. Helens in the background. The prominent scarp in the left foreground is the levee that separates material of the first slide block (left) from that of the second and third slide blocks (right). Photo taken in 1991.

tude 6.8. Newer buildings and bridges near the fault zone have been designed to absorb the shaking of an earthquake of this magnitude.

A *lateral moraine* from a glacier of Evans Creek age (22,000–11,000 yr B.P.) is visible on the northeast side of the lake. The long, sloping ridge to the east (separating North and South Coldwater Creeks) is mantled by drift of the older Hayden Creek glaciation. Landslide scars on the valley walls demonstrate that *mass wasting* continues to modify the glacial deposits.

The 1980 debris avalanche left a deposit typified by irregular topography. Hummocks and depressions, some containing ponds, create a surface with as much as 200 ft (60 m) of relief. Some hummocks poke out of the south end of Coldwater Lake as islands. The lake was created when the debris avalanche dammed the creek's valley. (For detailed explanations of the dynamics of the debris avalanche and the blast, see p. 29 and Stop A-5, p. 58.)

Deposition of the South Coldwater Creek delta began in 1980. However, the delta grew more rapidly starting in 1985 when water from Spirit Lake was first drained through a tunnel into the South Coldwater Creek headwaters. The increased flow began eroding the thick volcanic deposits in the upper reaches of the creek, and the sediment was deposited in Coldwater Lake. Deltas are typically formed where streams enter bodies of water because the stream slows down and loses energy, dropping its load of sediment.

44.7 [71.5] A light-colored dike is visible on the north side of the road.

45.3 [72.5] The road to the left slightly before the bridge over Coldwater Creek leads to the Coldwater Lake picnic area and boat launch. A short trail from

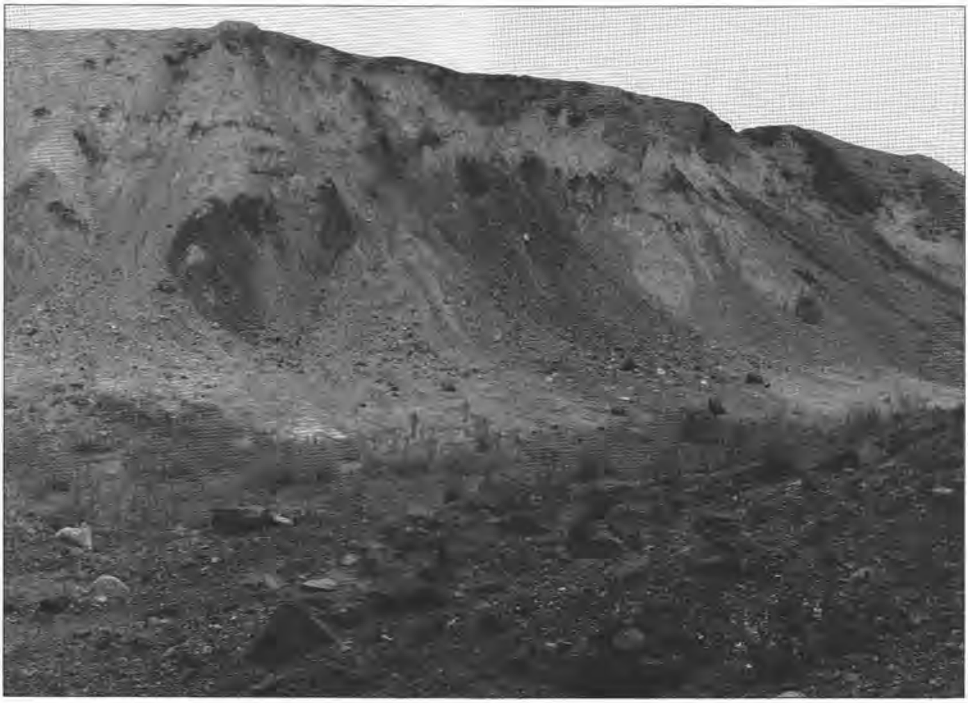


Figure 29. A "smear of the old mountain" along the Crater Rocks Trail. This view (north) shows the face of the levee of material from the first slide block where it was deposited along the north edge of the North Fork Toutle River valley. Flow of the debris avalanche was right to left. This material was derived from shallower parts of Mount St. Helens (Figs. 7 and 18, C and D) and thus is younger than the material in the later slide blocks, which is behind the viewer here. Material in the foreground may have slumped from the face of the levee, which is about 100 ft (30 m) tall.

the picnic area winds through the hummocks and offers views of the South Coldwater Creek delta.

45.4 [72.6] **Hummocks Trail**. This 2.2 mi (3.5 km) loop winds through the hummocks of the debris-avalanche deposit (Fig. 28). You can access the Boundary Trail, which leads to Johnston Ridge, by walking the Hummocks Trail to the east (see below). You will see large chunks of the pre-1980 cone of Mount St. Helens that were carried here. Some of the blocks of lava were transported as discrete chunks and deposited here in a smeared condition (Fig. 29). The variety of material from different parts of the pre-eruption Mount St. Helens cone accounts for the colors and textures of the hummocks here. As you look at the hummocks, see if you can spot the pastel altered masses of dacite *domes* of the Pine Creek eruptive period, the black basalt and basaltic andesite of the Castle Creek eruptive period, the bluish-gray dacite and dark reddish-brown andesite of the Kalama eruptive period, and the light-gray dacite of the Goat Rocks eruptive period. (See the discussion of the Spirit Lake eruptive stage on p. 26.)

Figure 30. A "jigsaw rock" or volcanic bomb. Volcanic bombs (rounded) or blocks (angular) cool quickly on the outside while they are still molten and plastic on the inside. The rind contracts as they cool, thus forming a network of prismatic, generally radial joints in the rock. (See Fig. 57.) Bombs found near the trail are composed of blast dacite, the juvenile volcanic material composing the cryptodome that intruded into Mount St. Helens between March 20 and May 18, 1980. (See Fig. 18B.) This bomb is about 18 in. (45 cm) in diameter.

Although deposits show that the flow front of the blast arrived here first, some *breadcrust bombs* lie on top of the debris-avalanche deposit (Fig. 30). These bombs could have been carried along piggyback by the debris avalanche, having been deposited atop the moving mass closer to the mountain.

Modern processes of *mass wasting* such as *raveling* and *slumping* continue to sculpt the debris-avalanche deposit. Deposits of recent debris flows, some generated by volcanic activity and others by rainstorms, crop out along the North Fork Toutle River in this area.

Boundary Trail. This trail, accessible 0.33 mi (0.5 km) from the Hummocks Trailhead, leads past a spectacular dike of Tertiary age (Fig. 31), through hummocks of the debris-avalanche deposit, and along the North Fork Toutle River. The velocity of the debris avalanche at the valley margin is suggested by the amount of runup on the dike. Johnston Ridge Observatory is a rigorous 3.1 mi (5 km) up the trail.

Figure 31. View east of a resistant, wall-like Tertiary dike in the west toe of Johnston Ridge along the Boundary Trail. Note that the debris-avalanche deposit on the upstream (right) side of the dike is 16 ft (5 m) higher due to runup. This runup indicates that the velocity of the flow was at least 22 mi/hr (10 m/s) at this location on the margin of the flow. Its velocity near the center of the valley probably reached 150 mi/hr (about 70 m/s).

46.5 [74.4] **South Coldwater Trail.** An unsorted deposit of rocks and finer material exposed along the trail here is glacial till. A hike of less than 2 mi leads to some logging equipment destroyed by the 1980 blast.

The highway ascends South Coldwater Creek valley. Before the 1980 eruption, this valley was a U-shaped canyon that headed in a *cirque* at its east end. A comparison of pre- and post-eruption topographic maps shows that the present valley floor is now more than

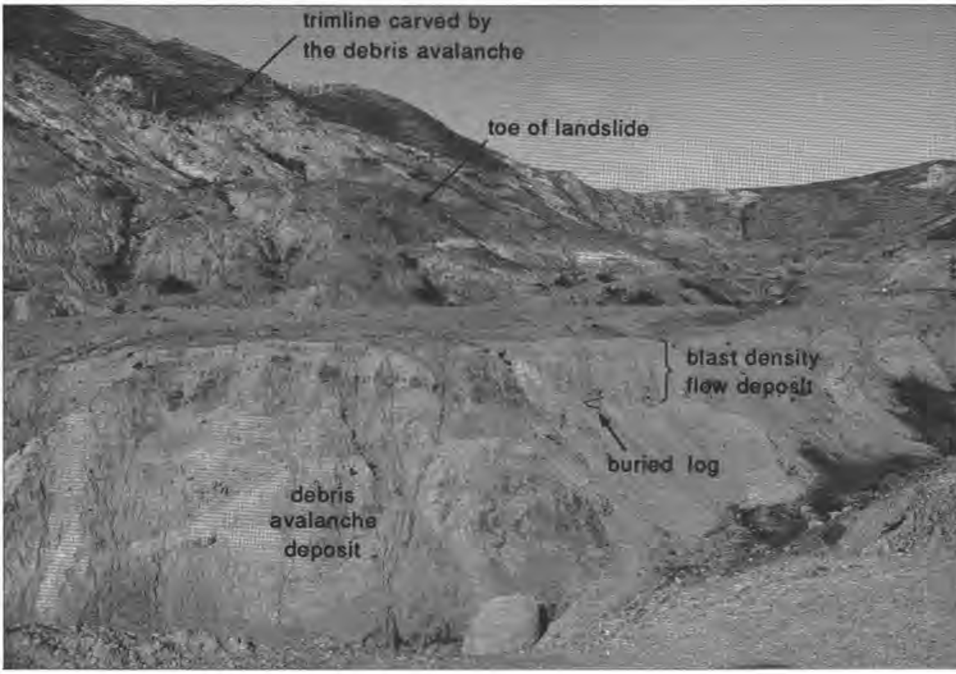


Figure 32. Blast deposit overlying deposits from the debris avalanche in the South Coldwater valley. View is to the northeast. Note the trimline cut by the debris avalanche. Downcutting and lateral erosion by South Coldwater Creek has undercut the toe of, and apparently reactivated, a landslide in Tertiary bedrock. This photo was taken in 1991 before completion of the road around the toe of the landslide.

240 ft (73 m) above the old surface at the west end of the valley and 80 ft (24 m) above it at the east end.

The debris avalanche resulted from retrogressive failure in a series of three slide blocks. Each succeeding slide block removed more of the mountain. (See Fig. 18.) Material from the first slide block ran up over a saddle between Johnston Ridge and Harrys Ridge, spilled over into the South Coldwater valley near its east end, and flowed west down the valley, creating the *trimline* now faintly visible on the north valley wall. Vegetation and most of the soil below the trimline were scraped off by this first part of the debris avalanche. Deposits from the blast, which explosively ripped through the second and third slide blocks, are found below, mixed with, and on top of the avalanche deposits in the South Coldwater valley. As a result of this mixing, the *stratigraphy* of the deposits here is complicated and not continuous from one part of the valley bottom to the next (Fig. 32). Further details of this eruption sequence are given in the text for last stop on this leg of the road guide.

48.8 [77.3] East Creek. Here and to the east of here for a short distance beautiful east-dipping beds of Tertiary volcanic bedrock are exposed on the north valley wall adjacent to the road. Glacial till and the 1980 debris avalanche deposit are plastered on the walls locally. The mounds of debris visible high on

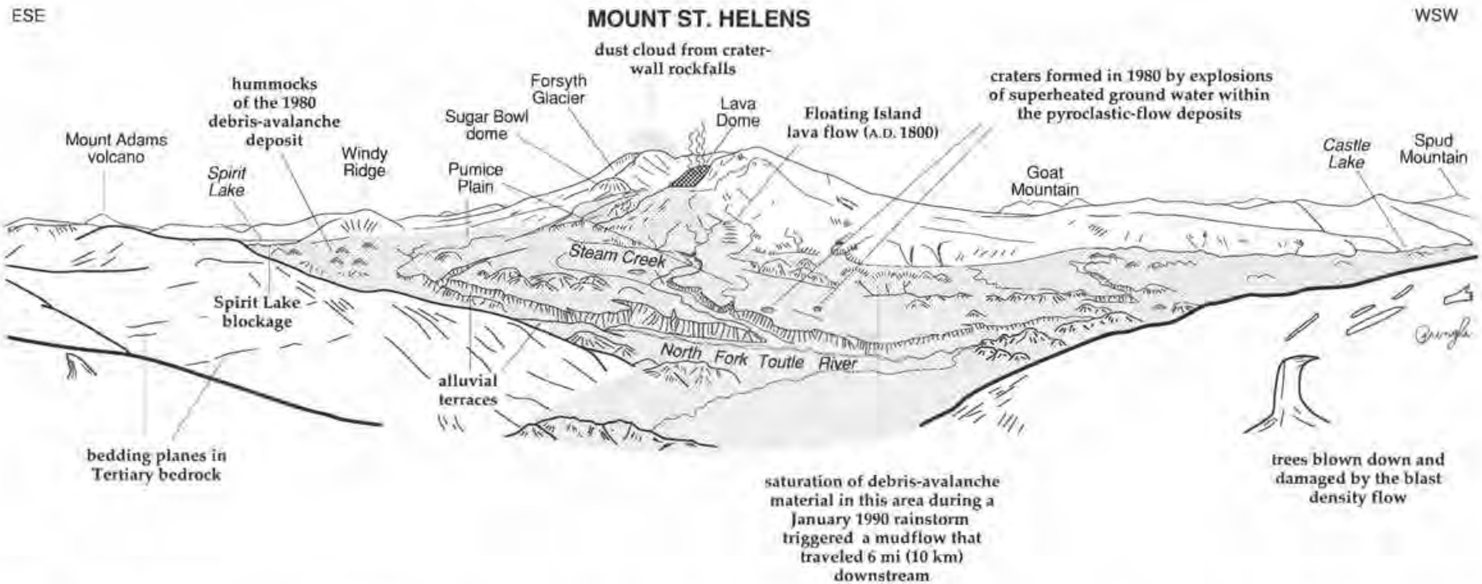


Figure 33. Panorama from the proposed Johnston Ridge Observatory to Mount St. Helens, about 4 mi (7 km) to the south. A visible volcanic gas plume often rises from the Lava Dome, a pile of viscous dacite lava that has been constructed in the center of the crater during the 17 eruptive episodes since 1980. Dust clouds are common during drier months when rock falls from the steep crater walls. Listen, because from this location you can often hear some of the larger rockfalls, owing to the orientation and acoustic properties of the amphitheater-shaped crater. Sugar Bowl is an ancient flank dome. The remnants of Forsyth Glacier, whose upper portions were removed by the catastrophic 1980 eruption, are visible just above Sugar Bowl dome. The North Fork Toutle River has cut into the 1980 debris-avalanche deposits and the pyroclastic-flow deposits of the Pumice Plain leaving behind a series of erosional terraces. Phreatic craters in the deposits were created by rootless steam explosions that resulted when ground water in the hot pyroclastic-flow deposits flashed to steam. The extreme southern end of Spirit Lake is visible just beyond the debris-avalanche blockage that impounds it.

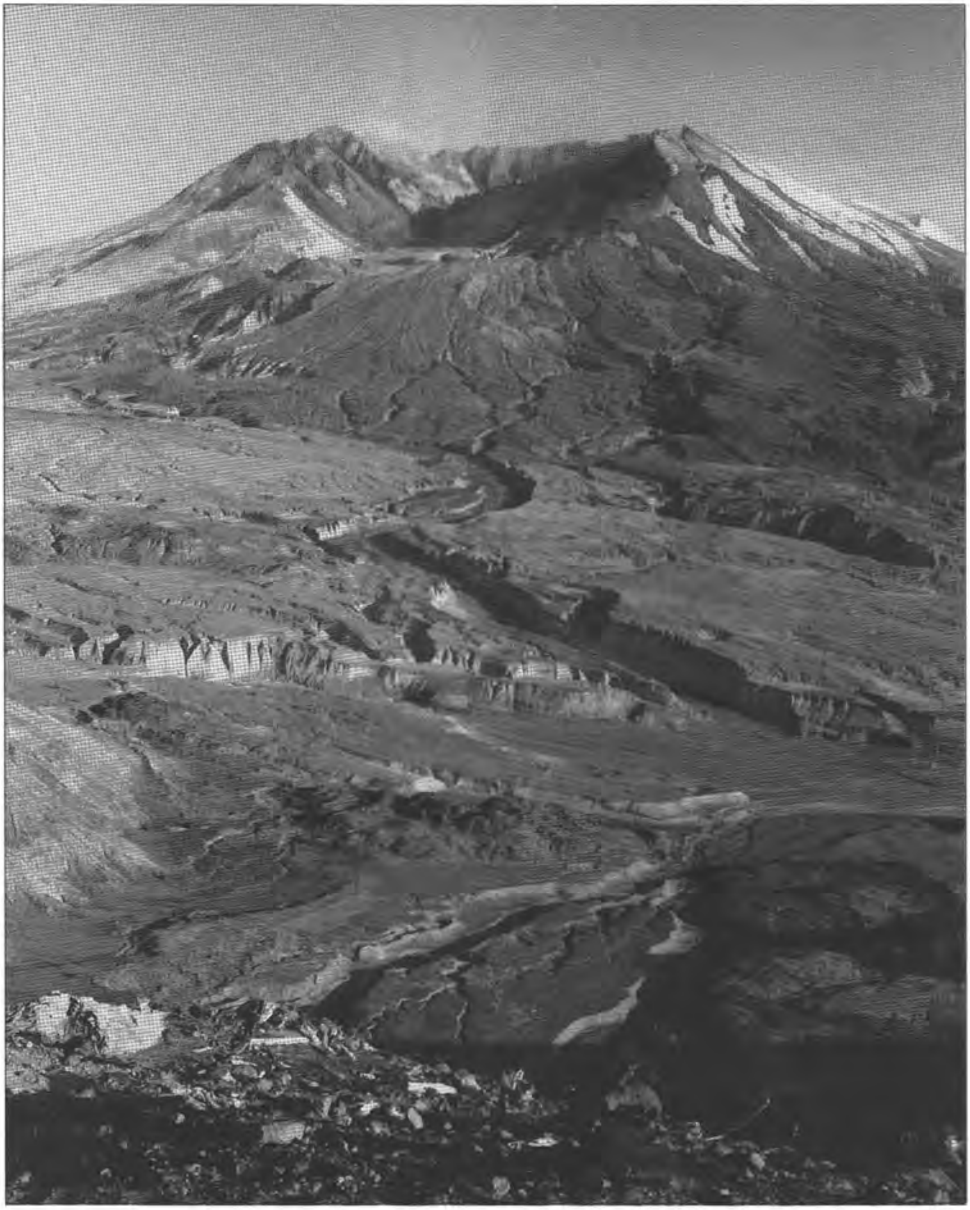


Figure 34. Mount St. Helens and the Pumice Plain from Johnston Ridge in 1991.

the ridge to the east are debris avalanche hummocks that were deposited when the flow ran up onto Johnston Ridge and into the South Coldwater Creek valley.

49.1 [78.6] Modern landslide. The road bends around the toe of large landslide. Notice that the deposits are fragments of rock in a finer-grained matrix. This landslide coincides with a north-trending zone of sheared and broken rock that extends across the valley. This shear zone may be a fault associated with the St. Helens seismic zone, which runs through Mount St. Helens and extends to the east northeast.

49.5 [79.2] Spirit Lake outlet tunnel. Water from Spirit Lake to the east has been diverted through this tunnel since May 1985. The water is drained to keep Spirit Lake from overtopping its debris avalanche dam.

Tertiary dikes and hydrothermally altered zones visible from the highway as it climbs Johnston Ridge are vestiges of a volcanic vent complex (30 Ma) that probably fed lava flows cropping out in the South Coldwater Creek valley.

51.6 [82.6] Loowit Viewpoint. Loowit is the ancestral name of Mount St. Helens (see p. 12.) This spectacular viewpoint is the closest road view of stumps that were shattered by the May 18, 1980, eruption. Boundary Trail passes by here 0.25 mi (0.4 km) farther east on its way to Johnston Ridge Observatory.

52.2 [83.5] **STOP A-5: JOHNSTON RIDGE OBSERVATORY.** The view from Johnston Ridge is one of the most spectacular in the Mount St. Helens National Volcanic Monument (Fig. 33). Johnston Ridge Observatory is located near the observation post where USGS geologist David Johnston was working the morning of the May 18, 1980, eruption. He was killed by the blast, which was unprecedented in the history of Mount St. Helens (although a much smaller lateral blast occurred during the Sugar Bowl eruptive period).

During clear weather, the Mount St. Helens crater and the Lava Dome are visible (Fig. 34). The north flank of the volcano is an extensive plain of debris, called the Pumice Plain, that was deposited during the May 18 eruptive events and during the subsequent 1980 eruptions. Low spots between the hummocks of the debris-avalanche deposit have been filled by the pyroclastic-flow and *ash-cloud* deposits of 1980 and lahars. Since then erosion has incised the pyroclastic deposits, and the ash-cloud deposits have been reworked by wind and water.

The following is a simplified reconstruction of the events that took place in this area after a magnitude 5.1 earthquake triggered the debris avalanche and the May 18, 1980, eruption unfolded:

(1) As material from the first slide block of the debris avalanche was topping the saddle between Johnston and Harrys Ridges at speeds greater than 60 mi/hr (27 m/s), the second and third slide blocks, which were penetrated in part by the blast and mixed with and propelled by blast material, caught up with the first slide block and passed it. This mixed material formed a hummocky deposit of shattered pieces and blocks of Mount St. Helens in a gravelly sand matrix.

(2) The debris-avalanche slide blocks dug as deep as 6.5 ft (2 m) into the pre-1980 soil. The avalanche left a distinct trimline on the valley walls of South Coldwater Creek as it flowed downvalley. Deposits of this phase of the debris avalanche are also hummocky and commonly contain tree trunks and limbs, clots of eroded soil picked up in transit, and some lenses of blast material.