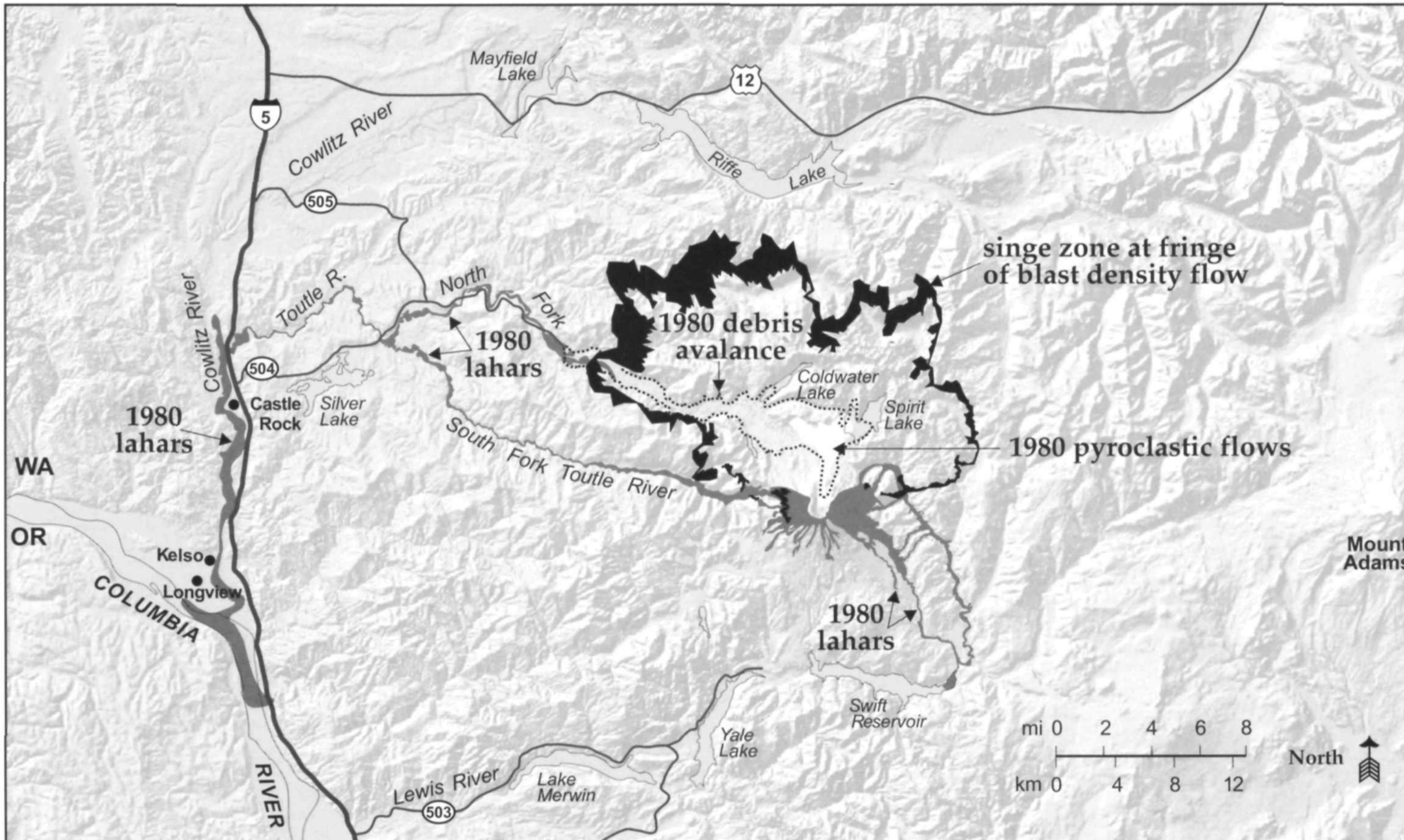
ROADSIDE GEOLOGY OF MOUNT ST. HELENS NATIONAL VOLCANIC MONUMENT AND VICINITY

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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WASHINGTON STATE DEPARTMENT OF
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

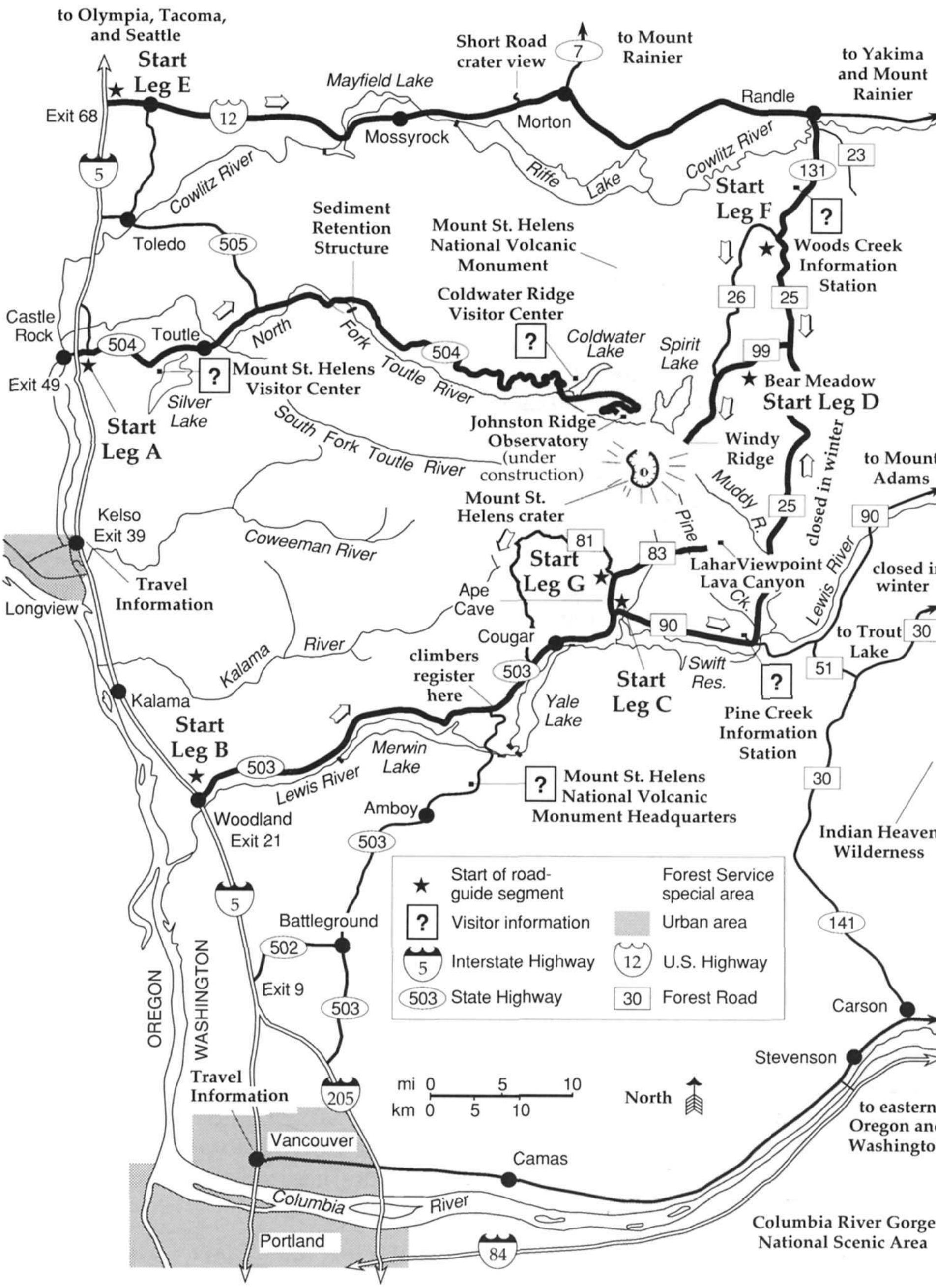


Figure 1. Location map of the Mount St. Helens area showing the national monument, major rivers, and various routes of the road guide. Symbols shown here are those used on maps throughout this guide.

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

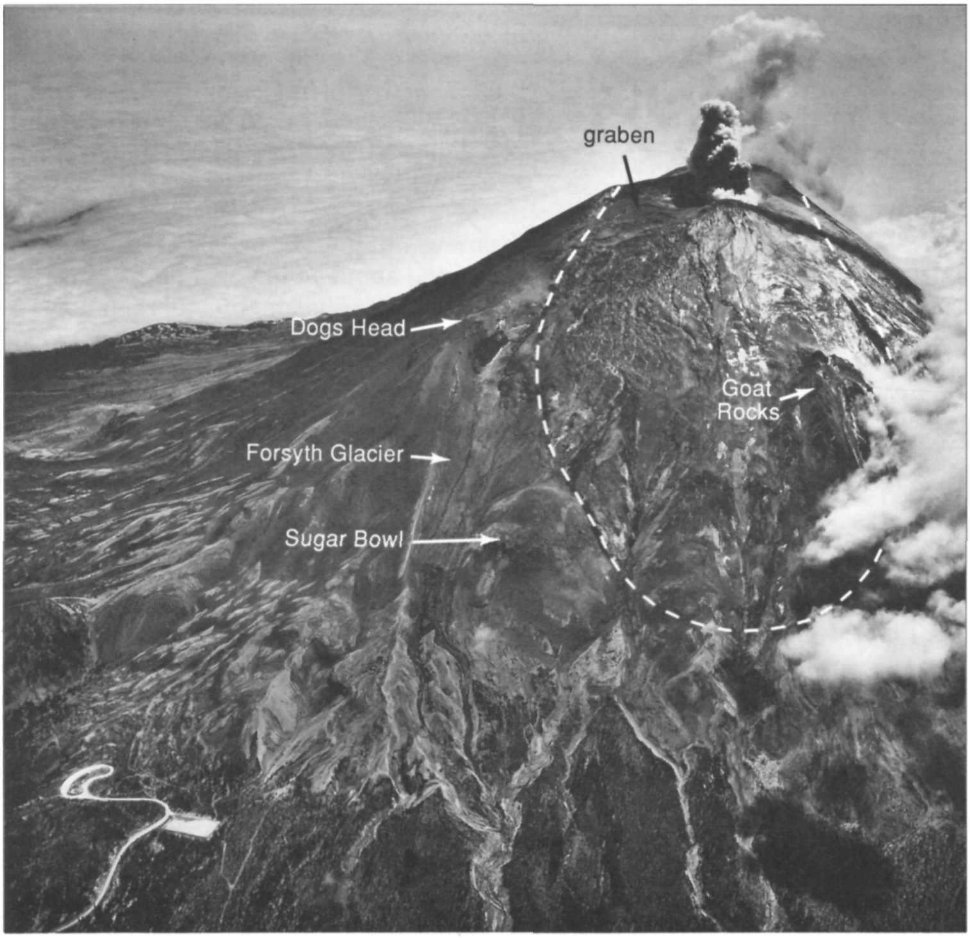


Figure 2. Small phreatic eruption at Mount St. Helens on May 11, 1980. Dashed line shows the approximate outline of the bulge. The graben, a down-dropped block, formed as the bulge was pushed outward by the rising magma. View is to the south and shows the Dogs Head, Sugar Bowl, and Goat Rocks dacite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

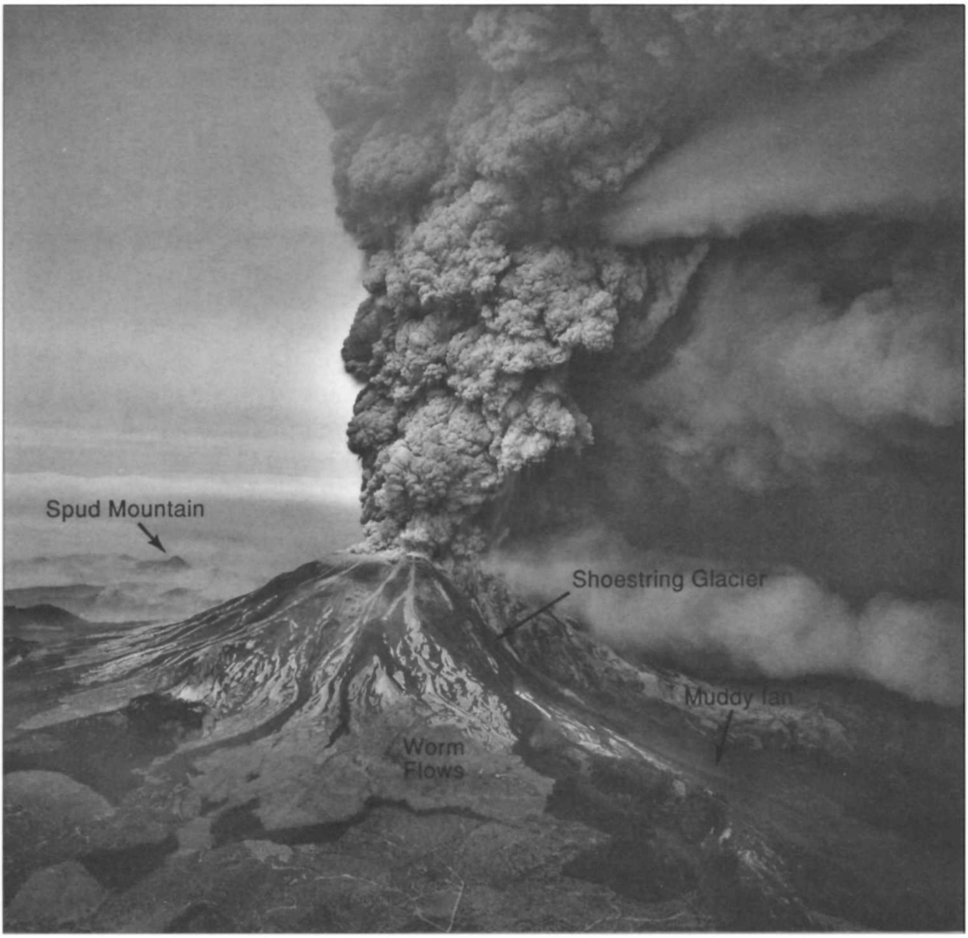


Figure 3. View to the north-northwest of the Plinian eruption column of Mount St. Helens during the early afternoon of May 18, 1980. Note the trace of the pyroclastic surge and lahar on Muddy fan downslope from Shoestring Glacier (lower right). Photo by Robert Krimmel, U.S. Geological Survey.

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

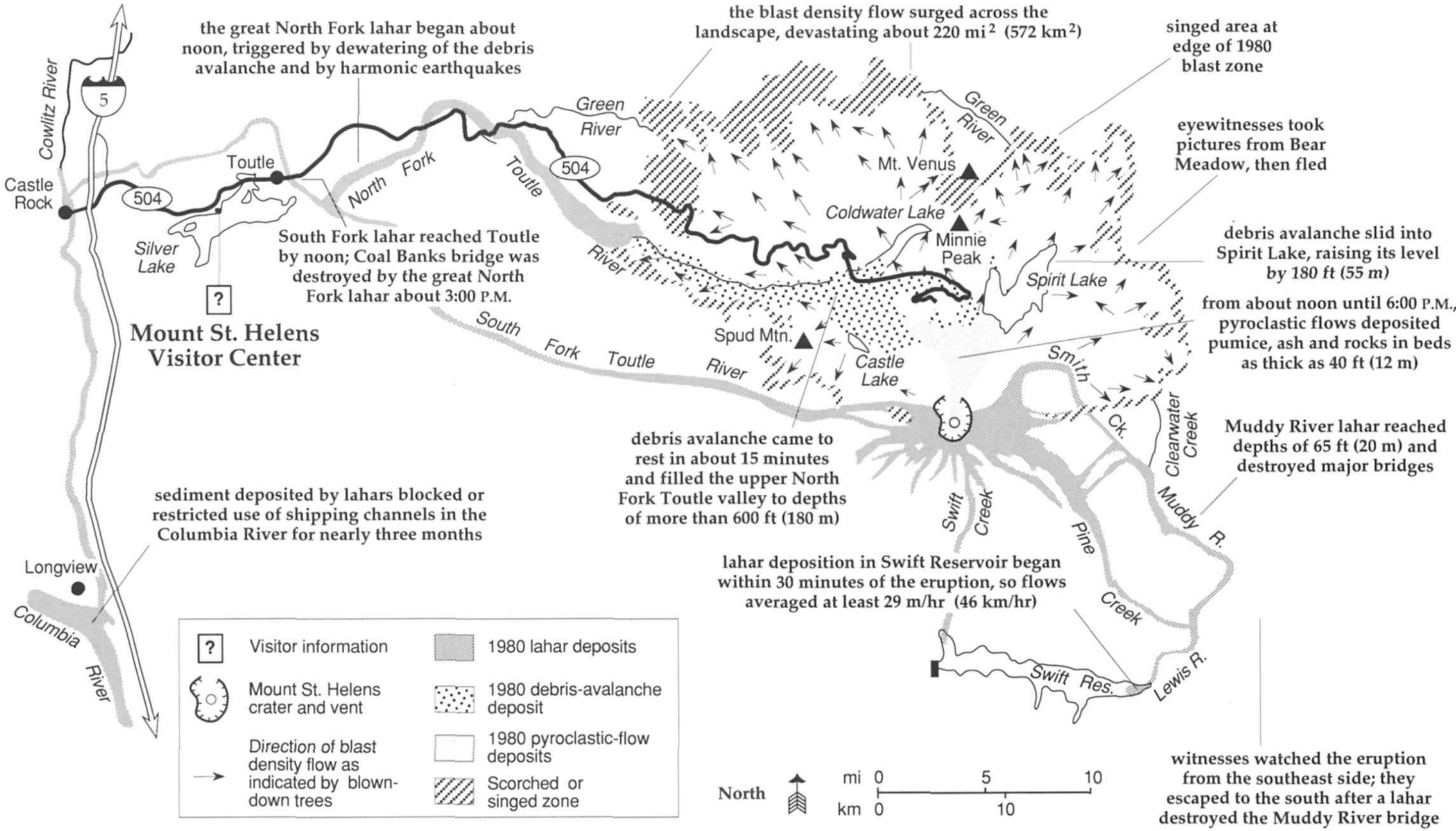


Figure 4. Generalized diagram showing the devastation caused by the climactic eruption of Mount St. Helens on May 18, 1980. The singe zone is at the periphery of the area affected by the blast. Other symbols used are identified in Figure 1. Modified from Lipman and Mullineaux (1981).

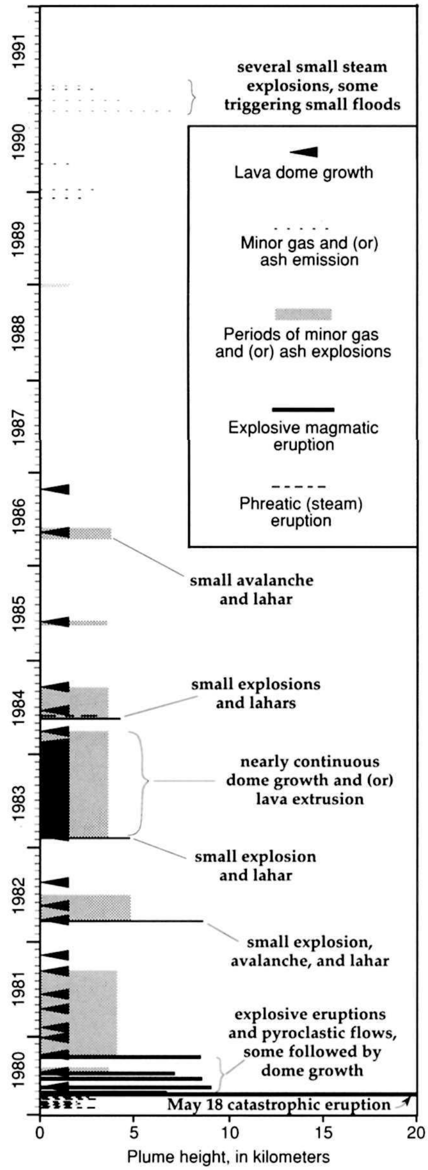


Figure 5. Diagrammatic summary of Mount St. Helens eruptive activity from 1980 to 1992. Modified from Tilling and others (1984).

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-

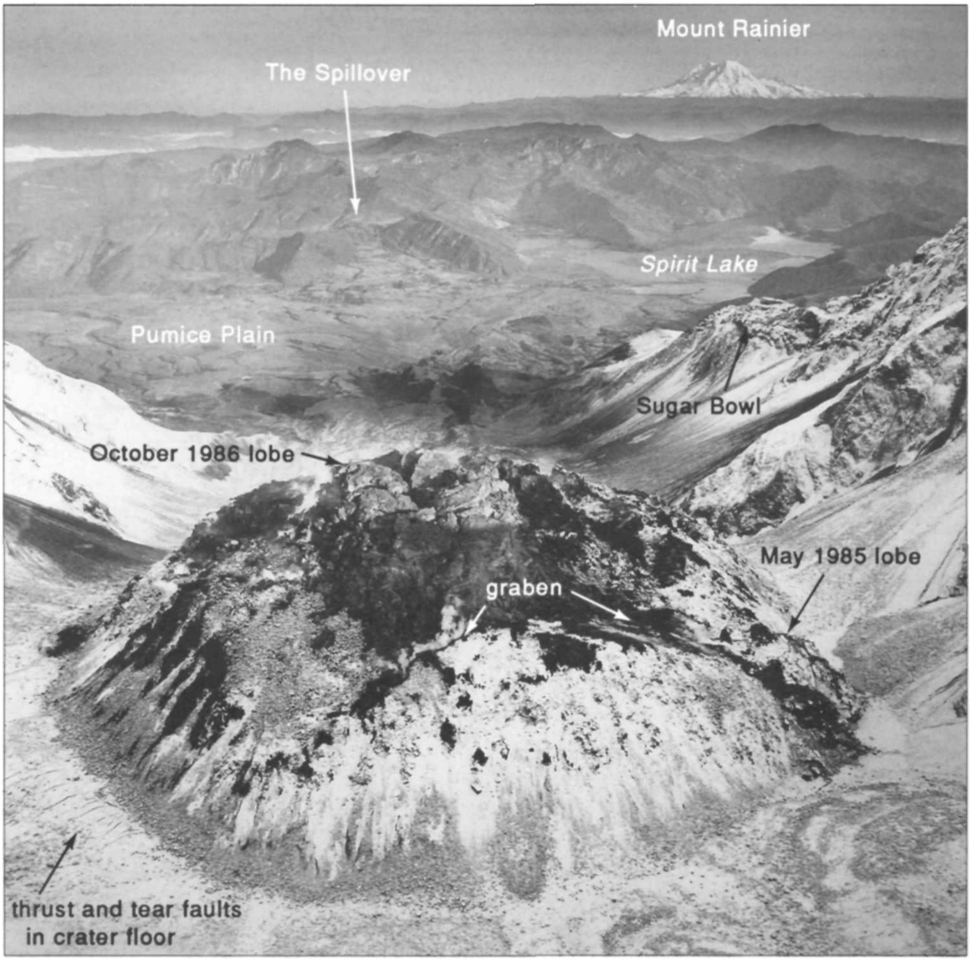


Figure 6. Lava Dome as seen from the south, showing the lobe of lava extruded on October 21 and 22, 1986. The thin lines in the snow on the west crater floor are thrust and tear faults that developed before this extrusion. Thrust faults are parallel to the perimeter of the dome, and tear faults are radial 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-

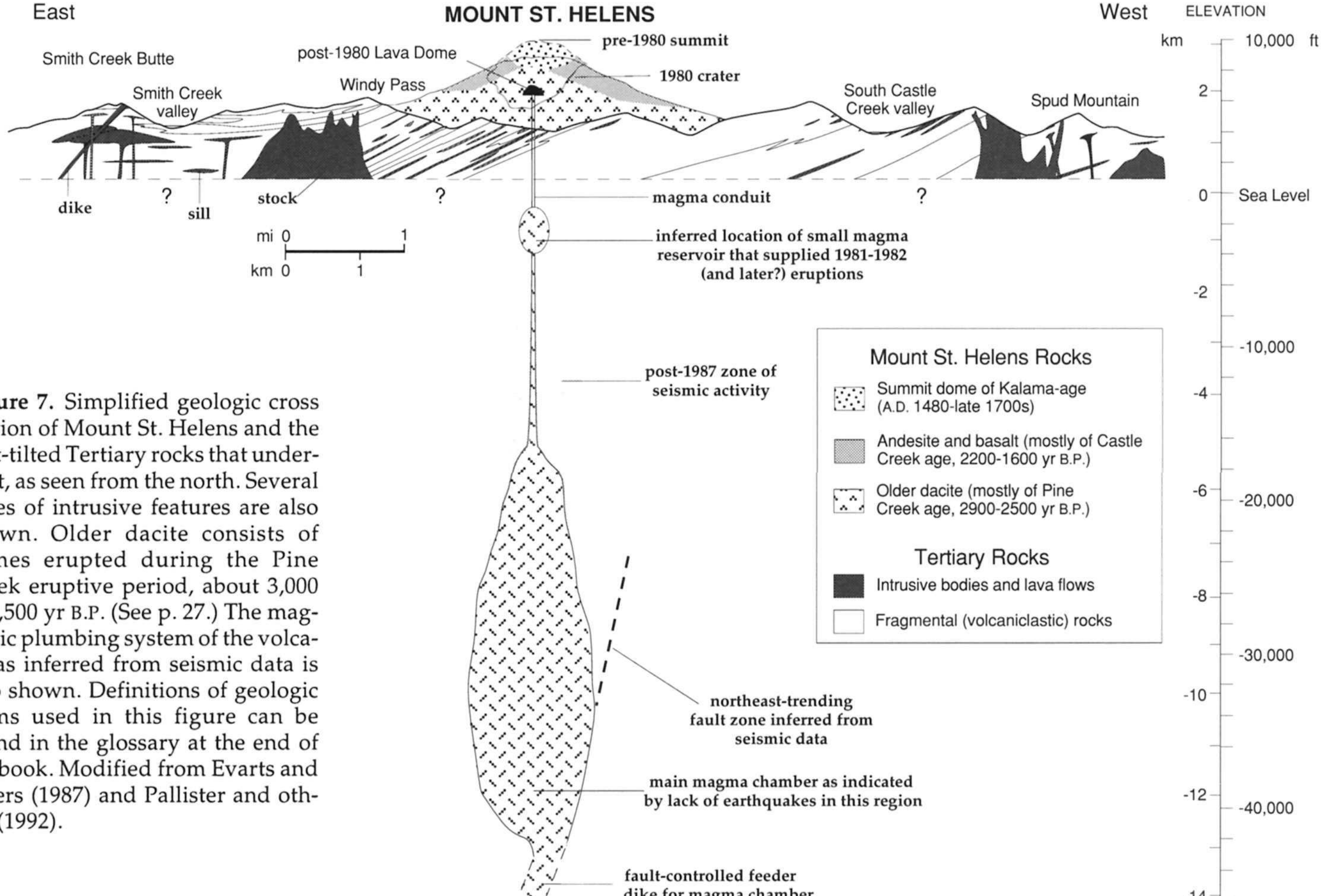


Figure 7. Simplified geologic cross section of Mount St. Helens and the east-tilted Tertiary rocks that underlie it, as seen from the north. Several types of intrusive features are also shown. Older dacite consists of domes erupted during the Pine Creek eruptive period, about 3,000 to 2,500 yr B.P. (See 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).

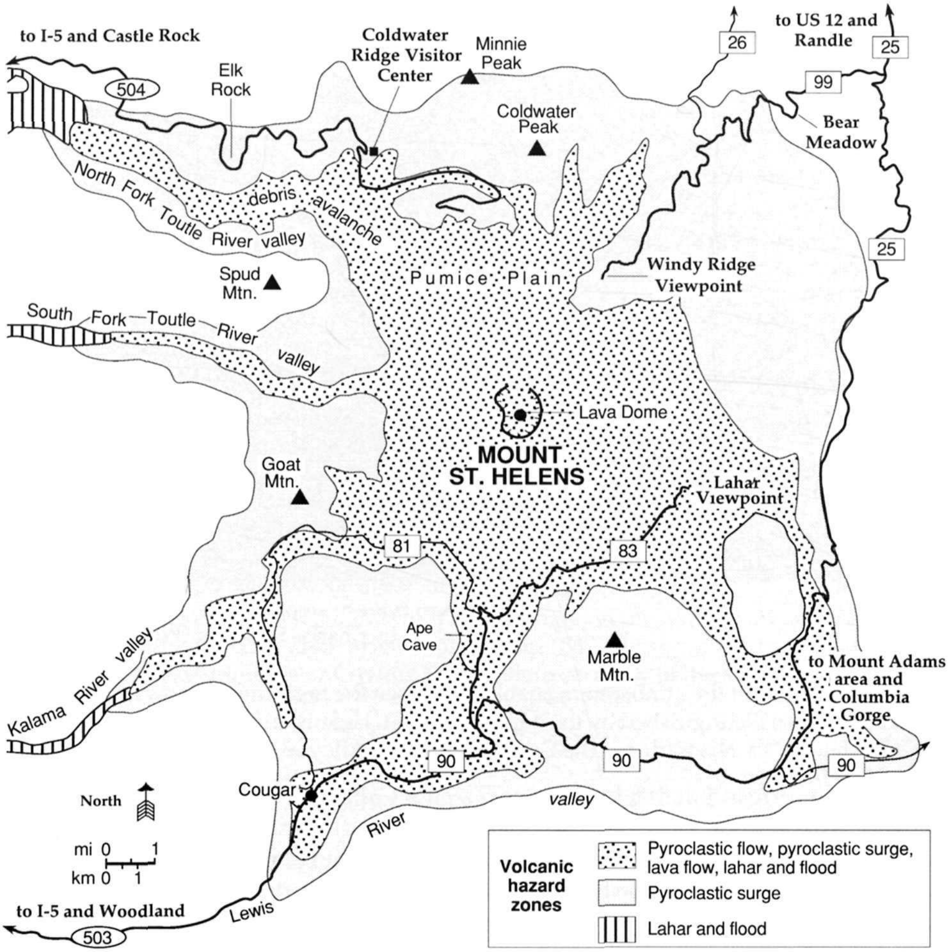


Figure 8. This preliminary volcanic hazards map, redrawn from one prepared by the U.S. Geological Survey (U.S. Forest Service, 1992), shows hazard zones close to the volcano that could be at great risk in the event of a major eruption. These areas would be evacuated and closed to the public. Such eruptive 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."

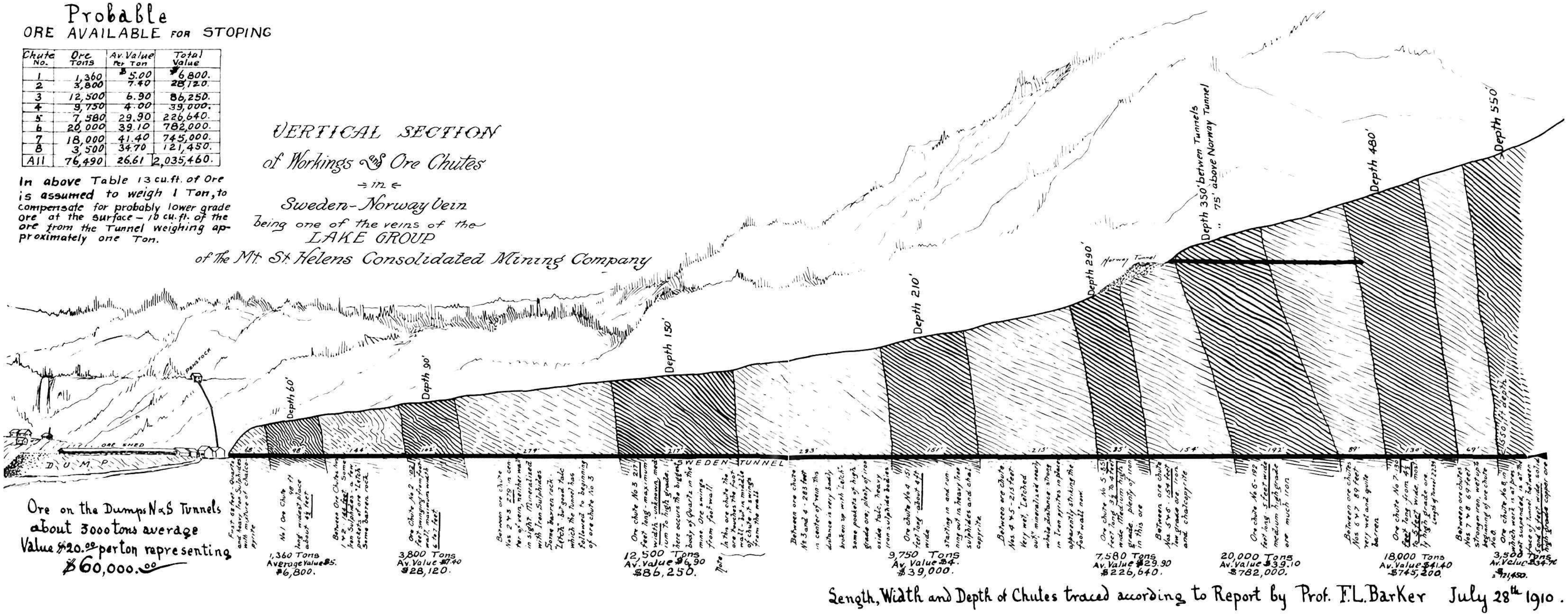


Figure 10. Diagrammatic cross section of the Sweden and Norway mines from a 1910 report by Prof. Barker of Eugene University. Areas of darker lines are ore chutes. These zones of hydrothermal alteration contained vein minerals, such as the sulfides pyrite and chalcopyrite. The Sweden tunnel was about 2,200 ft long.

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 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.

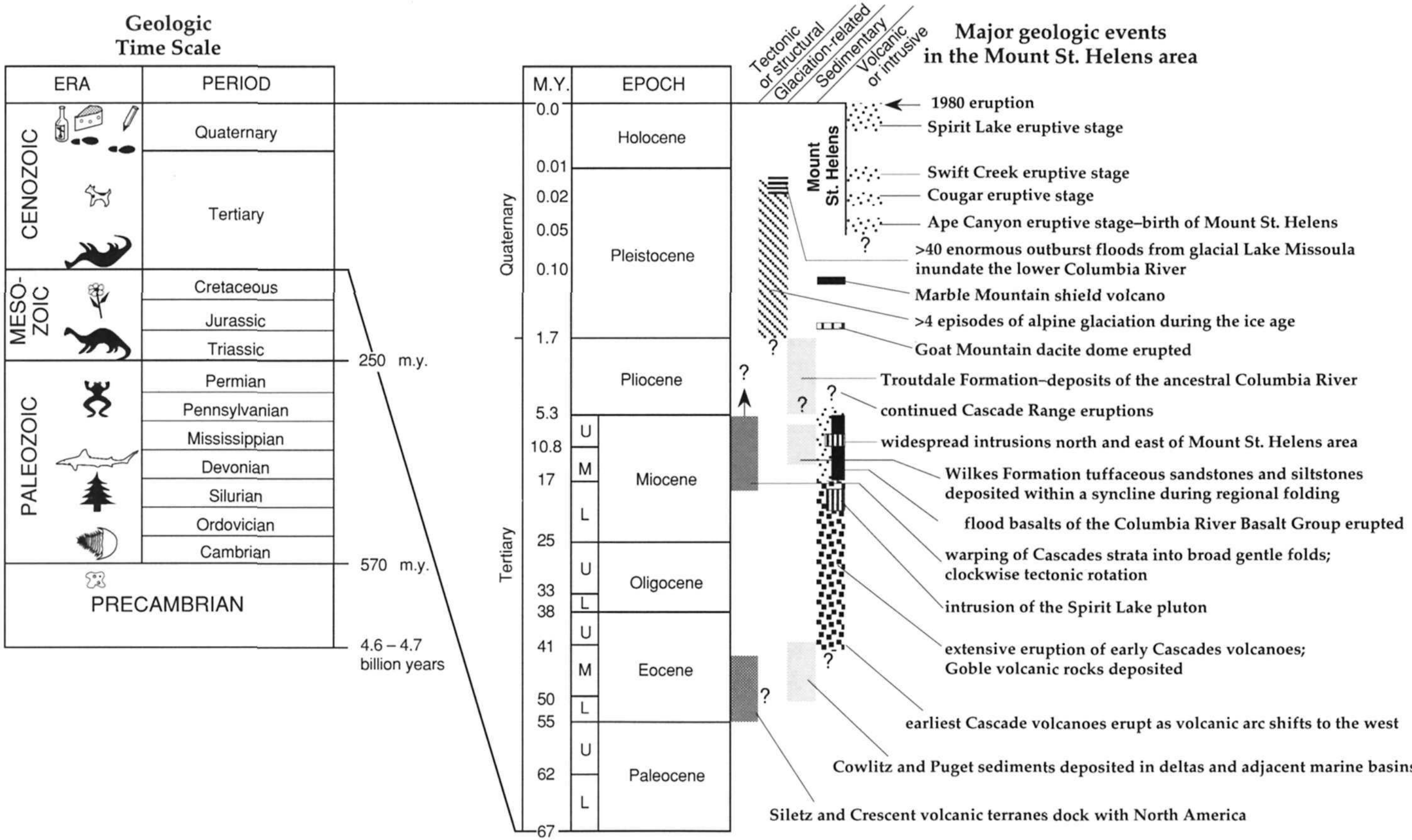


Figure 11. Simplified version of the geologic time scale (not to scale) showing major geologic events in the southwest Washington Cascades. U, upper; M, middle, L, lower; m.y., million years. The time scale is developed from those of Salvador (1985) and Aguirre and Pasini (1985). See Tables 3 and 4, 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.

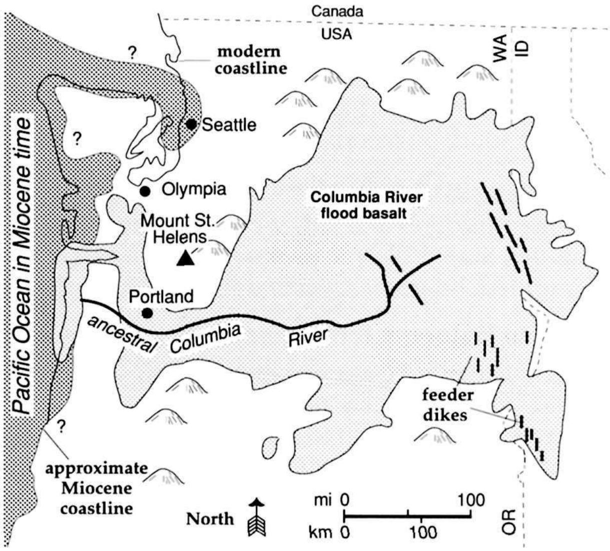


Figure 12. Miocene geography of the Pacific Northwest, showing the present location of Mount St. Helens; redrawn from Allen (1979). About 42,000 mi^3 (175,000 m^3) of lava was erupted between about 17 Ma and 6 Ma, most of it within the first several million years. During this time, more than 100 major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

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).

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).

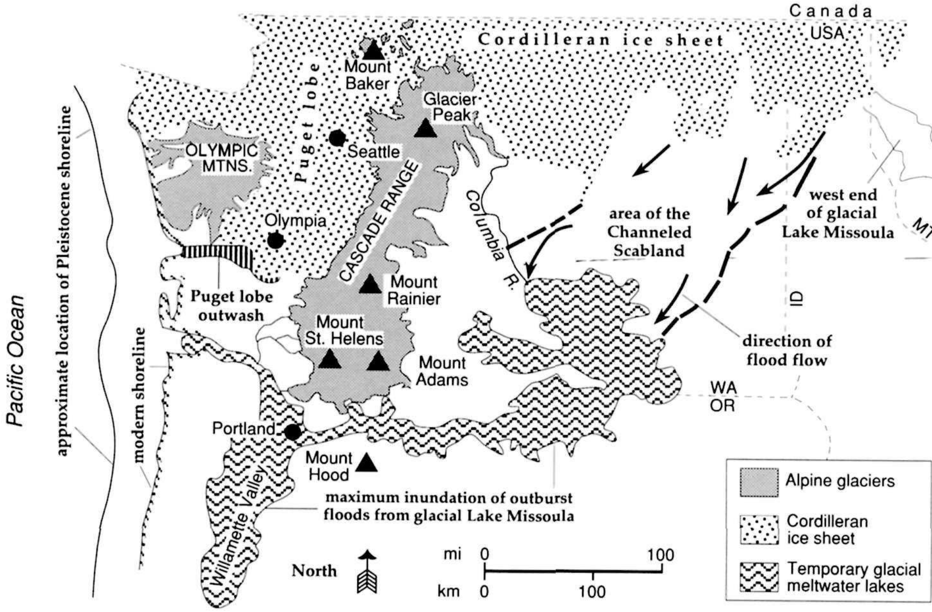


Figure 13. Diagrammatic sketch showing the approximate maximum extent of Pleistocene continental and alpine glaciers in Washington. Also shown are areas that were inundated by numerous outburst floods from glacial Lake Missoula, which filled a large valley in western Montana. The Channeled Scablands 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).

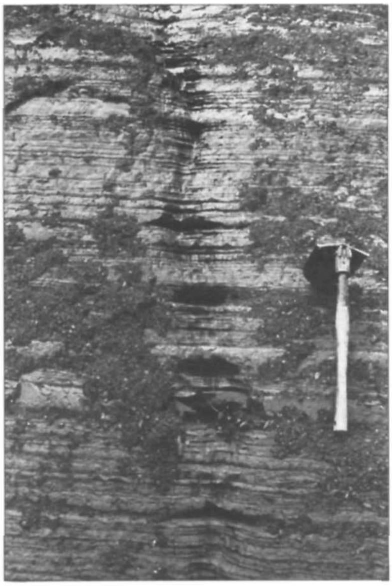


Figure 14. Annual layers of accumulated sediment (varves) deposited about 140 ka in a glacial lake of Hayden Creek age in Canyon Creek valley south of Mount St. Helens.

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

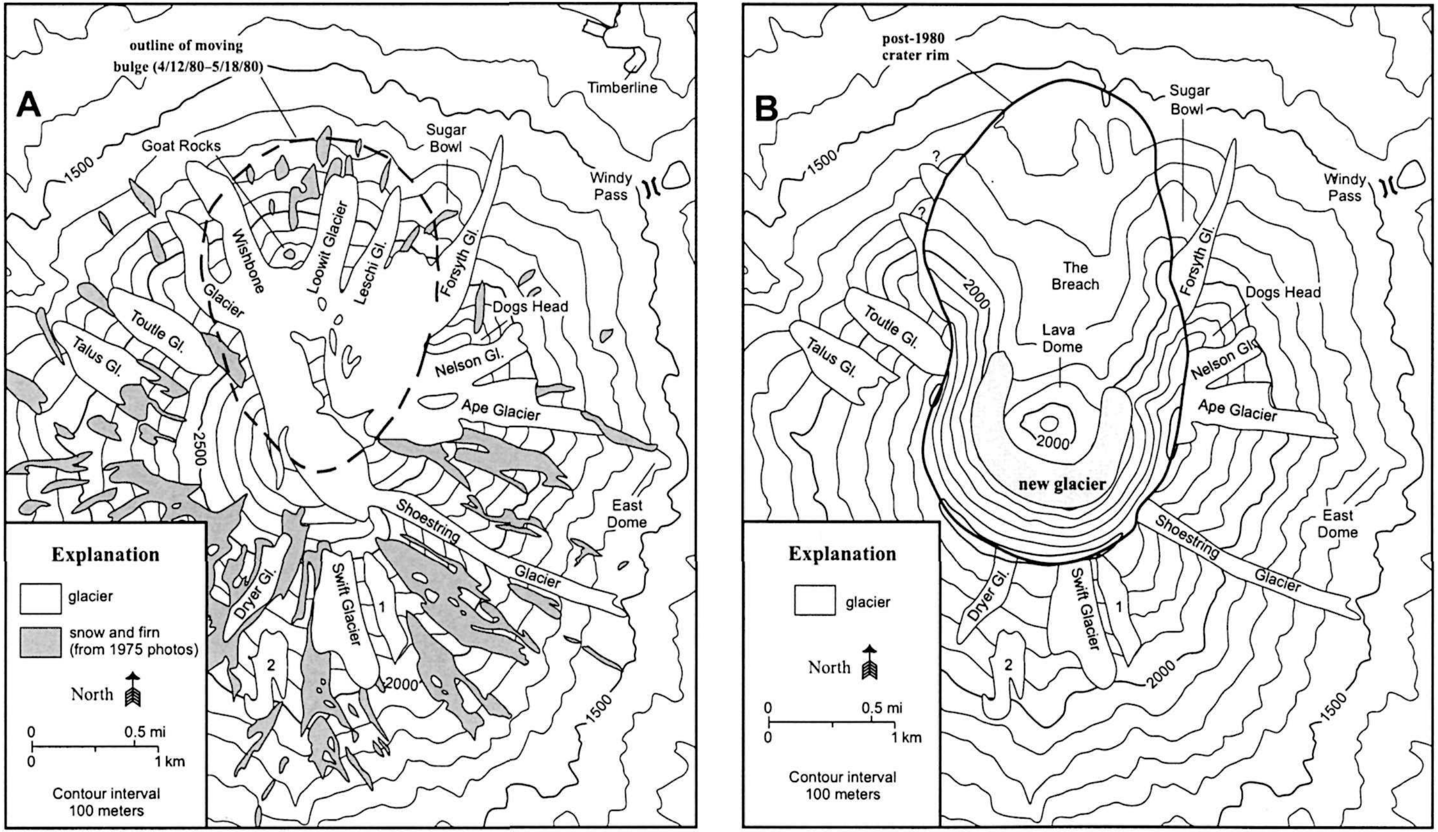


Figure 15. Glaciers of Mount St. Helens before and after the May 18, 1980, eruption. In **A**, the dashed line shows the outline of the bulge that developed on the volcano's north flank prior to the eruption. In **B**, the heavy solid line outlines the post-May 18 crater. The eruption removed more than 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.

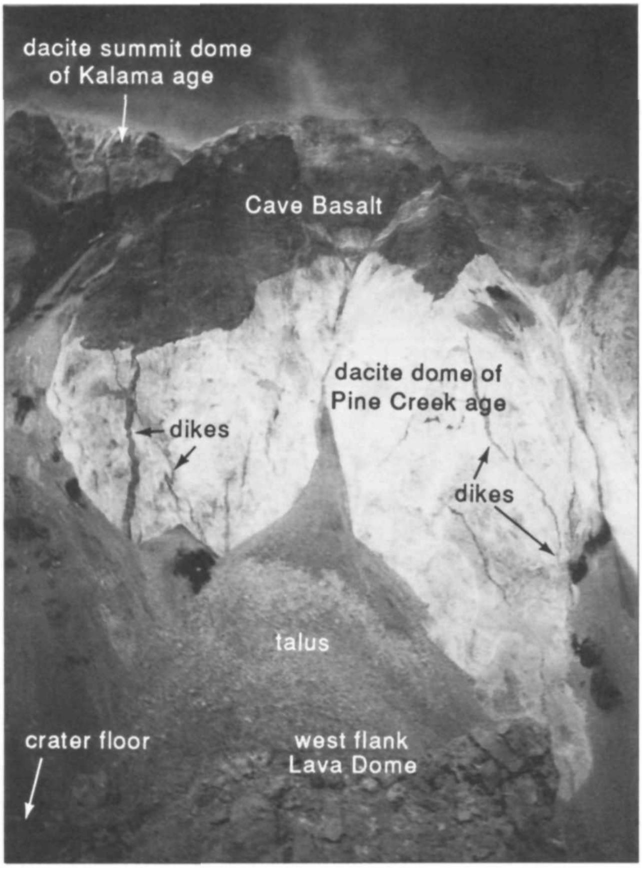


Figure 16. Wide-angle photo of the west crater wall taken from the west top of the Lava Dome. Note the dikes that intruded a dome of Pine Creek age exposed in the crater wall. The distance from the crater floor to the crater rim is about 2,000 ft (600 m).

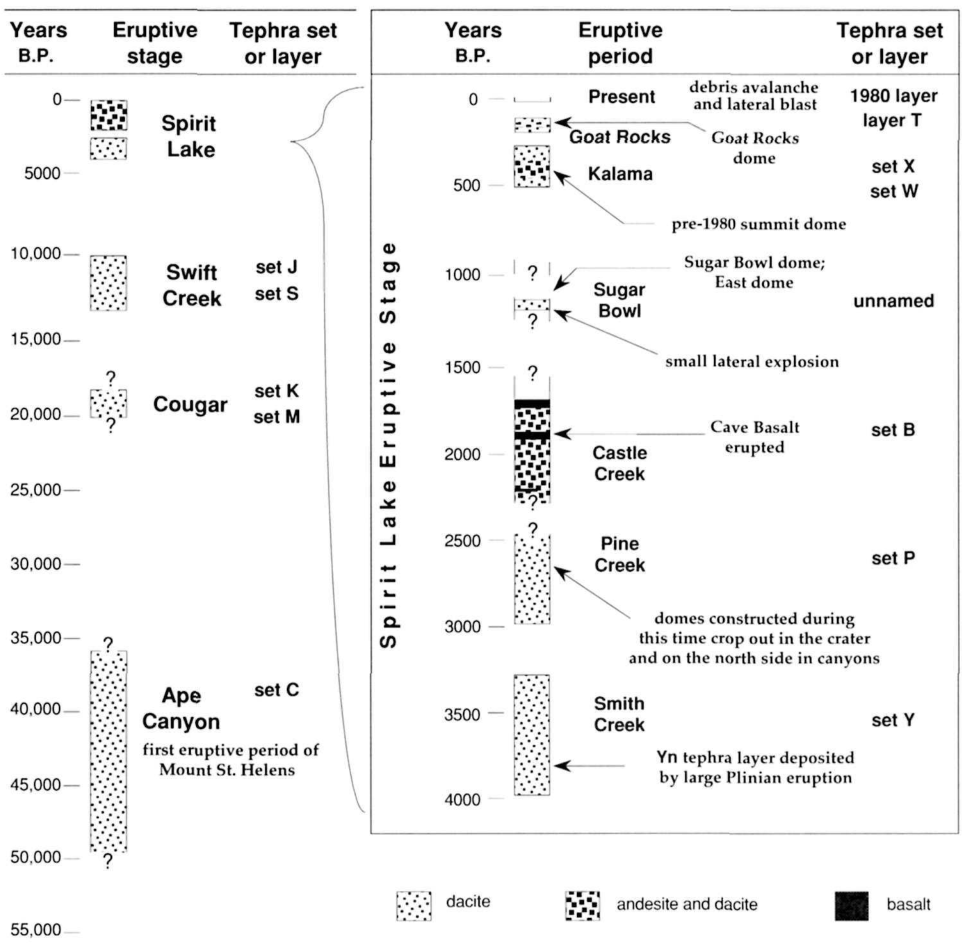
Ape Canyon Eruptive Stage (about 50 ka to 36,000 yr B.P.)

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

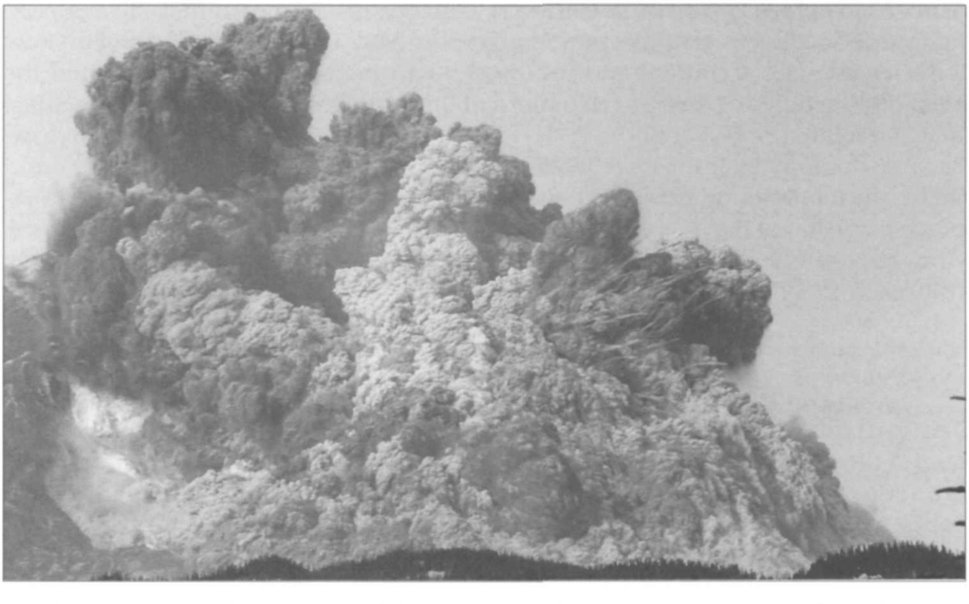


Figure 17. Initial moments of the May 18, 1980, eruption, as seen from Bear Meadow, 7 mi (11 km) northeast of the mountain. The top photo, taken about 14 seconds after the start of the eruption, shows the high-velocity cloud of the blast penetrating the second slide block of the debris avalanche and 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.

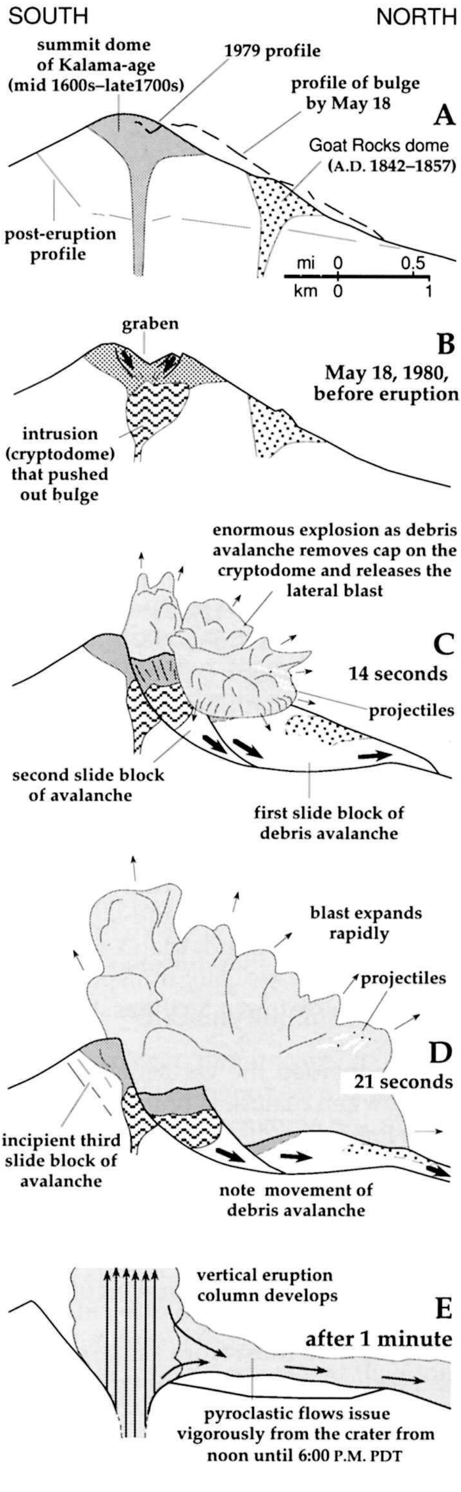


Figure 18. Diagram showing the intrusion of new magma into Mount St. Helens. The intrusion led to the formation of the bulge and disruption of the north flank of the mountain prior to the cataclysmic eruption of May 18. The failure of the individual slide blocks is discussed in the text. **A**, the configuration 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

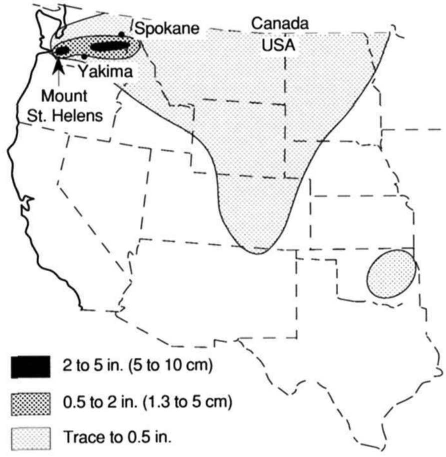


Figure 19. Extent of noticeable ash fallout from the May 18, 1980, tephra plume. Minor concentrations of ash from the same eruption traveled around the world in the stratosphere (above 36,000 ft or 11 km).

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

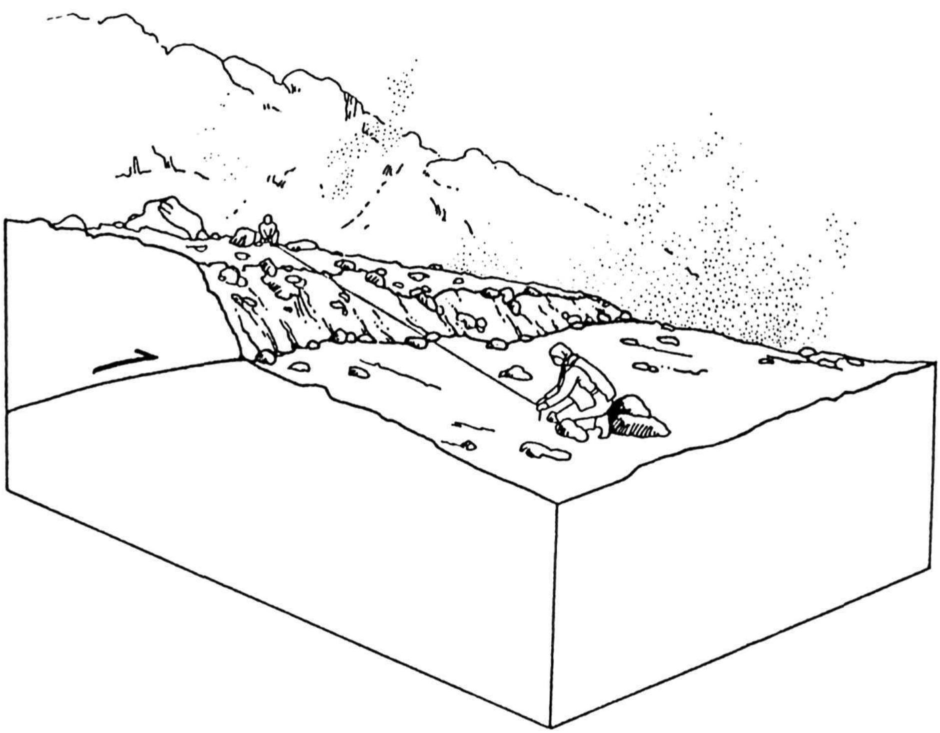


Figure 20. Measuring thrust fault motion on the crater floor adjacent to the lava dome. During 1980–1982, thrust faults were closely monitored on the crater floor. The upper block material (hanging wall, on the left part of diagram) is pushed over the lower block (foot wall) in response to magma intrusion 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 mea-

surements, 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.

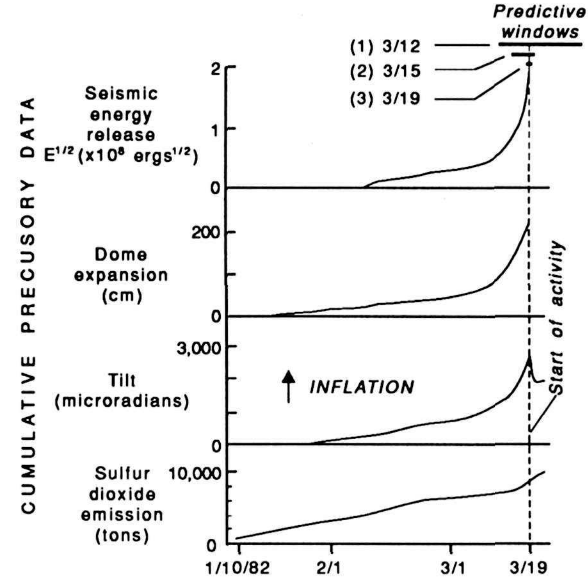


Figure 21. Increases in rates of precursory activity with time for the eruptive episode of March 19, 1982. Measurements showed simultaneous increases in several kinds of activity in the weeks preceding March 19. By relating the timing and rates of increase, scientists were able to predict the start of 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 scien-

tists 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.

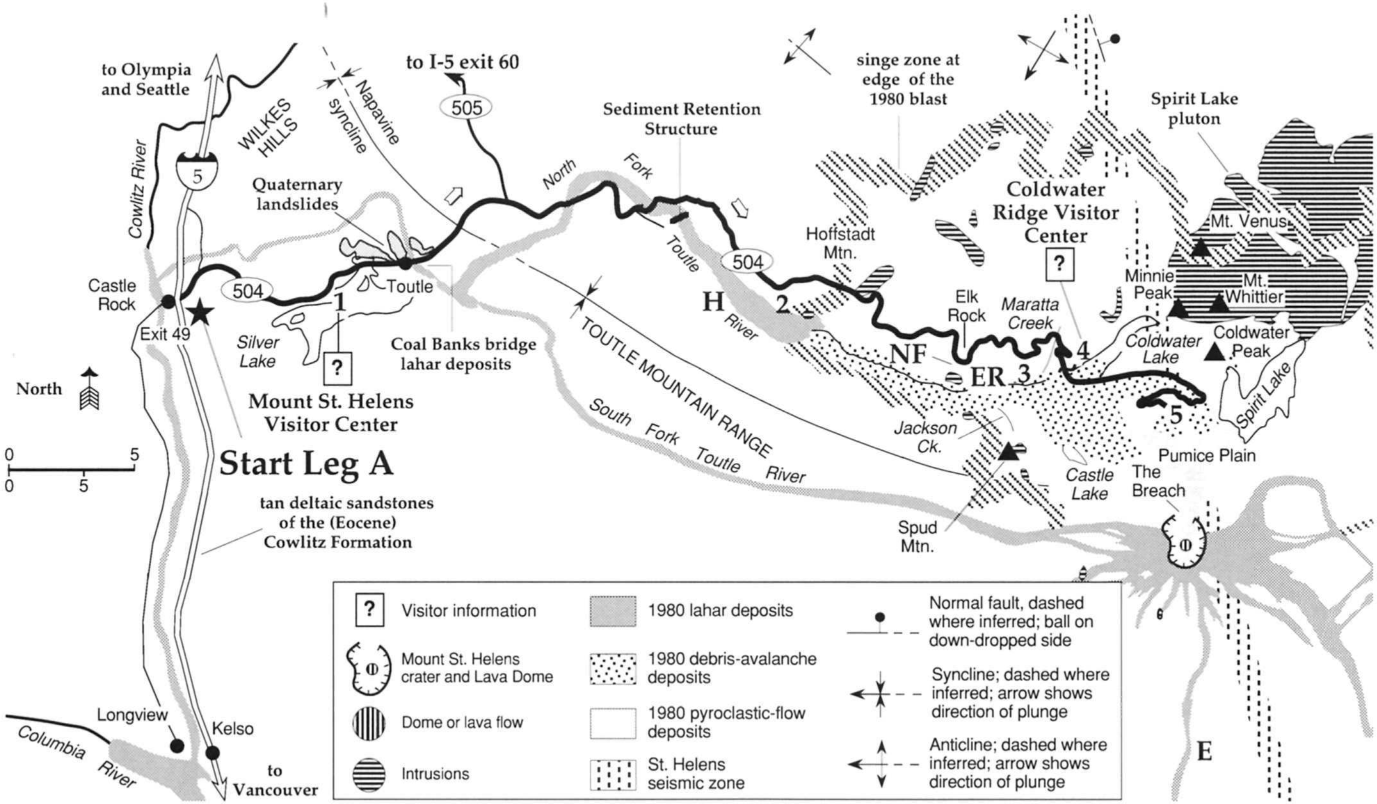


Figure 22. Sketch map for Leg A along SR 504, showing numbered road stops (referred to in text), geologic units, features, and structures, and May 18, 1980, Mount St. Helens deposits and generalized areas of devastation by the blast. E, approximate western and southern limits of glaciers of Evans Creek 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.

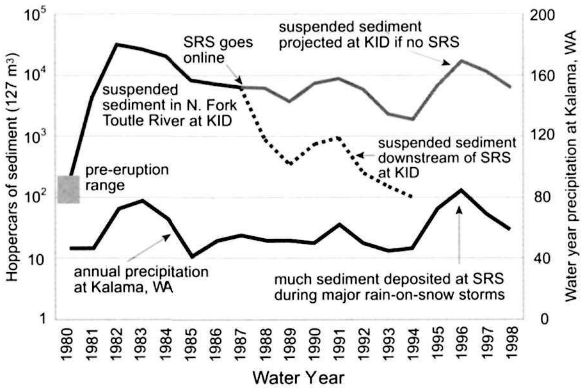


Figure 23. Graph showing the estimated suspended-sediment load in the Toutle River near Kid Valley (KID) for water years 1980 to 1998 plotted with annual precipitation measured at Kalama, Washington. (A water year begins on October 1 of the previous calendar year.) Kid Valley is about 27 mi (45 km) downstream 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).

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—

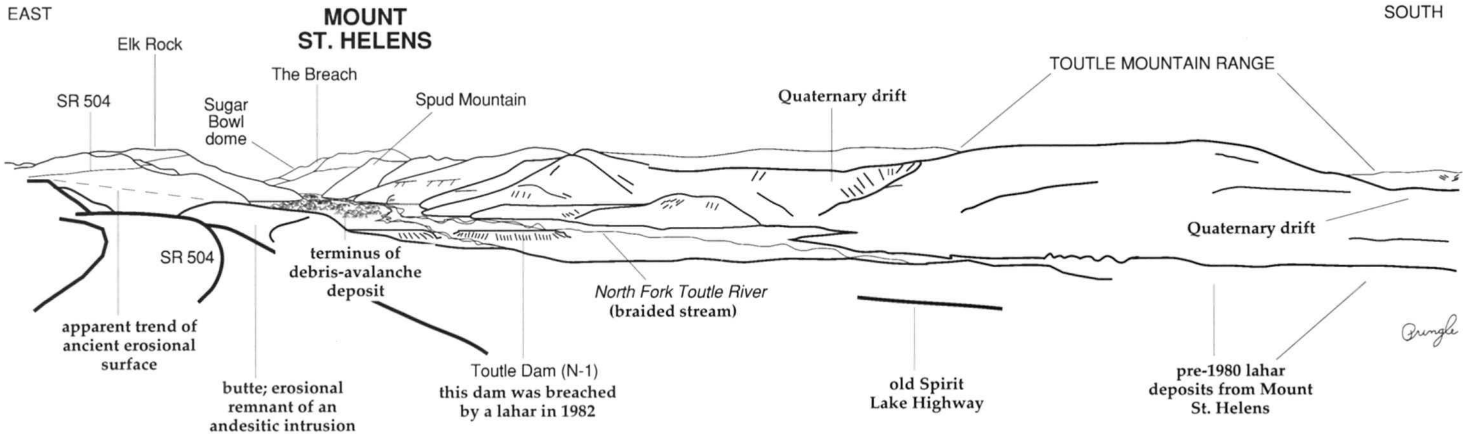


Figure 24. Panorama to the east and southeast from Hoffstadt Viewpoint, about 15 mi (25 km) from Mount St. Helens. The numerous hummocks of the 1980 debris-avalanche deposit dot the valley bottom of the North Fork Toutle River in the distance. Its terminus is slightly upstream of the N-1 dam. The dam 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.

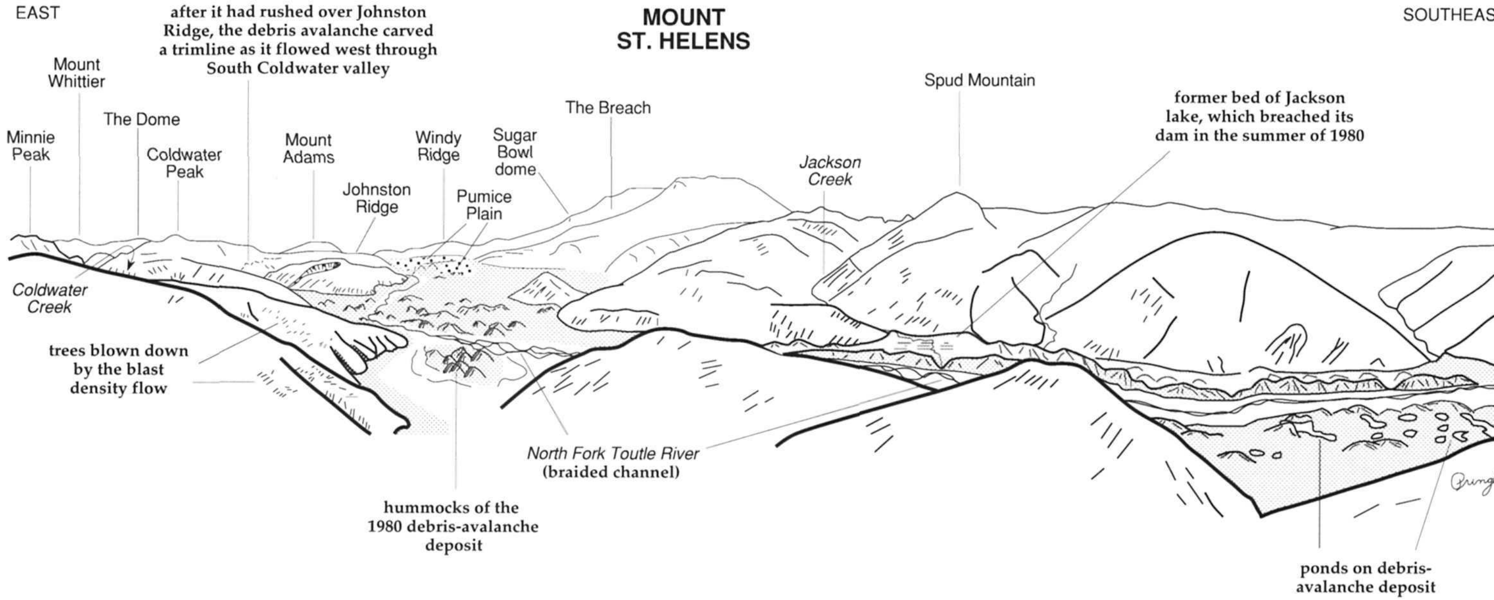


Figure 25. Panorama from Elk Rock Viewpoint, about 10 mi (15 km) from Mount St. Helens. The North Fork Toutle River has been incising and laterally eroding the hummocky 1980 debris-avalanche deposit. To the south, numerous ponds are visible on the surface of the avalanche. Jackson Creek was one of many 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.

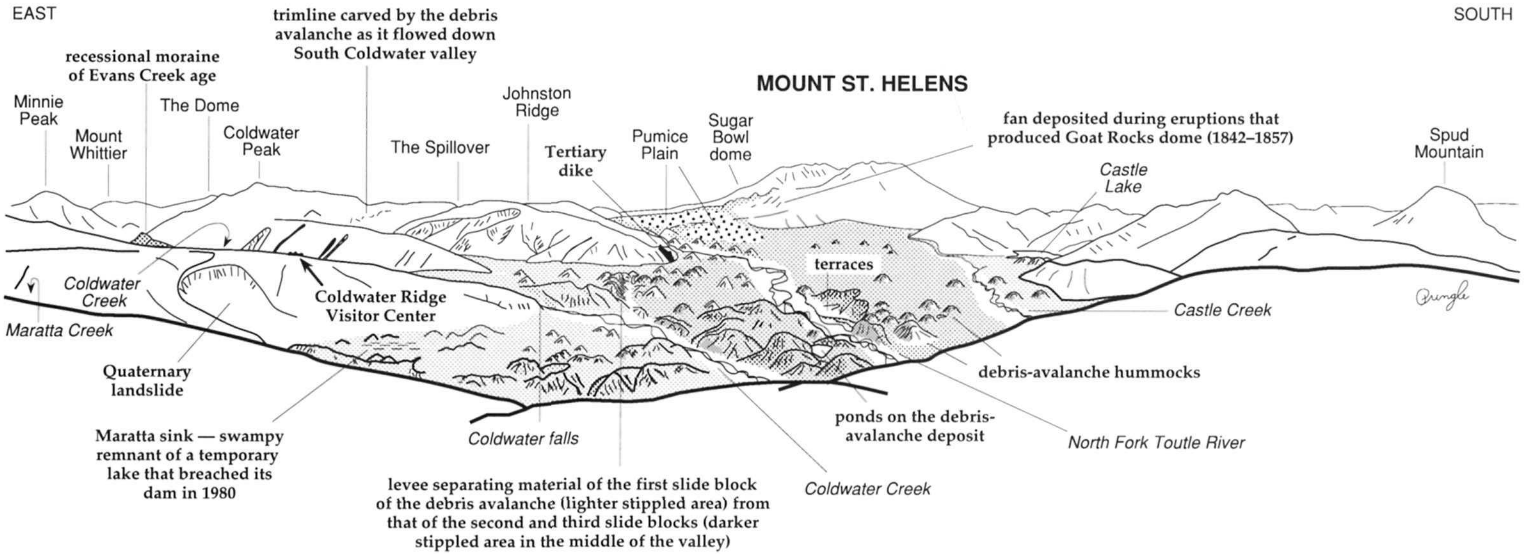


Figure 26. Panorama to the southeast from the Castle Lake Viewpoint, about 8 mi (13 km) from Mount St. Helens. This site presents a spectacular vista of the hummocky debris-avalanche deposit of May 18, 1980, and Mount St. Helens in the background. Sugar Bowl is an ancient lava dome. Goat Rocks fan is 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

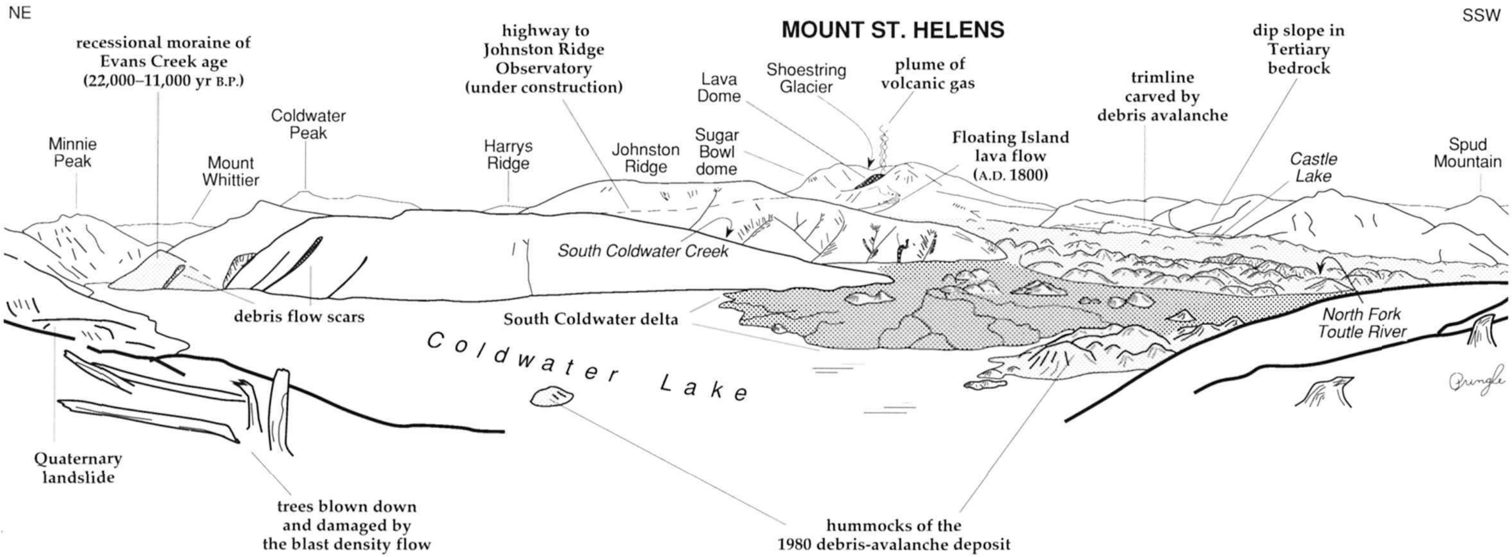


Figure 27. Panorama from the Coldwater Lake Visitor Center, about 7 mi (11 km) from Mount St. Helens. Coldwater Lake was created when Coldwater Creek was dammed by the 1980 debris-avalanche deposit. Most of the South Coldwater delta has been constructed since 1985, when a drainage tunnel through Harrys 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-*

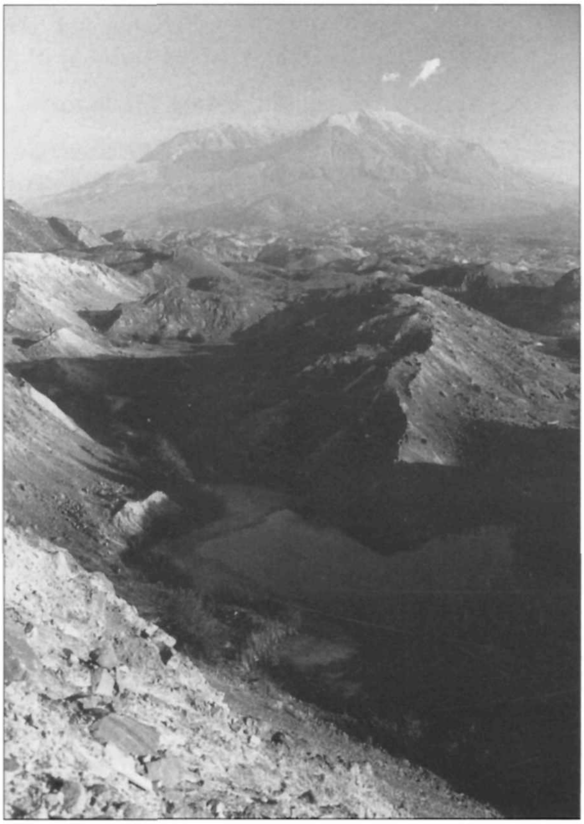


Figure 28. Debris-avalanche hummocks along the Hummocks Trail, Mount St. Helens in the background. The prominent scarp in the left foreground is the levee that separates material of the first slide block (left) from that of the second and third slide blocks (right). Photo taken in 1991.

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.

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.

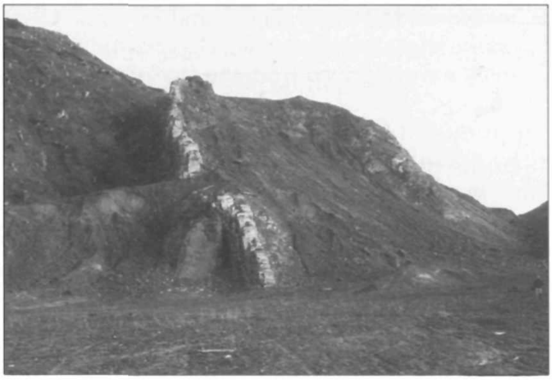


Figure 31. View east of a resistant, wall-like Tertiary dike in the west toe of Johnston Ridge along the Boundary Trail. Note that the debris-avalanche deposit on the upstream (right) side of the dike is 16 ft (5 m) higher due to runup. This runup indicates that the velocity of the flow was at least 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).

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

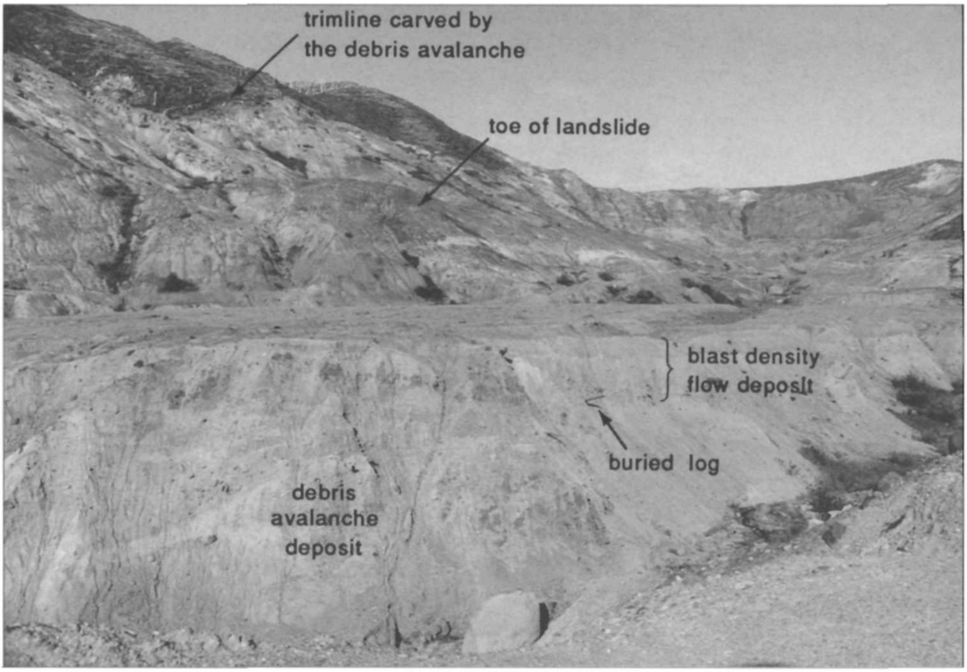


Figure 32. Blast deposit overlying deposits from the debris avalanche in the South Coldwater valley. View is to the northeast. Note the trimline cut by the debris avalanche. Downcutting and lateral erosion by South Coldwater Creek has undercut the toe of, and apparently reactivated, a landslide in Tertiary 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

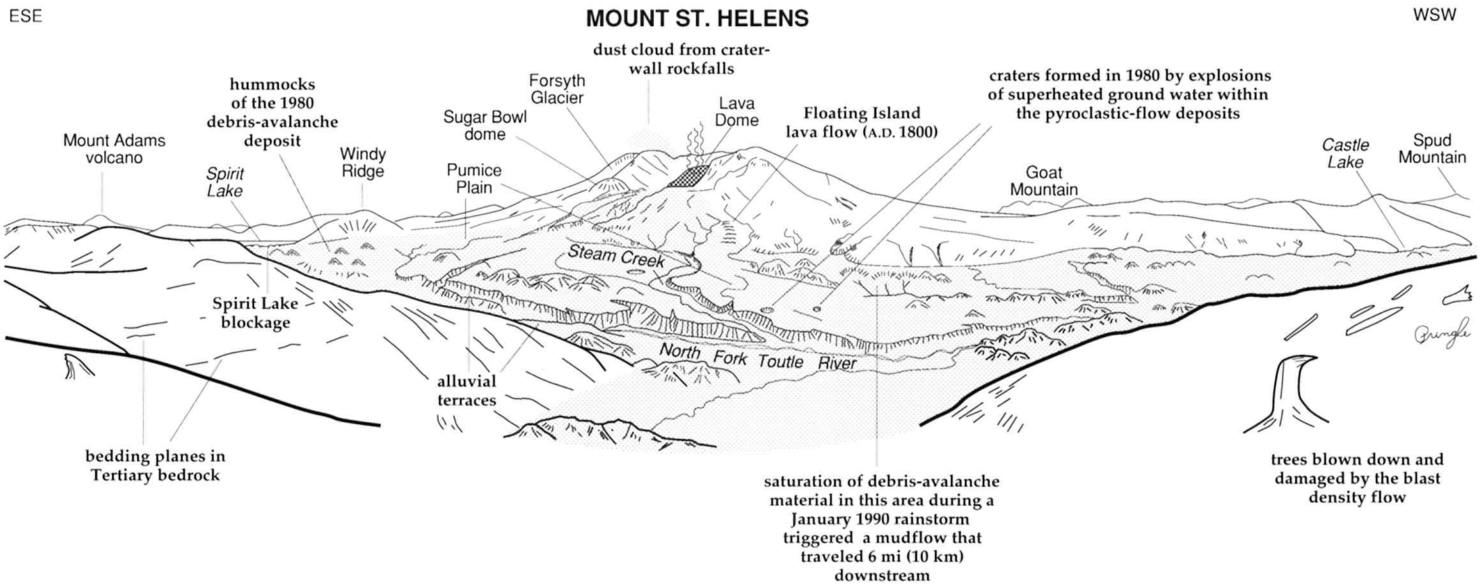


Figure 33. Panorama from the proposed Johnston Ridge Observatory to Mount St. Helens, about 4 mi (7 km) to the south. A visible volcanic gas plume often rises from the Lava Dome, a pile of viscous dacite lava that has been constructed in the center of the crater during the 17 eruptive episodes since 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.

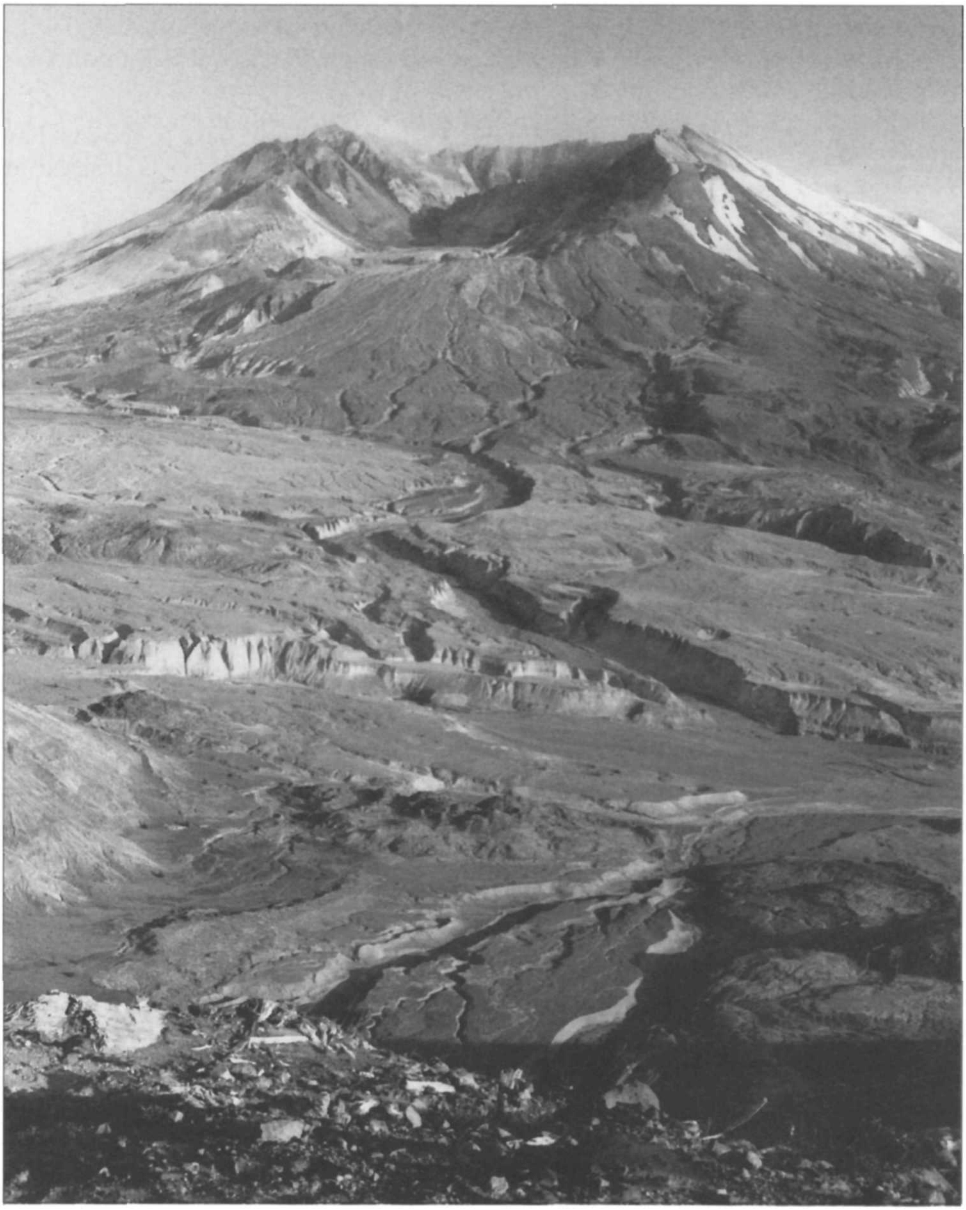


Figure 34. Mount St. Helens and the Pumice Plain from Johnston Ridge in 1991.

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.

(3) The slide-block material was followed closely by the main *surge* from the blast, which moved at speeds greater than 650 mi/hr (286 m/s). The blast left a sandy, rubbly deposit containing abundant *blast dacite*, remnants of the *cryptodome* that had intruded the mountain and pushed out the bulge. This flow deposit formed a veneer on the surfaces of some of the hummocks and was plastered on valley walls.

(4) Within minutes after the blast swept across Johnston Ridge and into South Coldwater Creek valley, the hot, freshly deposited material started to slide off many of the slopes steeper than about 25 degrees and flowed to the valley bottom as a secondary pyroclastic flow, covering many of the deposits mentioned in (3) with a layer of sand and rocks 3.5 to 7 ft (1–2 m) thick. The surface of this redeposited blast material is fairly flat and is banked up against the valley walls and fills the swales between the hummocks of the underlying debris avalanche. The blast may have consisted of two separate explosions. Eyewitnesses north of the volcano reported two distinct pulses that were more than a minute apart (Hoblitt, 1990). If so, the first was probably magmatic and the second phreatomagmatic (a reaction of the *magma* with the water contained in the mountain).

(5) All of the above deposits were then covered by a layer of *accretionary lapilli* that fell from the great mushroom cloud (p. 32) (including mudballs reported by some eyewitnesses) and, in areas nearer the volcano, by ash fallout from the ongoing pyroclastic flows as well.

(6) Beginning at about 9:00 A.M. and increasing in intensity until about noon, pyroclastic flows swept down the north face of Mount St. Helens and filled low spots between the freshly deposited hummocks of the debris-avalanche deposit to depths greater than 100 ft (30 m). These flows, dominantly fresh pumice, were driven by volcanic gases and gravity. Hot clouds of ash, pumice, and gas rose out of these pyroclastic flows and became turbulent surges of this light material. The surges left bedded ash-cloud deposits as deep as 30 ft (9 m). By late afternoon on May 18, the eruption column had subsided, and pyroclastic flows were on the wane. The flat, light-tan surface formed by the overlapping sheets, tongues, and lobes of the pyroclastic deposits is called the Pumice Plain.

For a more complete overview of the events occurring on the morning of May 18, 1980, refer to p. 29.

Temperatures in the pyroclastic-flow deposits were 780°F (415°C) two weeks after the eruption. Pits as much as 200 ft (60 m) across are scattered across the surface of the Pumice Plain. These *rootless explosion craters* near the northern margins of the Pumice Plain were created when ground water came in contact with the hot pyroclastic-flow deposits, causing steam-driven explosions. The deposits remained hot (above the local boiling point) for several years after the eruption, and steam explosions continued into 1982, some generating plumes of ash and steam that rose as high as 12,000 ft (3,660 m).

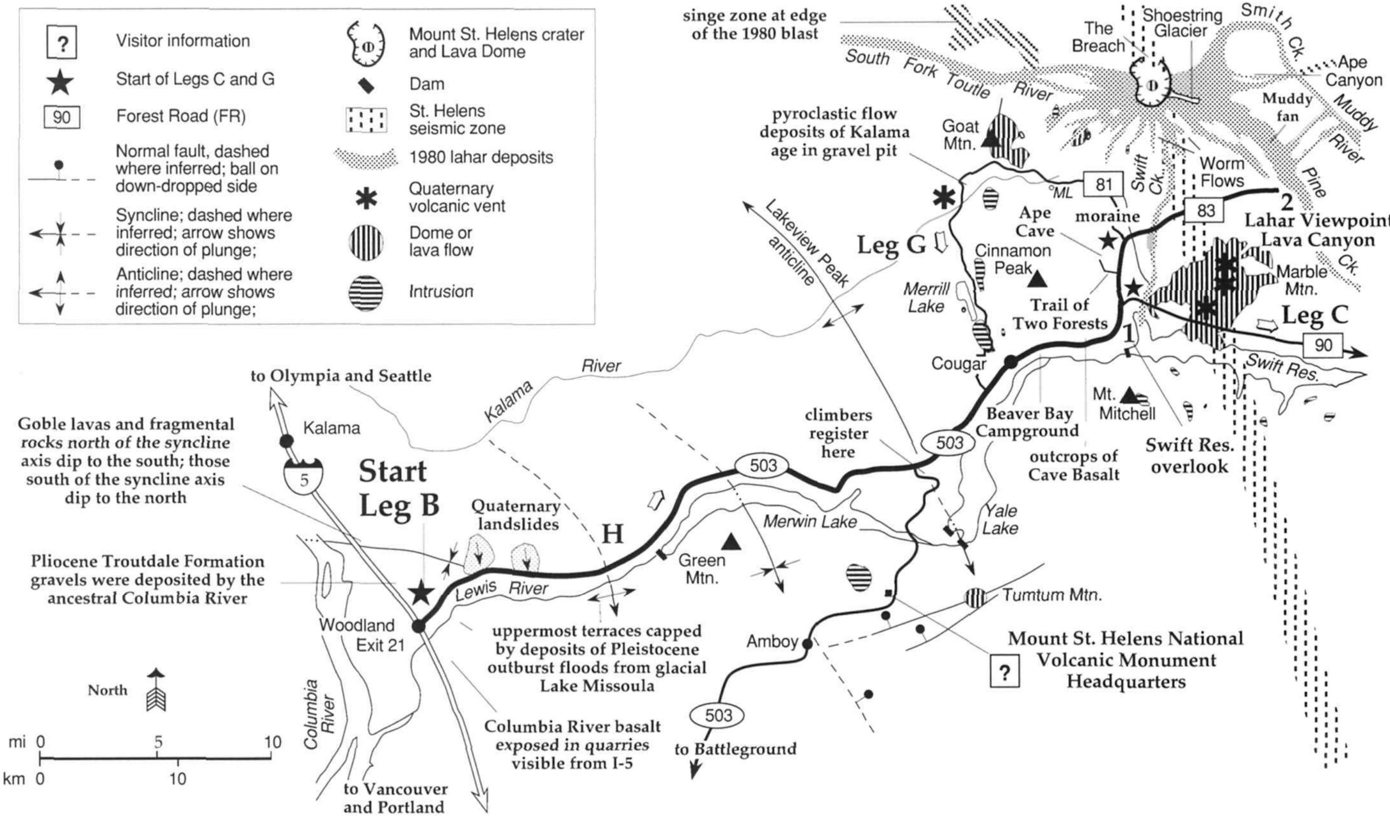


Figure 35. Sketch map of Leg B, showing numbered road stops (referred to in text) and areas of interest. Route of optional Leg G is also shown. (See p. 93.) Geologic features, structures, and deposits are shown, along with areas devastated by the 1980 lahars and blast. H, approximate maximum extent of a valley glacier that extended down the Lewis River valley about 140 ka (Hayden Creek age); *ML*, McBride Lake.

LEG B: SOUTHERN APPROACH—LEWIS RIVER VALLEY

Via State Route 503 and Forest Roads 25 and 83

This route to Mount St. Helens winds through the Lewis River valley and approaches the volcano from the south by way of Cougar (Fig. 35). It also provides access to Legs C and G. The route passes over ancient deposits derived from Mount St. Helens, *outwash* deposits left by alpine *glaciers*, and flat, silty and sandy terraces capped by the Missoula floods deposits. After about 9 mi (14 km), the road enters terrain carved by alpine glaciers more than 100,000 years ago and passes through a large, gentle *fold* in *Tertiary* bedrock. Conspicuous zones of red rock are ancient soils and other deposits baked by Tertiary *lava* flows.

A quarry high on the east valley wall of the Lewis River, about 0.6 mi (1 km) south of the Woodland exit on Interstate Highway 5 (I-5), has been cut into a flow of the Grande Ronde Basalt (16.5–15.6 Ma) of the Columbia River Basalt Group. This lava flow originated hundreds of miles (kilometers) to the east. The Columbia River Basalt Group is typical of a rare class of lava flows which, because of their enormous volumes, are called *flood basalt*. (See p. 19 and Fig. 12.)

Distances along the route are given in miles followed by kilometers in brackets.

<u>Distance</u>

0.0 [0.0] Mileage starts at I-5. State Route (SR) 503 has tight curves and truck traffic. Please drive carefully!

Terraces between 120 and 180 ft (36.6 and 54.9 m) elevation are visible on either side of the Lewis River for the first 3.5 mi (5.6 km) (Figs. 35 and 36). These terraces are composed of sand, silt, and gravel deposited by late Pleistocene *outburst floods* from glacial Lake Missoula. These enormous floods occurred between 15,300 and 12,700 yr B.P. when a large lake filling the Clark Fork valley in western Montana repeatedly breached its ice dam. The released water flooded parts of Idaho, Washington, and Oregon. (See p. 20 and Fig. 13.) More than 80 separate flood events are recorded in the sediments (although no one locality preserves evidence of all of these floods). The floodwaters racing north down the Columbia River near here were slowed by the bedrock narrows north of Kalama and formed a temporary lake at least 400 ft (120 m) deep upstream to Portland and into the Willamette Valley as far as

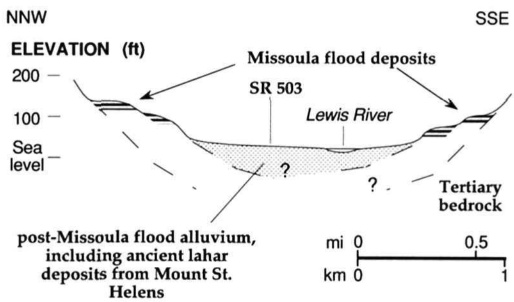


Figure 36. Diagrammatic cross section of the lower Lewis River valley about 1 mi (1.6 km) east of Woodland. Upstream view showing terraces made of Missoula flood deposits. The elevation of the deposits here indicates that the largest of more than 80 floods resulting from breakouts of glacial Lake Missoula (between 15,300 and 12,700 yr B.P.) backflooded this valley to a depth of more than 200 ft (60 m).

Eugene, Oregon. The composite thickness of these flood deposits is as much as 100 ft (30 m) in this area along I-5.

Terraces at lower elevations are cut in flood deposits of the Lewis River that are interstratified with *lahar* and *lahar-runout* deposits from Holocene eruptions of Mount St. Helens.

0.8 [1.3] One of the high terraces mentioned above is visible south of the river.

1.4 [2.2] Another high terrace.

2.7 [4.3] Quaternary landslide deposits on your left.

7.4 [11.8] The road rises to the top of, and for a short distance follows, a Missoula flood terrace.

9.7 [15.5] Bedrock *outcrops* of the Goble Volcanics (Tertiary) mark the westernmost appearance of rocks of the Cascade Range along this leg. The road passes through the axes of three folds in these rocks before reaching Cougar.

11.8 [18.9] A pullout provides a view of Merwin Dam.

13.4 [21.4] Thin beds of *coal* are visible under some lava flows. This lower Tertiary coal formed when peat deposits in abandoned river channels were buried by subsequent volcanic sediments or lava flows. Strata here dip to the north or northeast—they are the northeast limb of a southeast-plunging *anticline*. Red "baked" zones are oxidized soils beneath the lava flows, which indicates that these lavas were flowing over the land surface here.

15.2 [24.3] The broad, U-shaped valley visible to the south was carved by a large Pleistocene glacier or glaciers that occupied the Lewis River valley. Most of Green Mountain, the east-trending ridge to the south, was buried by ice during this glaciation. *Drift* deposits are visible at 17.6 mi (28.2 km).

20.0 [32.0] Tumtum Mountain, a small cone-shaped *volcanic dome* complex(?), is visible in the distance to the southeast. This *dacite* dome is adjacent to, and may be younger than, a *lateral moraine* of Hayden Creek age (about 140 ka). However, a *fission-track age* of about 12.5 Ma was obtained on zircon crystals from outcrops in a quarry on the north side of the mountain.

23.6 [37.8] Continue straight east at the intersection with SR 503, crossing a fairly flat surface that extends to the town of Cougar. This terrace is part of an extensive fan of fragmental volcanic debris composed of Mount St. Helens lahars and lahar runouts older than those of the Pine Creek eruptive period (about 2,500 yr B.P.).

26.0 [41.6] Yale Lake. Mount St. Helens can be seen in the distance from along the road. A quarry in Tertiary *andesite* (north side of the road) is near the axis of the Lakeview Peak anticline, and rocks there are almost horizontal.

28.6 Cougar. Remnants of Amboy Drift (glacial deposits of Hayden Creek age) are visible in roadcuts to the east of Cougar. *This is the last fuel stop before the 100-mi trip to Randle via Windy Ridge or the 160-mi round trip to Windy Ridge.*

31.4 [50.2] Lahar deposits of Castle Creek age (2,200–1,600 yr B.P.) underlie the Beaver Bay Campground east of Cougar. From the campground, you can walk a few hundred feet to the shore of Yale Lake and examine lahar deposits exposed there. When the water level is low (controlled at the dam), older clay-rich deposits crop out below the lahar along the beach berm.

31.7 [50.7] The Cave Basalt flows, erupted from Mount St. Helens during the Castle Creek eruptive period, are visible on the left past the rock embankment of the Swift Reservoir spillway. The eruption of this very fluid lava is unique in the history of Mount St. Helens. (See p. 27.)

Numerous mounds on the flow surface are tumuli. A tumulus forms when a *lava tube* becomes plugged and lava pressure builds within the tube upstream of the blockage, eventually bulging the surface upwards. (See p. 64.) The pine, cedar, western hemlock, and Douglas fir trees on these flows are stunted because the soil is rocky and poorly developed.

At the Skamania County line, SR 503 becomes Forest Road (FR) 90. Continue across the hydroelectric power canal and up the hill. An ancient *debris-avalanche* deposit is exposed in the roadcuts on the left; the reddish deposits are now almost covered by alder trees. This avalanche apparently occurred during an early part of the Cougar eruptive stage (20,000–18,000 yr B.P.). Similar deposits crop out along FR 81 near McBride Lake, about 4 mi (6.4 km) from FR 83. (See p. 92.)

34.9 [55.8] **STOP B-1: SWIFT RESERVOIR OVERLOOK**. This overlook is a good place to stop and view geographic features constructed during several eruptive stages of Mount St. Helens. (See Table 3, p. 25.) The terrace on which the parking lot is situated is the remnant of a debris fan constructed during the Cougar eruptive stage. A dissected part of the fan is visible on the south valley wall downstream.

Underlying this fan is a very old Mount St. Helens lahar deposit of the Ape Canyon eruptive stage (older than 36,000 yr B.P.). It crops out in the bank of the Lewis River downstream (not visible from here). Holes drilled into the valley bottom near the Swift Reservoir dam site penetrated an even older lahar deposit whose base is 160 ft (49 m) below the surface. The debris-avalanche deposit of Cougar age mentioned at 31.7 mi (50.7 km) overlies these two lahar deposits. *Pyroclastic-flow*, lahar, and *tephra* deposits of Cougar age overlie the debris-avalanche deposit. The pyroclastic-flow deposit exposed in a borrow pit across the road to the west traveled more than 10 mi (15 km) from the mountain.

A lahar deposit underlying the terrace is visible through the fence on the east side of the parking lot. To the east and across a bay on the north side of Swift Reservoir is a lower, younger fan composed of material deposited during the Swift Creek eruptive stage (13,700–9,200 yr B.P.).

If you look to the north-northeast, you can see Marble Mountain, a *shield volcano* composed of three *scoria* cones. An *andesite* cone on the south flank of Marble Mountain was built during the last eruption from the shield about 160 ka. Marble Mountain is part of a zone of volcanoes that extends from

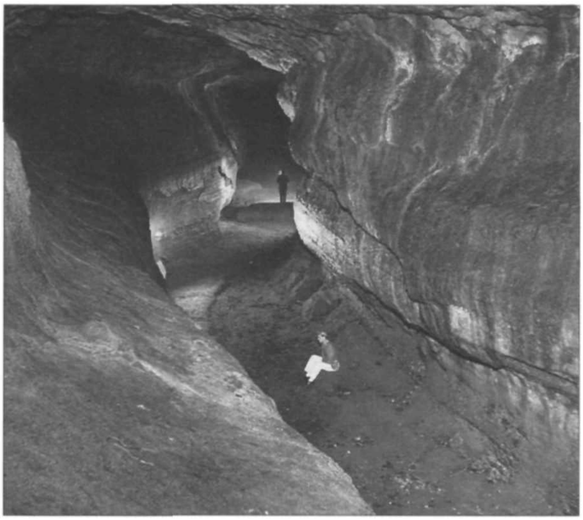


Figure 37. Interior of the Ape Cave lava tube, which was created during an eruption of the Cave Basalt (Castle Creek age, about 2,000 yr B.P.). The low, dissected terrace of fragmental material along the cave-floor margins contains W tephra and was probably deposited by a lahar that entered the cave during the early part of the Kalama eruptive period (late 1400s). Photo by Charlie and Jo Larson, Vancouver, Wash.

Mount St. Helens to the south more than 36 mi (60 km) toward the Columbia River and is roughly within with the *St. Helens zone* of seismicity.

Mount Mitchell, to the south, is cored by a Tertiary *granodiorite* intrusion.

35.7 [58.7] Junction of FR 90 and FR 83. Turn left on FR 83.

37.5 [60.0] **OPTIONAL SIDE TRIP: TRAIL OF TWO FORESTS AND APE CAVE.** Round trip on FR 8303 is 0.4 mi (0.6 km) to the Trail of Two Forests or 2 mi (3.2 km) to Ape Cave. The Trail of Two Forests is a barrier-free loop (900 yd or 500 m) on Cave Basalt flows that overwhelmed a forest about 2,000 years ago. The trail winds past hollow tree molds created when the basalt solidified around fallen trees that have since rotted away.

Ape Cave lava tube, which formed in one of these basalt flows, is the longest lava tube (12,810 ft or 3.9 km) in the conterminous United States (similar tubes are found in Oregon, California, and Idaho) and one of the longest in the world. The cave was constructed by a *pahoehoe* flow (Figs. 37 and 38) that crusted over; soon after, the molten lava on the inside drained away, leaving the outer crust in place. Lava stalactites and stalagmites and flow marks can be seen on the walls and floor of the cave. Lava stalactites, conical or cylindrical deposits of lava that hang from the ceiling of a tube, are formed by dripping; stalagmites are similar in shape and are formed on the floor of the tube by the accumulation of drips from the ceiling. Some time later, a sandy lahar flowed into the cave, possibly in A.D. 1480 or 1482 because the deposit contains white *pumice* granules that resemble W tephra. During the summer, a national monument interpretive naturalist leads tours through the lower part of the cave. Be sure to read the brochure (available at the cave entrance) to find out more about the cave and the equipment you will need if you plan to explore on your own. (Sturdy shoes or boots, warm clothing, and three sources of light are recommended.)

Return to FR 83. *Note: Mileage does not include this side trip. Reset your odometer if necessary.*

Figure 38. An active lava tube at Kilauea Volcano, Hawaii, in 1987. The flow is moving from lower right to upper left. View is through a collapsed roof or "skylight" in the top of the lava tube.

38.9 [62.2] Junction with FR 81 (Leg G). The sinuous lava flows visible on the flanks of Mount St. Helens from this vantage point are the Worm Flows (named for their shape), erupted in the early to mid 1500s during the Kalama eruptive period. (See Fig. 3 and Table 4, p. 28.)

39.2 [62.7] The thick outcrop of fragmental debris on the west side of the road includes a number of pyroclastic-flow deposits of Swift Creek age (13,000–10,000 yr B.P.). Farther down the road, before it crosses the creek, the pyroclastic-flow deposits lap onto a thick, bouldery *till* of Evans Creek age (22,000–11,000 yr B.P.). USGS geologist Dwight Crandell suggested that the south-sloping surface of the till deposits might be the leading edge of a *moraine*. The till was apparently deposited after about 18,560 years ago because it is not overlain by tephra deposits of Cougar age, but by set S tephra of Swift Creek age (about 13,000 yr B.P.), which suggests that the glacier advanced between 18,560 and 13,000 yr B.P.

39.3 [62.9] Cross West Fork Swift Creek.

39.6 [63.4] Near here, one of the largest andesite lava flows recognized at Mount St. Helens (Cougar age, 20,000–18,000 yr B.P.) is overlain by a pumiceous pyroclastic flow of the same age.

41.9 [67.0] Marble Mountain Snowpark

42.8 [68.5] June Lake trailhead. The Worm Flows are visible again from this area.

44.0 [70.4] West Pine Creek bridge. A lahar was generated when pyroclastic material from the *blast* rushed down the southeast side of the mountain in the early stages of the May 18, 1980, eruption. The lahar washed away a bridge at this location. (An even larger lahar traveled down east Pine Creek.) The lahar left a veneer of sediment about 1 ft (30 cm) thick on the terraces adjacent to west Pine Creek. Those surfaces are now mostly covered by alder trees.

44.7 [71.5] The abundant white tephra exposed near the surface here is probably the We layer (A.D. 1482) whose lobe extends east of the volcano. (See Table 4 on p. 28, and Fig. 39.)

46.6 [74.6] **STOP B-2: LAHAR VIEWPOINT**. Lahar Viewpoint, Stratigraphy Viewpoint, and Lava Canyon Trail are clustered near the end of Leg B. This area is an interpretive cornucopia. Many of the features discussed on the

next few pages are within walking distance of the parking areas. Fragmental material and lava flows from older eruptions of Mount St. Helens and dramatic effects (deposits, scarred and killed trees, *mudlines*, and stream channel adjustments) of the 1980 eruption are visible here (Fig. 40).

Effects of the 1980 pyroclastic surge and lahar

> "About 10 seconds after the avalanche was enveloped [by the blast], the cloud also began spilling over the east rim, descending the east side as a dense wall—thick, black, and rolling, but without much vertical extent."
>
> geologist Cathie Hickson,
> who witnessed the eruption from
> 10 mi southeast of the mountain

Take a short (several hundred yards or meters) trail over bouldery terrain to the east toward a small hill. Near here the lahar split, one branch flowing down Pine Creek and the other down the Muddy River gorge. A large, lone tree south of the road is scarred on its upstream side, showing the maximum height of the lahar in this location.

Eruptive events on the east slope of Mount St. Helens were pieced together by geologists who analyzed eruption photographs taken from various vantage points and talked with eyewitnesses. Photos and satellite images were compared with tape-recorded comments of radio operators observing the eruption cloud. The following is a reconstruction of the events:

Pyroclastic surge. Within 2 minutes of the May 18 eruption, a *pyroclastic surge* consisting of rocks, *ash*, and volcanic gas boiled over the edge of the crater and descended the east flank of Mount St. Helens at high velocity. This turbulent cloud was funneled into the valley of Shoestring Glacier and scoured as much as 27.4 ft (9 m) of snow and ice from the glacier. By the time it reached the base of the mountain—about 90 seconds later—it had generated a lahar. The aver-

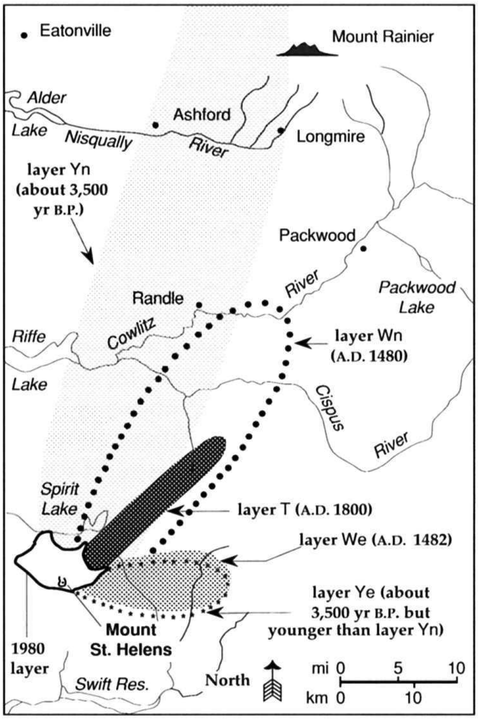


Figure 39. Distribution of major tephra deposits of Mount St. Helens during the Spirit Lake eruptive stage (about 4,500 yr B.P. to present). Each of these relatively large eruptions deposited more than 8 in. (20 cm) of material in the respective areas shown. The 1980 eruption includes tephra fallout from the May 18 eruption column and the initial blast. Layer Wn was deposited in A.D. 1480, although Fiacco and others (1993) favor late A.D. 1479. Calendar ages of the Wn, We, and T tephra layers were established by tree-ring studies.

age velocity of the pyroclastic surge was more than 110 mi/hr (about 50 m/s) over this distance. The surge then slowed down, and after about 80 more seconds, came to a stop on the upper reaches of Muddy fan. As the solid material began to segregate from the gases, the lighter components rose into the air and dispersed (Fig. 41).

Lahar. The lahar generated by the surge left a well-defined *trimline* on a hill at the north side of the fan (Fig. 40). Farther east and along the eastern fringes of the flow are so-called bayonet trees. These trees were young and flexible when the lahar hit. They were bent over, but not snapped off. The materials in the lahar acted like liquid sandpaper and filed the tree crowns to a point. Bayonet trees also can be seen along the Lava Canyon Trail and north of the trailhead. (See p. 71.)

Stratigraphy Viewpoint

At this stop you can examine the sequence of Mount St. Helens deposits on the north edge of the fan, slightly upstream of the road. This is a well-exposed section of tephra deposits, which are locally interbedded with lahar deposits (Fig. 42).

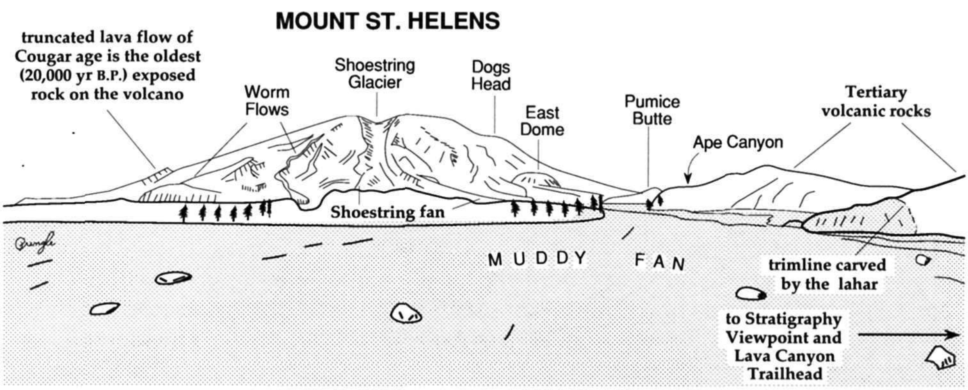


Figure 40. Panorama northeast from Lahar Viewpoint toward Mount St. Helens, 3.5 mi (6 km) away. Shoestring Glacier was decapitated during the catastrophic May 18, 1980, eruption and lost much of its zone of accumulation. A pyroclastic surge moved down the east flank of the mountain, eroded nearly 30 ft (9 m) of ice and snow from the glacier, and generated lahars that swept into Ape Canyon, across Muddy fan, and into Muddy River and Pine Creek. One lahar left a prominent trimline on the toe of a ridge composed of Tertiary volcanic rock north of the fan. The sinuous Worm Flows are rubbly andesite lava flows of Kalama age, probably erupted during the early to mid 1500s. The truncated lava flow to the left in this view is apparently an erosional remnant of a large lava flow erupted during the Cougar eruptive period (about 20,000 yr B.P.) It may be the oldest visible component of the Mount St. Helens edifice, most of which is less than 3,000 years old. Dogs Head dacite dome was erupted during the early part of the Castle Creek eruptive period. East Dome, also a dacite dome, was erupted sometime between the Castle Creek and Kalama eruptive periods. On clear days, Mount Hood volcano in Oregon is visible to the southeast, off to the left.

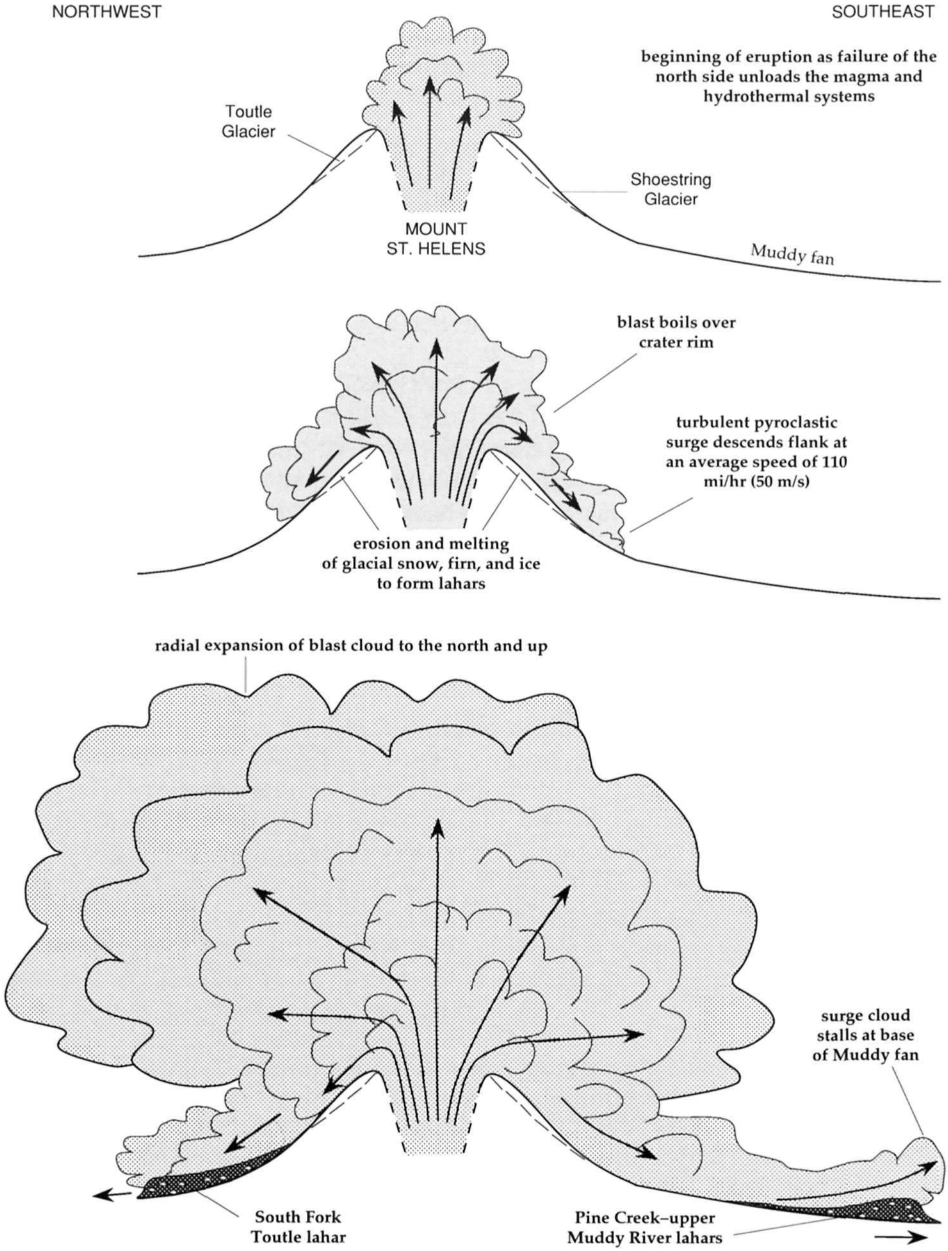


Figure 41. Diagrammatic sketch showing the May 18, 1980, blast and boiling over of pyroclastic debris onto the northwest and southeast flanks of the mountain and the resulting pyroclastic surge onto Muddy fan. Top: volcanic explosions drive material up and out. Middle: gravity takes over and drives the pyroclastic surge; as the surge ingests air, the heavier particles segregate out and the surge becomes turbulent and erosive. Bottom: a less concentrated ash cloud lifts and disperses rapidly; water derived from melted glacial snow and ice generates a lahar (volcanic debris flow).

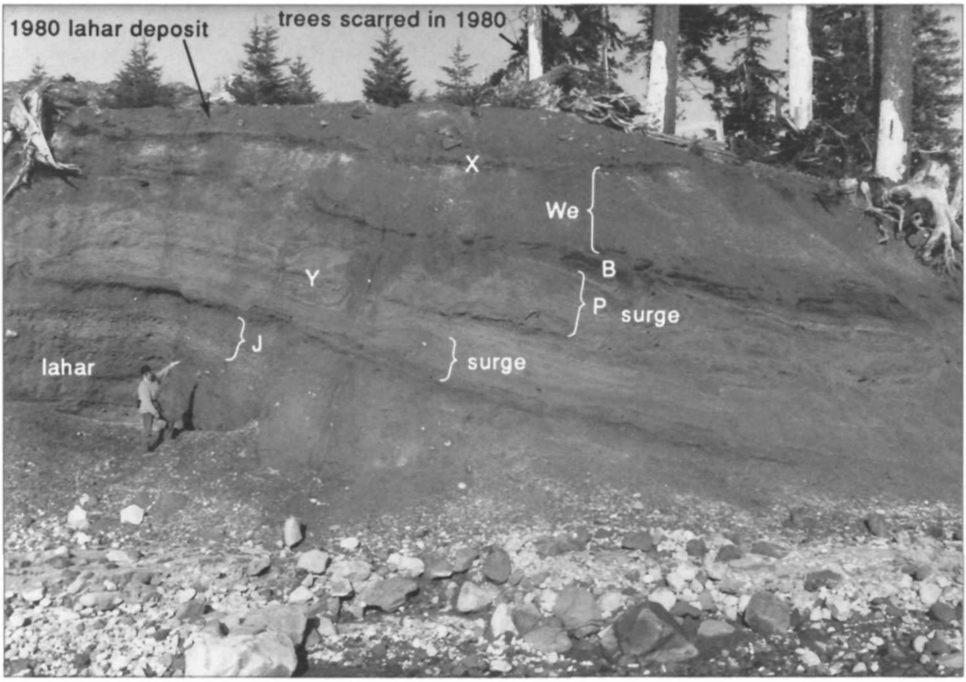


Figure 42. This sequence of deposits at Lahar Viewpoint includes numerous fall-out-tephra layers, pyroclastic-surge layers, and two lahar deposits from Mount St. Helens. Note the May 18, 1980, lahar deposit that caps the terrace and the trees scarred by the lahar on their upstream side. The outcrop changes annually as lateral erosion cuts farther into the terrace and as the level of the streambed changes. See Tables 3 and 4 for data on individual layers indicated by initials.

Tephra is a general term for pyroclastic material of all sizes that falls from an eruption cloud. Most tephra deposits are gravel- and sand-size particles that have been ejected into the air and carried downwind. Mount St. Helens has produced scores of tephra layers in its more-than-40,000-year eruptive history, and characteristics of its explosive activity are recorded by these layers.

During the ongoing Spirit Lake eruptive stage (encompassing the last 4,000 years), Mount St. Helens has produced about 2.4 mi^3 (10 km^3) of tephra. Although the Yn tephra (about 3,500 yr B.P.) was the single largest volume erupted (0.96 mi^3 or 4 km^3), one third of the total tephra volume of all Spirit Lake eruptive events has been produced in the last 500 years. These volumes are calculated by measuring the thickness of deposits and adjusting this figure to the equivalent of solid rock (because of voids within pumice and among the particles).

The widespread tephra layers are useful to geologists and archaeologists as *stratigraphic* markers over much of the western United States. The recognition of a layer of known age in an outcrop establishes a minimum age for the materials below that layer and a maximum age for materials above it.

Figure 43. Columnar jointing in an andesite flow of Castle Creek age along the Lava Canyon Trail. Tertiary volcanic rocks are visible below the lava flow.

The Shoestring Glacier Story

The May 18, 1980, pyroclastic flow scoured the surface of Shoestring Glacier and incorporated its water, snow, and ice to form the lahars that swept down across Muddy fan. Shoestring Glacier was beheaded, and most of the glacier's snow and ice accumulation zone was removed when the upper parts of the mountain collapsed during the early moments of the eruption. As a result, the glacier has undergone significant shrinkage (*ablation*). (See p. 108.)

Fortuitously, glaciologist Melinda Brugman had begun a study of the glacier just prior to the 1980 eruption and collected data that could be used to evaluate the effects of the eruption. Contour maps of the glacier predating the eruption were compared with post-eruption surveys to determine that almost 30 ft (9 m) of ice and snow were removed by the pyroclastic surge.

Brugman noted that in the year following the eruption, the glacier first advanced rapidly (possibly because of the weight of the volcanic debris that had been deposited on its surface and a fairly heavy snow load) and then it slowed dramatically. Since 1980, the lower part of the glacier has stagnated, shrunk, and become detached from the upper part, which has also shrunk.

Erosion along the edges of Shoestring Glacier caused by the eruption exposed a layer of debris that apparently had been deposited by a throat-clearing eruption sometime between 1842 and 1857. Brugman noticed that this tephra provided a low-friction boundary layer upon which the upper part of the glacier was moving as a solid block or thrust sheet (Brugman, 1988a). (See Fig. 66.) This layer and similar thrusting along weak zones of fragmental debris were also observed at other glaciers at Mount St. Helens.

While studying Shoestring Glacier, Brugman (1988b) found that the annual volume of meltwater at the glacier terminus amounted to only about 10 percent of that which could be expected from seasonal melting of snow and ice. In the process of tracking down the missing meltwater, she discovered that its isotopic chemistry was quite similar to that of the water *discharge*d at Moss springs (near Lahar Viewpoint). The spring water apparently originates in part from melting snow and ice high on the volcano and travels through the porous layers making up the cone before emerging at Moss springs.

The abundant water in the porous debris that composes Mount St. Helens may have contributed to the explosivity of the volcano during the May 18

eruption. Hoblitt (1990) has suggested that a second blast explosion may have included both magmatic gases and steam (a phreatomagmatic eruption) because of the scarcity of *juvenile clasts* in its deposit.

Lava Canyon Trail

This barrier-free trail leads to a view of the canyon cut by the upper Muddy River. An andesite lava flow traveled through this canyon about 1,900 years ago. The river has since cut into the weaker Tertiary volcanic deposits and left the younger, more resistant lava flow as an erosional remnant. Some of the outcrops of lava along the trail exhibit a platy *jointing* that is typical of viscous andesite lava (Fig. 43).

LEG C: EAST SIDE OF THE MONUMENT

Via Forest Roads 90, 25, and 99

Caution! These narrow roads have tight curves.

This leg takes you east along the north side of Swift Reservoir to the east side of the volcano and Forest Road (FR) 99. The destination is Bear Meadow (Fig. 44). The road is in the Lewis River watershed for most of the trip, but near the end of the route, it moves into the Cowlitz watershed at Elk Pass. *Tertiary* volcanic rocks (many altered) and lava flows from Marble Mountain *shield volcano* (Pleistocene) crop out in the stretch along the reservoir. Columnar *joints* in *basalt* flows from Marble Mountain are visible en route locally, and fossil wood can be seen in some *outcrops*.

Older Mount St. Helens deposits are visible in roadcuts toward the east end of Swift Reservoir. Slightly beyond the Pine Creek Information Station (closed in winter), FR 90 turns east and then south, but the guide route continues north on FR 25 to its junction with FR 99. FR 25 crosses Pine Creek and Muddy River, both sites of *lahars* on May 18, 1980. The road then climbs the east wall of Muddy River valley and heads north, passing outcrops of Mount St. Helens *tephra* layers and offering several views of the volcano. North of Elk Pass (closed in winter), this leg connects with Leg D, FR 99 to Windy Ridge.

Distances along the route are given in miles, followed by kilometers in brackets.

<u>Distance</u>

0.0 [0.0] Leave the junction of FRs 90 and 83 and drive east on FR 90.

0.5 [0.8] Deposits of volcanic debris of Swift Creek age (13,000–10,000 yr B.P.).

0.8 [1.3] High bridge over Swift Creek. Half a mile farther along this route, the debris fan constructed during the Swift Creek eruptive stage will be visible to the south-southwest. Some of the peaks visible to the south are Tertiary volcanic rocks, and others, such as McClellan Mountain, are *intrusive* (*diorite*) rocks.

11.3 [18.1] Swift Forest Camp.

12.0 [19.2] Pine Creek Information Station (closed in winter).

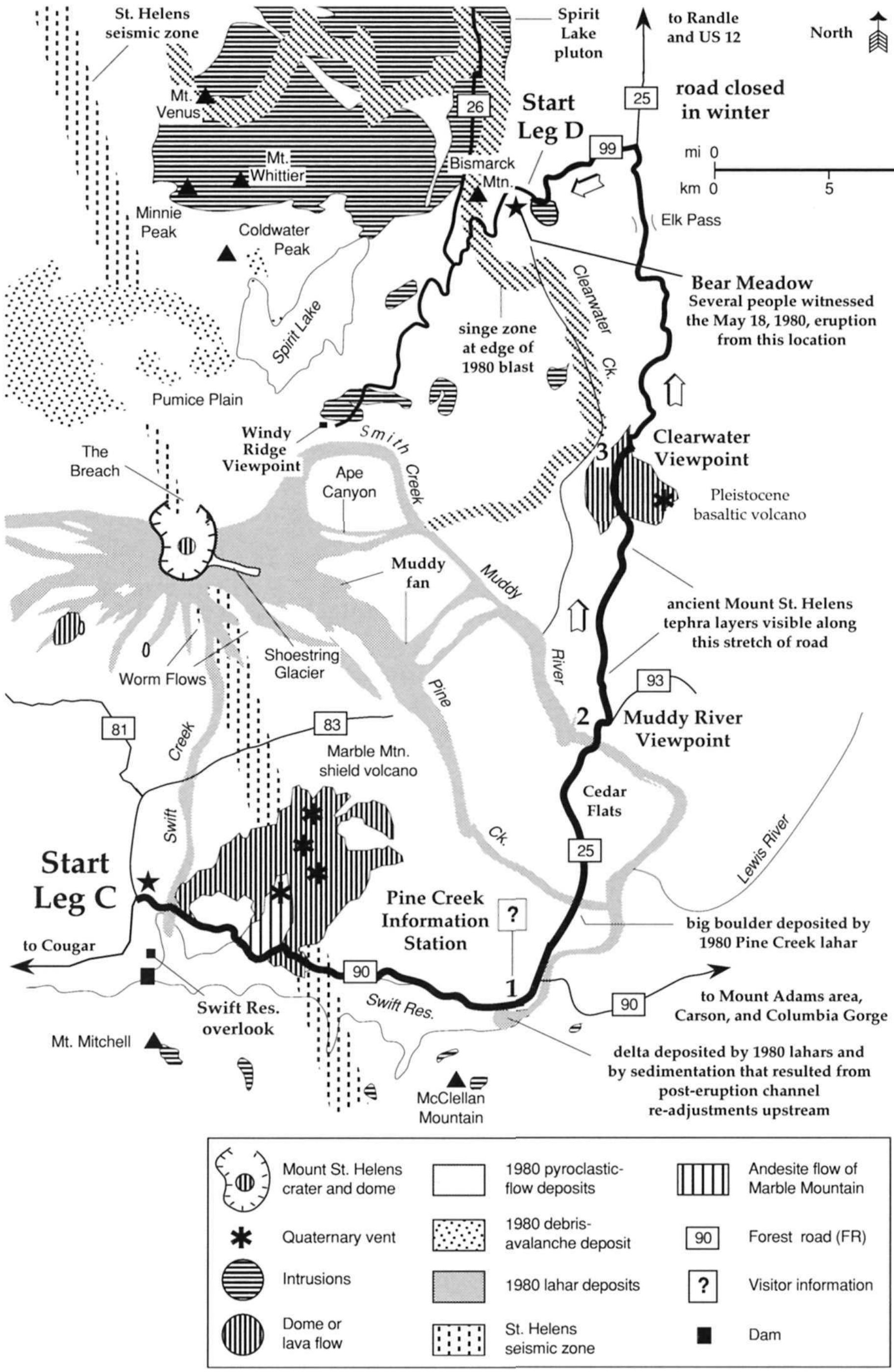


Figure 44. Sketch map of Leg C showing numbered road stops (referred to in text), geologic features and points of interest. The leg starts at the intersection of Forest Roads (FRs) 83 and 90 and continues on FRs 25 and 99 to Bear Meadow.

12.2 [19.5] Junction of FRs 25 and 90. Continue straight on what is now FR 25.

12.9 [20.6] **STOP C-1: PINE CREEK BOULDER**. Adjacent to the small turnout on the west side of the Pine Creek bridge is a 37-ton boulder that was deposited in the old roadway 33 ft (10 m) above the creek by the May 18, 1980, lahar. This lahar was generated by the *pyroclastic surge* that descended the east slope of Mount St. Helens and swept across Muddy fan. (See p. 65 and Fig. 41.) Older material in the pit on the east side of the bridge and visible upstream in the northeast bank of Pine Creek is composed of pyroclastic-flow and lahar deposits of the Pine Creek eruptive period (3,000–2,500 yr B.P.). Abundant alders and other pioneer plant species have revegetated the banks of Pine Creek since 1980.

Continue across the fan of Pine Creek age past the Cedar Flats Research Natural Area. Cedar Flats is underlain by lahars of the Pine Creek eruptive period and older deposits from the latter part of the Swift Creek eruptive stage (deposited after tephra layer S). (See Table 3, p. 25.) The fan of Swift Creek age temporarily blocked the river near here.

16.9 [27.2] **STOP C-2: MUDDY RIVER VIEWPOINT**. The Muddy River bridge was destroyed by a lahar on May 18, 1980. The area is now largely regrown with alders. A painted line about 10 ft (3 m) above the ground on the pole adjacent to the parking area shows the maximum height (stage) of the lahar in this area, as determined by *mudlines* on trees bordering the lahar. Large boulders of yellowish Tertiary bedrock were transported by the lahar from outcrops miles upstream and are visible along a trail to the river.

As the road climbs up the east wall of the Muddy River valley and continues north, tephra layers from Mount St. Helens become more prominent. These layers of tan, white, yellowish, and orange *pumice* and *ash* can be seen just under the modern soil layer at the tops of most outcrops.

17.2 [27.7] Junction of FR 25 with FR 93. FR 93 connects with FR 90 and leads to recreation sites along the Lewis River and near Mount Adams to the east. *Keep left. Stay on FR 25.*

22.4 [36.0] You are now entering the area covered by fallout from the Mount St. Helens We tephra plume (A.D. 1482). The deposit is noticeable as large white pumice pebbles at the top of outcrops. (See Fig. 39 for distribution of this tephra.)

27.1 [43.6] **STOP C-3: CLEARWATER OVERLOOK**. The broad, U-shaped valley of Clearwater Creek (Fig. 45) was carved by a *glacier* of Hayden Creek age (about 140 ka) and possibly by an earlier glacier. On May 18, 1980, the hot *blast* moved into the upper reaches of the valley, destroying most of the forest (much of it recently logged). Slope failures, mostly *debris slides*, were common during the next few years in this and nearby valleys affected by the blast. Experimental forest plots were set up to investigate the causes of the slope failures. One reason was that trees died after the 1980 eruption and their roots stopped providing cohesive strength to the soil.

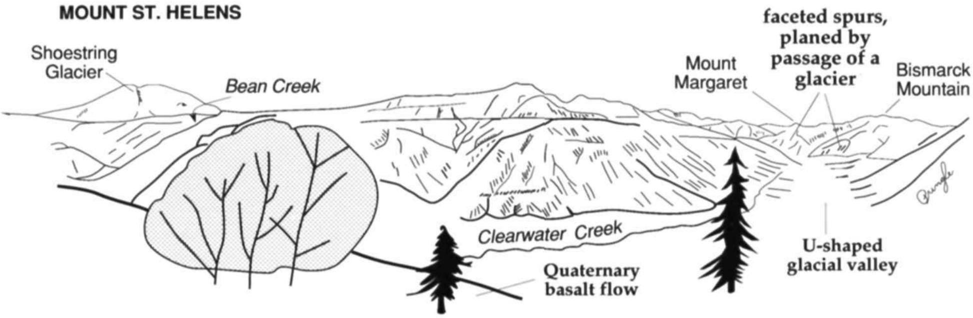


Figure 45. Panorama from the Clearwater Overlook, about 10 mi (15 km) east-northeast of Mount St. Helens. A valley glacier(s) that previously occupied the Clearwater valley carved the faceted spurs (beveled noses of ridges) and gave the valley its U shape. The Quaternary basalt flow originated at a vent immediately to the southeast and is probably an outlier of the Indian Heaven volcanic field located farther to the southeast. (See Fig. 1.)

On the east side of the road, across from the parking area, a dark basaltic *sill* of Tertiary age intrudes a lighter colored *dacite* (Fig. 46).

Gabions (cobble-filled wire mesh baskets) have been used here in an attempt to reinforce the slope at the edge of the road.

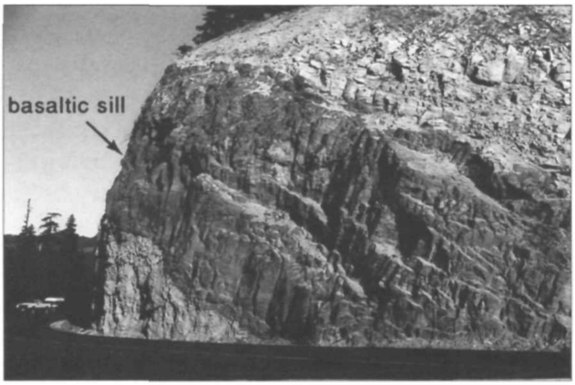


Figure 46. Tertiary basaltic sill intrudes dacite bedrock across from the Clearwater Overlook.

34.0 [54.7] Boundary Trail #1 crosses Elk Pass.

37.0 [59.5] Turn left onto FR 99. In 5.7 mi (9 km), you will reach Bear Meadow Viewpoint, the starting point for Leg D.

LEG D: FOREST ROAD 99 TO WINDY RIDGE

Reset your odometer to zero at Bear Meadow Viewpoint for the approach to Windy Ridge. This leg of the guide offers a new view of the effects of the May 18, 1980, eruption at every turn in the road (Fig. 47). Forest Road (FR) 99 passes from a verdant forest through a fringe zone of singed trees to the core of the zone devastated by the *blast*. *Tephra* layers from ancient eruptions of Mount St. Helens are visible in roadcuts along the way. These layers change in thickness as the road

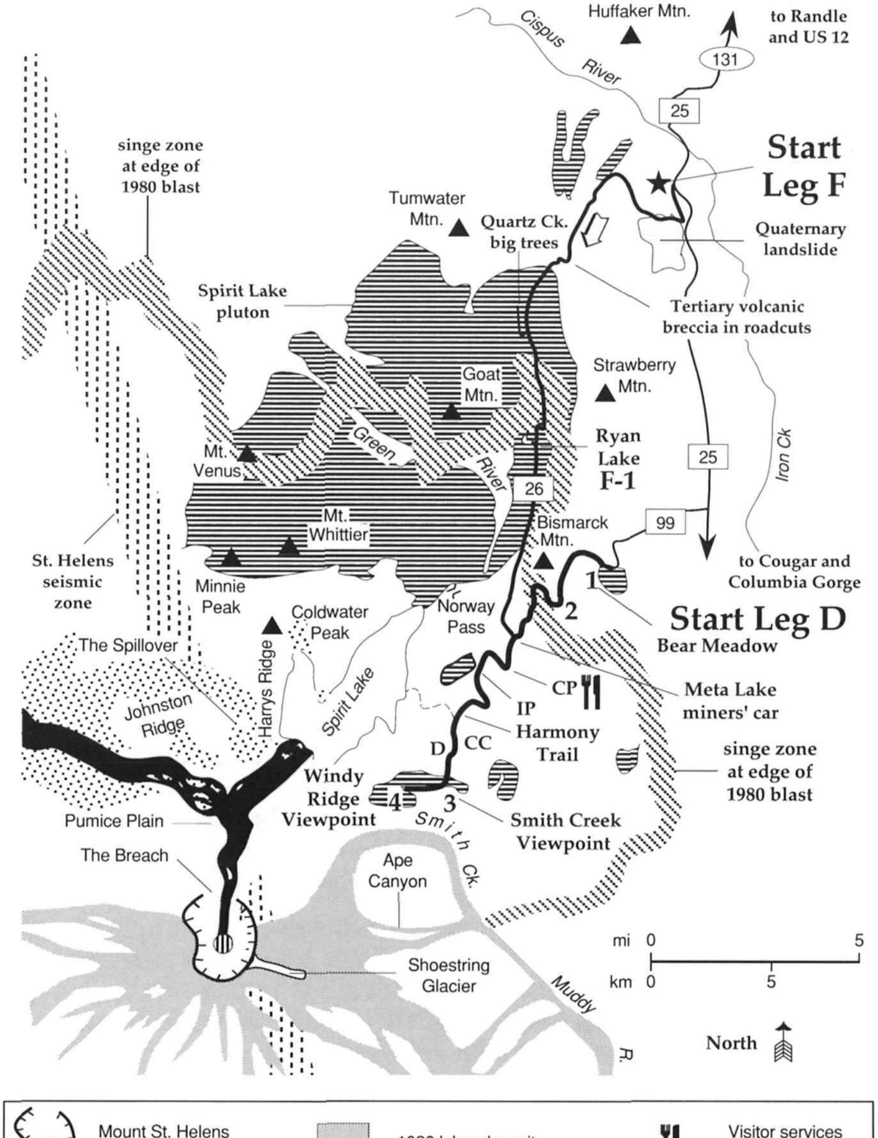


Figure 47. Sketch map of Leg D, FR 99 to Windy Ridge, and Leg F along Forest Road 26, showing numbered road stops (referred to in text) and points of interest. Optional stops also shown are CP, Cascade Peaks; IP, Independence Pass; CC, Cedar Creek Viewpoint; and D, Donny Brook Viewpoint.

travels across the axis of the tephra lobes. (See Fig. 39.) Some of the beds are more than 6 ft (2 m) thick and contain blocks and bombs as large as grapefruits— an impressive reminder that Mount St. Helens has an explosive history and that many of its ancient eruptions were larger than, or equivalent in size to the one in 1980.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

0.0 [0.0] **STOP D-1: BEAR MEADOW VIEWPOINT**. Gary Rosenquist and Keith Ronnholm, who were camped here on the morning of May 18, took photos that recorded the dramatic initial eruptive activity that day. The photographs show the early movement of the slide blocks of the *debris avalanche* and the shape of the initial eruption cloud that developed within seconds. (See Fig. 17.) As you leave Bear Meadow and drive into the *devastated area*, note the location and severity of tree damage caused by the *blast*.

The road takes you from Iron Creek in the Cowlitz River watershed to Clearwater Creek, a tributary of the Muddy River in the Lewis River watershed. Orange-stained Tertiary dacite visible along the north side of the road as you leave the parking lot was probably part of a *dome* that was altered by *fumarolic* action while the rock cooled.

2.1 [3.4] **STOP D-2: BLAST-EDGE VIEWPOINT**. The road passes through an area of dead but upright trees that fringe the outer boundary of the blast zone. (See Fig. 22.) Temperatures at the edge of the zone were estimated to have been between 122°F and 482°F (50° and 250°C). Downed trees are found closer to the center of the blast zone. The orientations of the downed trees indicate the direction of the *blast density flow* as it moved across the hilly terrain. Smaller trees that survived were understory trees in the mature coniferous forest that was killed by the blast. Many of these smaller trees were protected by snow drifts and emerged undamaged later when the snow had melted. (For more information on the blast, see p. 31 and 107.)

Across the road is a sequence of tephra deposits from the Spirit Lake eruptive stage (4,500 yr B.P.–present). (See Table 3, p. 25.) The orange basal tephra layer overlying the reddish Tertiary bedrock is layer Yn, erupted from Mount St. Helens about 3,600 yr B.P. The volume (dense rock equivalent) of layer Yn deposits, calculated from its extent and thickness, is nearly 1 mi^3 (4 km^3), making it one of the largest eruptions from Mount St. Helens and similar in size to the A.D. 79 eruption of Vesuvius in Italy. The dark, fine-grained material overlying the orange *pumice* is composed of numerous layers of *ash* produced during a 3,000-year interval between the deposition of layer Yn and layer We (the whitish band about 2 ft or 0.6 m thick) in A.D. 1482. The dark material retains moisture because it is so fine grained. Overlying this layer is a dark forest duff and then another thin tephra layer (T) from an eruption in A.D. 1800. A similar tephra sequence is visible in many places along the road as you approach Windy Ridge.

4.5 [7.2] Junction of FR 99 with FR 26 (Leg F). Miners' Car. This damaged automobile belonged to a family that was killed on May 18, 1980, while working at their small mine.

4.7 [7.5] **OPTIONAL STOP: META LAKE**. A short paved trail (barrier-free) leads to Meta Lake, which occupies the bottom of a *cirque* of Evans Creek age (22,000–11,000 yr B.P.). Ice covered the lake during the eruption on May 18, 1980, so plants and animals in the water were insulated from the volcanic violence. Numerous trees and shrubs buried in snowdrifts in this area also survived the eruption. Compare the number of standing trees on the south and north sides of the valley. The platform at the lake is a good place to observe the swirls of downed trees. *Drinking water is available at this stop.*

6.0 [9.6] **OPTIONAL STOP: CASCADE PEAKS VIEWPOINT**. Many of the Cascade peaks are visible from this viewpoint, including Mount St. Helens, Mount Adams, Mount Hood, and the Indian Heaven volcanoes. (See also Fig. 50.) Across the road from this viewpoint, Mount St. Helens tephras Yn, Wn, and T crop out in sequence. T is at the top.

A refreshment stand at the viewpoint is open from mid-May to late October, depending on weather conditions.

9.7 [15.5] **OPTIONAL HIKE: HARMONY VIEWPOINT AND TRAIL**. This 3-mi (4.8 km) round trip descends the wall of a cirque of Evans Creek age (22,000–11,000 yr B.P.) and takes you to the east shore of Spirit Lake. Harmony Trail offers views (Fig. 48) of a wide variety of geologic features that include Tertiary welded *tuff* and Pleistocene glacial deposits, as well as a good view of the Mount St. Helens crater and the Lava Dome.

White pumice fragments from tephra layers Wn and T are exposed in cuts along the trail. The first bedrock you find on this hike is the nearly vertical outcrop of a Tertiary dacite intrusion. About halfway down to the lake, a lava flow with columnar *jointing* is exposed, but most of the bedrock along this hike is composed of fragmental volcanic rock (*breccias* and tuffs).

As the trail flattens out on the floor of the cirque, a *trimline* is visible on the north side of the cirque. This scar was left by the wall of water created when the debris avalanche slid into Spirit Lake on May 18, 1980. The giant wave stripped vegetation and soil from hillsides around Spirit Lake. The wave swept into Harmony Falls basin and scraped material off the valley walls at heights of more than 500 ft (150 m) above the present level of the lake. The water and debris then rushed back out into the Spirit Lake basin. Smaller waves probably washed into Harmony basin immediately after the first.

The trail rises slightly as it passes over a *moraine* at the mouth of Harmony basin before descending to Spirit Lake. Boulders poke out of *till* of Evans Creek age along the way. Just after the trail turns to the south (toward the volcano), smooth, glacially grooved surfaces are visible on the dark reddish welded tuff erupted by an Oligocene volcano (Fig. 49). Run your hand along this surface toward Spirit Lake to feel the grooves and polished surface. White pumice pebbles can be seen in this rock; some were flattened while still hot by the weight of overlying sediments about 30 Ma (Fig. 50). Harmony Falls is formed by this resistant rock and by a light greenish gray *dike* that cuts the tuff.

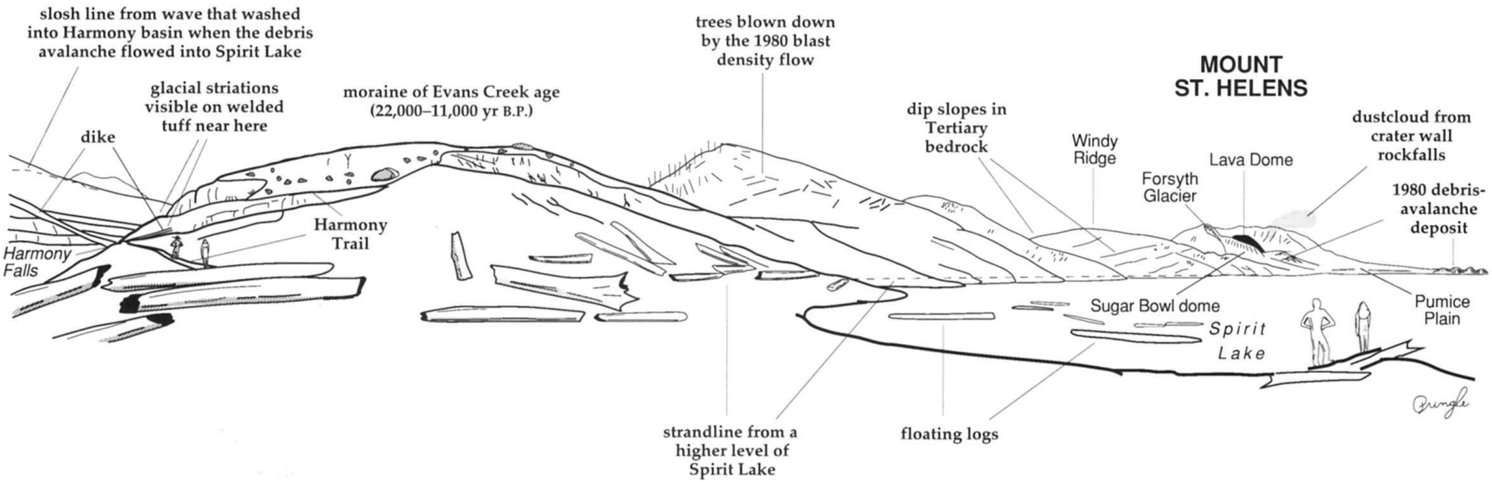


Figure 48. Panorama from the Harmony Trail at Spirit Lake, about 4 mi (7 km) northeast of Mount St. Helens. It is worth taking the 2-mi (3 km) round trip hike to Spirit Lake to see this view of the Mount St. Helens crater and the Lava Dome. Harmony Creek originates in a cirque whose glacier carved the glacial striations visible in outcrops of welded tuff (shown in Fig. 49) along the trail and also deposited the moraine, possibly of Evans Creek age (22,000–11,000 yr B.P.), shown in this sketch. Harmony Falls is formed by the resistant welded tuff and by a dacite dike. The strandline (at an elevation of about 3,420 ft or 1,043 m) was left by the highest level of Spirit Lake in 1982 before efforts to drain the lake had begun.

Figure 49. Glacial striations and smoothing on a Tertiary welded tuff along the Harmony Trail, north of Mount St. Helens.

The trail ends at Spirit Lake. A strandline of logs sits about 20 ft (6 m) above Spirit Lake, evidence of higher lake levels in 1982, before the lake level was stabilized by an outlet tunnel. The bedded pebbles and cobbles west of the mouth of Harmony Creek were deposited as a delta when the lake was at this higher level.

Continue south toward Windy Ridge. Roadcuts expose tephra layers J, Yn, Wn, and T in sequence. T is at the top.

10.0 [1.6] **OPTIONAL STOP: CEDAR CREEK VIEWPOINT**. The view of Spirit Lake and the denuded landscape of Tertiary rocks is the chief attraction.

10.1 [16.2] **OPTIONAL STOP: DONNY BROOK VIEWPOINT**. Although it presents only a partial view of the crater and dome, this site has excellent views of the debris avalanche that impounds Spirit Lake and of The Spillover, the ramp-like deposit left when the debris avalanche flowed over Johnston Ridge and down the South Coldwater valley. The outlet tunnel drilled to maintain the lake level is visible across the lake. Weather permitting, you can see Mount Adams and the Indian Heaven volcanic field to the east.

10.7 [17.1] **STOP D-3: SMITH CREEK VIEWPOINT**. On clear days, this site affords a view of Mount Adams, Mount Hood, Indian Heaven volcanoes, and other Cascade peaks. Also visible on the Smith Creek landscape are various features caused by the eruption and subsequent erosion and sedimentation (Fig. 51).

A thorough study of the 1980 deposits in this area has revealed that at least four distinct flows entered the Smith Creek drainage during and immedi-

Figure 50. Flattened pumice in a Tertiary welded tuff exposed along the Harmony Trail. Beds have been tilted by gentle regional folding; true vertical is shown by the pen (black cap points down). The pumice was deposited in a molten state and squashed by the weight of the overlying sediments of the pyroclastic-flow deposit about 30 Ma.

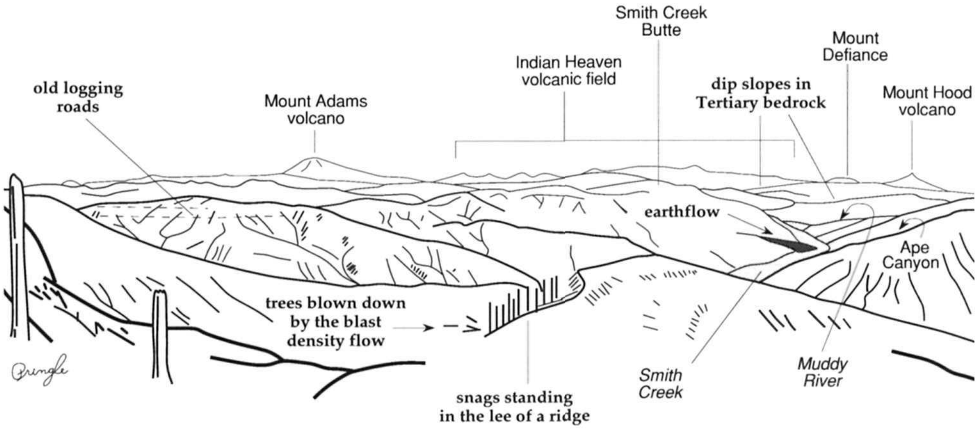


Figure 51. Panorama to the east and southeast from the Smith Creek Viewpoint, 3.5 mi (6 km) northeast of Mount St. Helens. The May 18, 1980, blast density flow swept over Windy Ridge into Smith Creek valley, leaving complex deposits and chaotic arrays of blown-down trees. Compared to pre-eruption conditions, far more material was available to be washed off the slopes. The tephra deposits were easily eroded, and the loss of soil cohesion when trees were killed meant that the slopes became more susceptible to both mass wasting and removal by rain and snowmelt. On May 18, a lahar rushed down Ape Canyon and ran up the east valley wall of Smith Creek. Another lahar flowed down the Muddy River. An earthflow constricts the channel of Smith Creek just downstream of Ape Canyon. Mount Adams (30 mi [50 km] east), the Indian Heaven volcanic field, and Oregon's Mount Hood (69 mi [115 km] south-southeast) have all erupted during the last 10,000 years.

ately after the 1980 eruption. The blast poured into Smith Creek valley from various directions, producing complex deposits. As interpreted by Brantley and Waitt (1988), this sequence was deposited as follows:

(1) Two layers of pyroclastic debris were deposited by the blast as it swept northeastward into Smith Creek valley. The lower layer is similar to the deposit from the leading edge of the blast that is found on the surrounding hills. A thicker and much coarser layer overlying this layer is inferred to have formed as the denser rocks separated from the lighter, smaller particles and swept down the valley as a localized *pyroclastic flow*.

(2) A *lahar* was generated by the blast as it mixed with and incorporated pyroclastic debris from the fresh basal deposits and underlying soil. It left a hummocky deposit overlying the blast layers.

(3) Secondary pyroclastic flows swept down from the valley walls (as they did in South Coldwater valley, p. 59) and were deposited atop the lahar and blast deposits.

(4) The blast cloud dropped a thin layer of silt-size material that capped these deposits. Mixed in as well were *accretionary lapilli* that began falling about 20 minutes after the eruption.

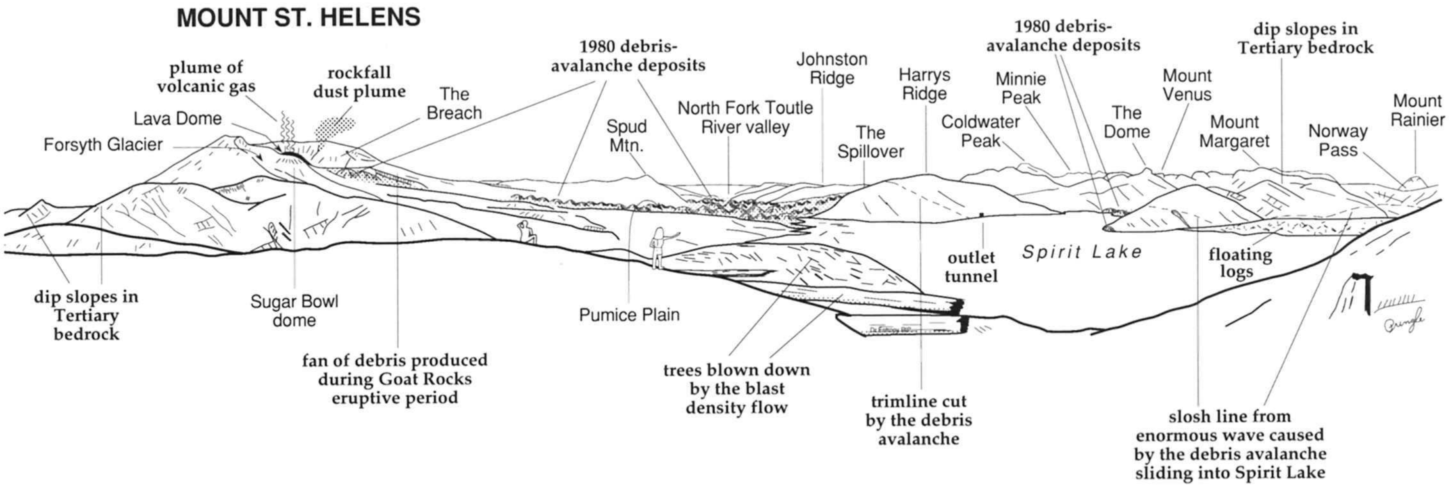


Figure 52. Panorama from the hill north of Windy Ridge, 2.5 mi (4 km) northeast of Mount St. Helens. This is an excellent place to view the devastated area immediately north of the volcano. The hummocky debris avalanche that impounds Spirit Lake and The Spillover, where the debris avalanche ran up on and spilled over Johnston Ridge into South Coldwater valley, are visible to the west. The debris avalanche also ran up onto Harrys Ridge and the south-trending ridge that plunges into Spirit Lake, stripping trees and soil and leaving a trimline. When the debris avalanche flowed into Spirit Lake, it caused an enormous translational wave that surged up onto the northern banks of the lake, leaving a slosh line. The maximum height of the wave's runup was 852 ft (260 m). The Pumice Plain is a fan of fragmental debris that was constructed on top of the debris-avalanche deposit by the pyroclastic-flow, ash-cloud, and lahar deposits of May 18, 1980, and later events. The Lave Dome, constructed by 17 eruptive episodes since 1980, is just visible behind Sugar Bowl, a 1,200-year-old dacite flank dome. Plumes of volcanic gas are commonly visible rising from the Lava Dome; dust clouds are also common because of rockfall activity from the steep crater walls. Coldwater Peak and The Dome are composed of Tertiary volcanic rocks. Minnie Peak, Mount Venus, and Mount Margaret are composed of the resistant granites and granodiorites of the Spirit Lake pluton, which intruded the Tertiary rocks between 22 Ma and 20 Ma. On clear days, Mount Rainier is visible 40 mi (70 km) to the north-northeast.

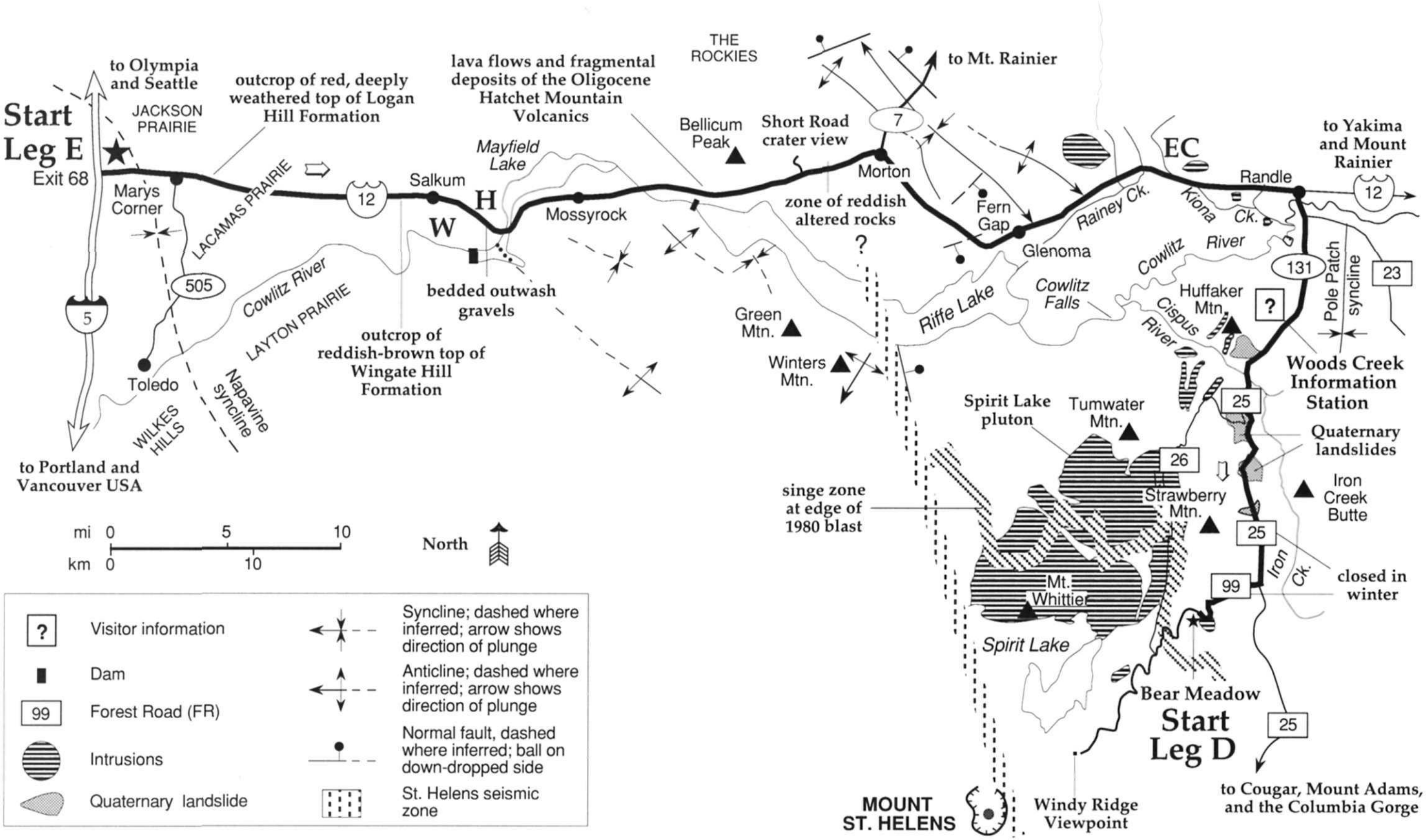


Figure 53. Sketch map of Leg E. Shown are folds (synclines and anticlines), faults, intrusions, and other features of interest. W, H, and EC show the maximum extent of a valley glacier that occupied the Cowlitz River valley during the Wingate Hill, Hayden Creek, and Evans Creek glacial advances respectively (about 500 ka, 140 ka, and 20,000 yr B.P.). The glacier originated at an extensive icecap in the Mount Rainier area that existed during each glaciation. The top of Bellicum Peak, just over 2,200 ft (671 m) elevation, was not glaciated.

(5) Finally, a small lahar entered upper Smith Creek valley along the west margin of the hummocky lahar deposits.

11.7 [18.7] **STOP D-4: WINDY RIDGE VIEWPOINT**. Windy Ridge is one of the best places to get an overview of the area devastated by the 1980 eruption (Fig. 52). The landscape is littered with sand and gray rocks from that event. Deposits of the debris avalanche are visible to the west. These include the lower parts of The Spillover, where the debris avalanche traveled up over Johnston Ridge and into the South Coldwater valley.

The blast stripped most vegetation and some soil from many of the older bedrock surfaces, revealing to geologists and visitors previously hidden chapters in the geologic history of the area.

Rockfalls from the crater walls stir up ash clouds that curl over the edges of the crater rim, especially in late summer. A faint bluish-white volcanic gas plume is often visible rising from the Lava Dome, and sometimes *fumaroles* or clusters of fumaroles can be seen there.

A walk up the steps on the hill north of the parking area provides a better view of the devastated area adjacent to Spirit Lake. The 1980 debris avalanche roared over part of a ridge that protrudes into Spirit Lake from the north and carried all the downed trees off the slope and into the lake, leaving a distinct trimline (Fig. 51). The avalanche also displaced water from Spirit Lake, creating a giant wave that carved a slosh line along the shore. Many of the logs that now float in the lake were carried in by this wave; others have been eroded off the slopes since then. Wind moves the logs to different locations on the lake.

The water level of Spirit Lake is maintained at about 3,406 ft (1,038 m) by draining water through a gravity-feed tunnel completed in 1985. The 2,500-ft (762 m) -long tunnel was cut through Harrys Ridge (named for Harry Truman, the Spirit Lake resident who refused to leave his home and was killed by the May 18, 1980, eruption) to South Coldwater Creek. The portal is just visible about midway along the western shore of the lake. Had the lake level not been stabilized, its dam probably would have been breached, possibly causing catastrophic floods in the Toutle River.

LEG E: NORTHERN APPROACH — COWLITZ RIVER VALLEY

Via U.S. Highway 12, State Route 131, and Forest Road 25

This approach follows the Cowlitz River valley to the east and at Randle turns south toward Mount St. Helens (Fig. 53). U.S. Highway (US) 12 descends a series of progressively younger glacial *terraces* (named Jackson, Lacamas or Cowlitz, and Layton prairies) in stairstep fashion. The older surfaces are at higher elevations, the younger nearer the valley floor because erosion, possibly combined with a minor component of regional tectonic uplift, has deepened the valley before each succeeding episode of deposition. About 4 mi (6.4 km) west of Morton, the road crosses a divide into the Tilton River drainage and remains in that watershed for

about 9 mi (14.4 km) before descending back into the Cowlitz River valley near Fern Gap.

East of Mayfield Lake, dark-colored rocks of the Hatchet Mountain Formation (*Tertiary*) crop out along the highway, indicating that you have entered the eroded Cascade mountains. *Lava* flows and fragmental volcanic rocks of this age crop out all along the route.

South of Randle, State Route (SR) 131 crosses the wide glacial valley of the Cowlitz River and climbs the valley wall to a terrace of hummocky glacial deposits (end *moraine* and ice-marginal deposits) of Evans Creek age (22,000–11,000 yr B.P.). The road becomes Forest Road (FR) 25 when it crosses the National Forest boundary. It then follows the Cispus River and its tributary, Iron Creek, south through forested terrain. Outcrops of Miocene volcanic rocks are visible en route, as are ancient deposits of Mount St. Helens tephra that get thicker as the road nears the volcano.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

0.0 [0.0] Mileage starts at the junction of Interstate Highway 5 and US 12. The road passes east over Jackson Prairie, a gently rolling terrace of the lower(?) Pleistocene Logan Hill Formation. This surface, which may be about a million years old, displays as much as 40 ft (12 m) of relief. Here the Logan Hill Formation consists mainly of a compacted mixture of cobbles and pebbles in a sandy clay matrix. The sediment is *outwash* from an ancient *glacier* whose source was in the southern Washington Cascade mountains near Mount Rainier.

2.4 [3.8] Marys Corner.

3.0 [4.8] Roadcuts expose the clayey, reddish, deeply weathered top of the Logan Hill Formation. Weathering reaches depths greater than 50 ft (15 m).

4.5 [7.2] Descend from the Jackson Prairie to Lacamas Prairie, the surface of a middle(?) Pleistocene Wingate Hill outwash deposit. Notice that Lacamas Prairie is flatter than the older Jackson Prairie—it displays relief of only a few feet. The Wingate Hill *Drift* is thought to be between 300 ka and 600 ka.

9.3 [14.9] Wingate Hill outwash is exposed in a roadcut about 300 ft (90 m) west of milepost 76. The reddish-brown weathering of this deposit extends to depths that range from 16 to 32 ft (5 to 10 m) and does not have the deep red hue of the older Logan Hill deposits.

11.4 [18.2] Near Salkum, the road descends to a terrace underlain by outwash deposits of Hayden Creek age (about 140 ka) and then crosses Mill Creek. *Till* of Wingate Hill age (about 500 ka) is visible to the right just after you pass Mill Creek. The Wingate Hill terminal moraine is about a mile (1.6 km) west of here, whereas the maximum extent of the Hayden Creek glacier was about a mile (1.6 km) to the east. The hills and mountains of the Cascades come into view as you continue farther east.

15.2 [24.3] Cross Mayfield Lake (a reservoir). The concrete arch dam was completed in 1962. Glacial outwash deposits are visible north of the highway on

both sides of the reservoir. Dark Cascade Range volcanic rocks begin to crop out in roadcuts near here.

21.0 [33.6] Cross the Cowlitz River.

23.1 [37.0] **OPTIONAL STOP: RIFFE LAKE VIEWPOINT**. Riffe Lake (a reservoir) is situated in the glacially carved valley of the Cowlitz River. In this area, the Goble Volcanics (Tertiary) are visible in roadcuts on the north side of the highway; the layers dip to the east at the viewpoint. Beds of fragmental volcanic rocks crop out about 0.5 mi (0.8 km) farther to the east. *Vugs* in the lava contain opal. Opal is composed of amorphous (non-crystalline) silica and commonly contains a small percentage of water. The opal was deposited by ground water that percolated into cavities in the rock. Vertical *dikes* of *basaltic andesite* are also visible locally.

The road climbs past glacial drift, out of the Cowlitz drainage, and then crosses a drainage divide into the Tilton River watershed.

27.2 [43.5] **OPTIONAL STOP: SHORT ROAD CRATER VIEW** (1.3 mi or 2 km round trip). If the weather is good, this viewpoint affords a distant view of the Mount St. Helens crater, neighboring mountains, and the glacially carved valley of the Cowlitz River. Bellicum Peak, the sharp mountain to the northwest as you climb Short Road, was not covered by glaciers during the Pleistocene Epoch. Imagine this lonely peak sticking up in the middle of a broad sheet of glacial ice during the extensive Hayden Creek glaciation.

29.4 [47.0] As the road descends into Morton, a zone of reddish altered rocks is exposed on the left. *Slickensides* are common on these rocks, although there is no evidence of a *fault*.

The smooth southwest-facing hillslope visible northwest of Morton is the dip slope of a limb of a northwest-trending *anticline*. Folding near Morton is more complex and tightly spaced than the gentle folding typically found in the region. Whereas the crest spacing (wavelength) of the *folds* in the older rocks north of Rainey Creek ranges from about 2 to 6 mi (3–10 km), the spacing in the younger rocks south of Rainey Creek ranges from about 6 to 18 mi (10–30 km). Because of this more intense folding, the rocks are generally more shattered and altered, and erosion has cut a window through the volcanic rocks into the older sedimentary rocks of the Eocene Puget Group. Landslides abound in this area, which lies between two active, north-northwest-trending seismic zones, the *St. Helens zone* and the West Rainier zone. The West Rainier zone is about 12 mi (20 km) north-northeast of the St. Helens zone. (See p. 111.)

31.9 [51.0] Junction of US 12 with SR 7 at Morton. Continue east on US 12.

33.8 [54.1] Sedimentary rocks of the Puget Group crop out on the south side of the highway. These rocks for the most part predate the Cascades, but they do interfinger with the earliest Cascade volcanic rocks.

33.5 [53.6] About 3.5 mi (5.6 km) past the SR 7 junction, the road crosses a northeast-trending *normal fault*, and you are back in the Goble Volcanics. Although the fault motion was down-to-the-southeast, the topography is

inverted and the down-dropped rocks now stand higher than those rocks across the fault, perhaps because the Goble Volcanics are more resistant to erosion than the sedimentary rocks of the Puget Group.

The highway starts to climb once it reaches the volcanic rocks, passes again into the Cowlitz River drainage and the valley of Rainey Creek at Fern Gap, and then descends to Glenoma.

The south valley wall (the elongated ridge south of Glenoma) along Rainey Creek is composed of upper Oligocene basaltic rocks, mostly lava flows. These rocks were derived from a volcanic center south of Riffe Lake.

43.0 [68.8] Deposits of yellowish *tephra* are visible in roadcuts and stream banks near where the road crosses Rainey Creek. The pebble-size *pumice* is the Yn tephra layer from Mount St. Helens, erupted about 3,600 yr B.P.

44.6 [71.4] Cross the drainage divide between Rainey and Kiona Creeks, located on coalescing alluvial fans from those two creeks.

46.6 [74.6] Cross Kiona Creek. Slightly east of here the highway passes through a terminal moraine of the Cowlitz River glacier of Evans Creek age.

49.0 [78.4] Randle. *Note: There are no service stations between here and Cougar (about 100 mi or 160 km), so make sure you have plenty of fuel.*

Turn right on SR 131 to reach the east side of the Mount St. Helens National Volcanic Monument. The road crosses the Cowlitz River, the main fork of which originates on Mount Rainier. The greenish gray color of the water is caused by rock flour, the silt and clay carried in suspension by the river. Rock flour is created by the grinding action of rocks at the bed of a glacier.

49.7 [79.5] A swampy area east of the highway about 0.8 mi (1.2 km) south of Randle is the remnant of an oxbow lake. The Cowlitz River has meandered back and forth across the valley in this reach. At some time in its past, the river abandoned a channel here and moved farther to the north, plugging its old channel and leaving an oxbow lake. In this stretch from Randle west to Cowlitz Falls, the Cowlitz River meanders for some 14 river miles (23 km) to travel only 9 mi (14 km). It then abruptly changes its character at Cowlitz Falls and flows in a nearly straight course for 3.2 river miles (5 km) to cover the 3.0 mi (4.8 km) from Cowlitz Falls to Riffe Lake. The Cowlitz River has cut into the Tertiary rocks at Cowlitz Falls, forming an entrenched meander. Resistant lava flows and *flow breccia* and at least two northeast-trending *porphyritic* dikes have created the falls and may also have established a base level that controls the gradient and thus the meandering course of the Cowlitz River upstream of the falls. Holocene lahar deposits from Mount Rainier underlie this flood plain, but none are exposed nearby.

50.0 [80.0] Junction of SR 131 and FR 23. Bear to the right and follow SR 131.

50.6 The road climbs the south wall of the Cowlitz River valley. After about 0.8 mi (1.3 km), the road passes through hummocky terrain on a prominent terrace, an ice-marginal area of the Evans Creek glacier.

The road crosses into the Woods Creek drainage and follows a fairly flat surface on Evans Creek drift.

54.7 [81.0] **OPTIONAL STOP: WOODS CREEK INFORMATION STATION**. You can stop here to pick up maps and interpretive, weather, road access, and miscellaneous information about the national monument. This facility is operated by the U.S. Forest Service.

57.6 [92.2] After crossing the Cispus River, SR 131 becomes FR 25. Leg F, an alternate approach to Windy Ridge, takes off to the right (nearly straight ahead) here on FR 26, a one-lane road with turnouts. *Trailers and large recreational vehicles are advised not to take FR 26.*

61.0 [97.6] **OPTIONAL STOP: IRON CREEK CAMPGROUND**. This is a good place to camp the night before a visit to Mount St. Helens.

As the road winds up a series of switchbacks, white and yellowish layers of tephra from ancient eruptions of Mount St. Helens are increasingly evident in roadcuts. Because prevailing winds blow to the east, greater amounts of tephra are deposited on this side of the volcano than on the west.

At the beginning of the second sharp switchback to the right, and for the next 1.5 mi (2.4 km), the road climbs smoothly across a large Quaternary landslide deposit that originated on the northeast side of Strawberry Mountain. Deposits of a similar landslide crop out on the right side of the road north of Benham Creek at 61.5 mi (98.4 km).

FR 25 continues south up the west valley wall of Iron Creek, a north-flowing tributary of the Cispus River. Outcrops of bedrock are scarce in this heavily wooded area, but upper Oligocene to lower Miocene lava flows, fragmental deposits, and *intrusive* rocks and deposits of glacial drift of at least two episodes of alpine glaciation can be seen in roadcuts along this stretch.

Geologists have been able to study extensive exposures of these rocks in the steep streams draining Strawberry Mountain. *K-Ar* dates on rocks in this area are about 23 Ma. The Strawberry Mountain rocks include *dacite* dikes and small *domes* and breccia that appear to be relics of an ancient dacite eruptive center. These Strawberry Mountain domes may have been emplaced in much the same way as those on the flanks of Mount St. Helens, such as East Dome and Sugar Bowl dome. *Lapilli-tuff* breccia and andesite flows stratigraphically above this volcano are exposed near a small turnout at about mile 68 (109 km).

Iron Creek Butte, a mesa having nearly horizontal bedding, is visible on the ridge top to the east-southeast from this turnout, across the valley of Iron Creek. The flat-lying rocks of that mesa are about 2.5 mi (4 km) west of the axis of the Pole Patch *syncline*. (See also Stop A-4, p. 51.)

68.1 [109.0] Strawberry Mountain Viewpoint turnoff.

70.4 [112.6] Junction of FR 25 with FR 99. Turn right on FR 99.

76.1 [121.8] End of Leg E. Starting point for Leg D. (See p. 77.)

LEG F: ALTERNATE NORTHERN APPROACH

Via Forest Road 26

Forest Road 26 is a winding, one-lane road with turnouts. It is not recommended for recreational vehicles or trailers.

Those who approach the *devastated area* via Forest Road (FR) 26 will be treated to spectacular evidence of the dynamics of the Mount St. Helens *blast*. The route of this leg is shown in Figure 47 on page 76.

FR 26 winds around the north toe of Strawberry Mountain and heads south up the valley of Quartz Creek, which drains north into the Cispus–Cowlitz River system. The road continues south into the area devastated by the 1980 blast and crosses a low divide into the glacially carved upper reaches of the Green River watershed, tributary to the Toutle–Cowlitz River drainage system.

Along this route, the road passes from volcanic rocks (25 Ma–23 Ma) into the rocks of the Spirit Lake *pluton*. The pluton is a cooled magma chamber formed from 23 Ma to 20 Ma. It may have produced some of the volcanic material a few miles to the east, but those rocks have not been firmly correlated with the pluton, and there is little evidence for a vent. Copper deposits prospected locally were created by shallow *hydrothermal* activity during, and for several million years after, the intrusion of the pluton. Vegetation covers much of this rock for the first several miles (or kilometers) of this leg. As the road enters the devastated area, however, the amount of exposed rock increases dramatically.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

0.0 [0.0] Mileage starts at intersection of FRs 25 and 26. In the first 1.5 mi (2.4 km), FR 26 traverses the northern part of a large landslide that originated on Strawberry Mountain. The road then passes through layers of *volcaniclastic* rocks and *lava* flows (mostly hidden by vegetation) that were erupted from several nearby lower Miocene volcanoes, including Strawberry Mountain to the south and Tumwater Mountain to the north.

3.0 [4.8] About here the road enters a zone of rocks that have been baked and altered by the intrusion of the Spirit Lake pluton (between 23 Ma and 20 Ma). Roughly 0.3 mi (0.5 km) farther along, the road enters a zone of coarse, poorly sorted *breccia* and other fragmental volcanic rocks several hundred yards (or meters) thick. Geologists have interpreted these deposits as possible *caldera* fill.

4.0 [6.4] The first of two roadcuts in the caldera-fill(?) deposits. These rocks have been hydrothermally altered. They typically appear dark green and have white flecks.

4.3 [6.9] This is the second of two roadcuts in the caldera-fill(?) deposits; here you can see *pumice* in an altered tuff.

6.2 [9.9] The light-colored rock in this outcrop is a *dacite dike* that cuts *granite* of the Spirit Lake pluton.

8.3 [13.3] **OPTIONAL STOP: QUARTZ CREEK ROAD (FR 2608).** The 2-mi (3.2 km) round trip to the Quartz Creek Big Trees Trail provides a glimpse of the old-growth forest that once covered much of this area. This grove is just outside the area devastated by the blast of May 18, 1980. However, many of the trees in this grove and in nearby forests were within the fallout zone for older *tephra* layers Wn, We, and T, and they experienced physical and thermal damage caused by the *ash* and *pumice* from those respective eruptions. The evidence of that damage was first noted in tree rings and later used to date the eruptions precisely. (See discussion of tree-ring dating, p. 97.)

About halfway to the grove, the road crosses Quartz Creek. Most of the large rocks in the stream bed are granite and *granodiorite* of the Spirit Lake pluton. Cross-bedded layers of mostly pre-1980 pumice are exposed in the bank of the stream.

Continue south on FR 26 into the blast zone.

Note: Mileage does not include the side trip to Quartz Creek Big Trees. Reset your odometer if necessary.

9.2 [14.7] Three Mount St. Helens tephra layers are visible here in roadcuts: Yn, Wn, and T. (See Fig. 39.) T is at the top. This site is near the north edge of the tephra deposit from the May 18, 1980, eruption.

At about 10 mi (16 km), the road enters the zone of blown-down trees in the valley bottom. The effects of the blast have been visible higher up on the slopes for the last mile. The *singe* zone is quite evident here and to the north toward Tumwater Mountain (on the skyline).

Like Strawberry Mountain, Tumwater Mountain is a stack of lower Miocene lava flows, *flow breccias*, and pyroclastic deposits that composed the flanks of an ancient volcano. These lavas include basaltic *andesite*, *porphyritic* andesite, and dacite domes.

10.3 [16.5] Where the road makes a sharp left-right S-turn, the jointed rock to the north is granite of the Spirit Lake pluton. This rock has a porphyritic texture; the large crystals (*phenocrysts*) are *feldspar* and *pyroxene*.

En route to Stop F-1, notice the shallow landslides on the steep hillsides. The deterioration of trees in the downed forest and the resulting loss of root strength contributed to slope instability.

13.2 [21.1] **STOP F-1: RYAN LAKE VIEWPOINT AND LOOP TRAIL.** Ryan Lake Viewpoint and the 0.5-mi (0.8 km) loop trail provide a good overview of the effects of the blast at a point 12 mi (19 km) north of the crater (Fig. 54).

Research on the effects of heat on conifer needles shows that the temperature of the blast at this site reached an estimated 300°C (572°F). As much as 6 in. (15.2 cm) of ash fell here. Two people died in this area on May 18, 1980, as a result of asphyxiation caused by inhaling the ash. Another person somehow hiked nearly 10 mi (15 km) farther north and then succumbed, also to asphyxiation.

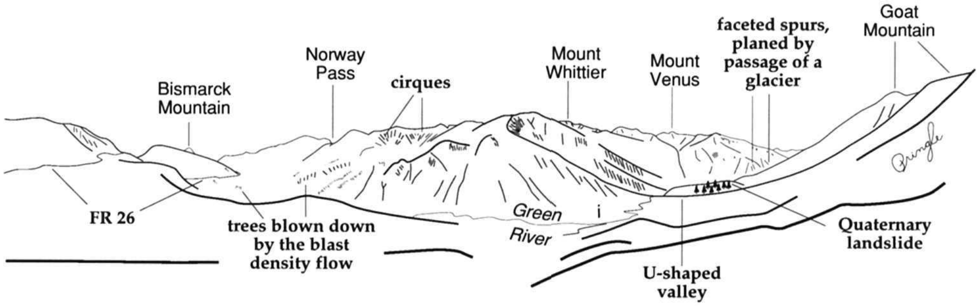


Figure 54. Panorama from the Ryan Lake trail, about 10 mi (15 km) northeast of Mount St. Helens. The blown-down trees show the intensity and turbulence of the May 18, 1980, blast density flow that swept into the Green River valley from the Spirit Lake basin to the south. The blast was apparently segregating into a lower, denser flow phase and an upper, more buoyant and less concentrated surge phase in this area. The basal portion ran out of energy just north of here, as indicated by the marginal singe zone and green trees beyond. The wide U-shaped valley of the Green River was carved by Pleistocene glaciers that originated in an ice cap on the resistant granite and granodiorite highlands of the Spirit Lake pluton. Mount Whittier, Mount Venus, and Goat Mountain are composed of those rocks. Bismarck Mountain is part of a Tertiary volcano.

Notice that trees on the lower parts of the valley wall were blown down locally, whereas those on upper parts of the valley wall still stand (Fig. 55). By the time the blast reached this location, particle segregation within it had created a heavier "flow" phase, which blew down trees in lower areas, and a lighter "surge" phase, which left trees standing in higher areas. (See also p. 31 and 105.)

Mount St. Helens tephra layers Y, W, and T crop out in cuts along this trail. Rock of the Spirit Lake pluton was quarried for road construction at a site on the south edge of the parking area.

14.1 [22.6] Goat Mountain, to the northwest, is composed of *granodiorite* of the Spirit Lake pluton. This area contains a large, low-grade deposit of copper and molybdenum. (See p. 14.)

14.7 [23.5] More tephra is visible in this roadcut; it lies over granodiorite.

Bismarck Mountain, to the east, is a thick pile of lower Miocene lava flows and *flow breccia* that is probably a remnant of an old *andesite* cone like Tumwater Mountain and Strawberry Mountain.

15.1 [24.1] The downed trees in this area display extraordinary swirled patterns, evidence of the turbulence in the blast.

17.0 [27.2] **OPTIONAL STOP: NORWAY PASS TRAIL.** Norway Pass Trail, a segment of Boundary Trail #1, is a 2.2-mi (3.5 km) hike through the blown-down forest to Norway Pass and impressive views of Mount St. Helens crater and Spirit Lake. The north-ascending slosh line on the valley walls at the extreme northern end of Spirit Lake was created when a lobe of the *debris*

Figure 55. Southwest view of the Green River valley wall south of Ryan Lake showing trees blown down and damaged by the blast. In the blowdown area here, only the weaker trees were leveled. Stronger trees or those shielded by hills were left standing.

avalanche flowed into the lake on May 18, 1980, and generated a huge wave that stripped soil and trees from the hillslopes as much as 850 ft (260 m) above the original lake level.

After 1.5 mi (2.5 km), the trail passes near the site of the old Chicago mine. The Norway and Sweden mines were down the ravine south of Norway Pass. Beginning in 1900, minor amounts of copper, gold, silver, and zinc were mined from these and other nearby mines of the St. Helens mining district. (See Fig. 10 and mining history on p. 14.) The entrance or portal to the 2,291-ft (699 m) -long Sweden mine tunnel was at an elevation of 3,340 ft (1,019 m). It is now below the waters of Spirit Lake (elev. 3,406 ft or 1,039 m).

17.9 [28.6] Junction of FR 26 with FR 99. End of Leg F.

LEG G: ALTERNATE SOUTHERN LOOP

Via Forest Road 81

This 18-mi (29 km) side trip (Fig. 35) traverses the south and southwest flanks of Mount St. Helens and provides access to Ptarmigan Trail and Climber's Bivouac (starting point for the Monitor Ridge climbing route), Forest Road (FR) 8123 to the Goat Marsh area, hiking trails on the volcano's west side, and Merrill Lake. The route of this leg is shown in Figure 35 on page 60.

The road leaves the Swift Creek watershed and crosses into the Kalama River watershed; then it heads south past Merrill Lake and back into the Lewis River drainage. The route passes through an end *moraine* of Evans Creek age (22,000–11,000 yr B.P.), exposures of Cave *Basalt*, an *outcrop* of a *debris avalanche* of Cougar age (20,000–18,000 yr B.P.) from Mount St. Helens, and across a debris fan of Kalama age (A.D. 1480 to late 1700s). The road skirts Goat Mountain, a Pleistocene *dacite dome* complex. South of Merrill Lake the road passes through several outcrops of *Tertiary* bedrock and *till*.

Distances along the route are given in miles followed by kilometers in brackets.

<u>Distance</u>

0.0 [0.0] Mileage starts at the intersection of FRs 83 and 81. Take FR 81.

0.5 [0.8] Pass through an end moraine of Evans Creek age.

1.8 [2.9] FR 830 to Ptarmigan Trail and Climber's Bivouac. *Lahar* deposits of Kalama age buried a mature forest in this area, and the tree *snags* are visible locally in stream cuts or gravel pits.

2.5 [4.0] Exposure of Cave Basalt (Castle Creek age, 1,900 yr B.P.).

4.0 [6.4] McBride Lake area. Deposits visible on the northeast side of the road include a debris avalanche of Cougar age, which is overlain by *pyroclastic-flow* deposits of Cougar age and till of Evans Creek age.

4.4 [7.0] Some of the trees in this area were killed by a small lahar from the south flank of Mount St. Helens that was generated by the May 18, 1980, eruption.

5.2 [8.3] Junction of FR 81 with FR 8123. FR 8123 provides access to Goat Mountain and Goat Marsh Lake, as well as to Sheep Canyon and the upper South Fork Toutle River. Goat Mountain is a *dacite* plug dome. *Radiometric ages* range from 3.2 Ma to 0.8 Ma, so the dome is interpreted to be either of late Pliocene or early Pleistocene age. Goat Marsh Lake and Blue Lake were created when debris of Kalama age dammed or altered the drainage of the small streams that feed into them.

Note the distinct *terraces* of a debris fan of Kalama age in this area. The vegetation on the fan is similar to, but more mature than, vegetation on the slightly younger Old Maid Flat debris fan west of Mount Hood along the Ramona Falls Loop Trail (a few miles northeast of Zigzag in the Mount Hood National Forest). The sandy, well-drained deposits composing large areas of both fans support a forest assemblage that can survive under conditions of limited soil moisture: salal, huckleberry, pinemat manzanita (bearberry or kinnikinnick), lodgepole and white pine, and Douglas fir, for example. Forest succession on the 1980 debris fan in the upper reaches of the South Fork Toutle River could develop in a similar way.

8.6 [13.8] Pyroclastic flows of Kalama age crop out in this quarry. Blocks of dome rock in one of the deposits suggest the flow may have occurred early in the Kalama eruptive period, possibly as early as A.D. 1482.

9.2 [14.7] The small dome visible to the west about 0.3 mi (0.5 km) from the road apparently postdates the Evans Creek glaciers. Its petrographic similarity to dacite of the Swift Creek eruptive period (13,000–10,000 yr B.P.) suggests it may be 13,000 yr B.P. or less.

10.5 [16.8] Cave Basalt crops out north of the road near here. Tumuli (pressure ridges) are visible on the surface of the flows.

11.4 [18.2] Merrill Lake. Geologists have suggested the lake was formed when a short tributary to the Kalama River was dammed about 1,900 yr B.P. by Cave Basalt flows and underlying fragmental deposits from Mount St. Helens.

12.1 [19.4] Entrance to Merrill Lake Campground, managed by the Washington Department of Natural Resources. The primitive campground is closed November through April. *Drinking water is available.*

17.7 Return to SR 503. End of Leg G.

PART III: A GEOLOGIC PRIMER — PROCESSES AND ROCK TYPES

WHAT IS GEOLOGY?

Geology has traditionally focused on the study of planet Earth—the materials of which it is made, the processes that shape its surface, and its history and life forms. The technical advances of the space age have broadened the scope of geology to include the study of our solar system.

To the casual observer, the rocks that compose the Earth may appear to be unchanging materials that have existed since the beginning of time. Looking more closely, however, those with a trained eye can "read" these rocks and uncover many clues to their age and origin.

Understanding geology can give us an appreciation of the scenery around us, and it can provide a historical perspective, a perception of the duration of geologic time. In addition, it can help us visualize the complex processes that have shaped the Earth and the interconnection of those processes with life on our planet. Because geology is a science whose chief laboratory is the outdoors, our knowledge is transferable anywhere in the world. When we learn to read the rocks in one area, we can recognize similar rocks and geologic processes at work in other areas and piece together their geologic history.

Although it is Mount St. Helens volcano that draws us to this spectacular, denuded and scorched landscape, the lava flows and fragmental deposits produced by Mount St. Helens throughout its more-than-40,000-year history are dwarfed by the volume of deposits laid down during the previous 40 m.y. of volcanic and tectonic activity in the southern Cascades. The 1980 eruption of Mount St. Helens is only the most recent episode in the volcanic history of the Cascade Range.

The following geologic primer reviews the types of rocks in the area, how they were formed, and how they have been transported, rotated, deformed, and changed. Because Pleistocene *glaciers* were responsible for much of the relief in the landscape around Mount St. Helens, we will briefly examine glacial processes as well as other erosional processes. Words defined in the glossary at the end of Part IV have been italicized on first usage in the text.

ROCK TYPES

Rocks are aggregates of one or more *minerals*. Geologists have categorized rocks into three major groups, based on their mode of formation: (1) *igneous* rocks, (2) *sedimentary* rocks, and (3) *metamorphic* rocks.

Igneous Rocks

Igneous rocks are rocks that have solidified from a molten state. They are subdivided into *intrusive* igneous rocks and extrusive igneous rocks. Specific rock types, such as granite or basalt, are typically classified by grain size, silica content, and mineral composition. Terms for various types of igneous rocks are shown in Tables 6 and 7. Igneous rocks predominate in the Mount St. Helens area.

Table 6. Simplified classification scheme for igneous rocks found in the Cascades

Intrusive rock	Extrusive rock	Silica content
granite	rhyolite	>69%
granodiorite	dacite	62-69%
diorite	andesite	54-62%
gabbro	basalt	45-54%

Intrusive rocks. Intrusive igneous rocks form when *magma* solidifies before reaching the Earth's surface. Intrusive rocks cool slowly; thus large crystals have time to grow. Pre-Mount St. Helens intrusive rocks crop out mainly along Forest Roads (FRs) 26 and 99, where erosion has exposed them. Several types of intrusive features are shown in Figure 7. These include *dikes*, which cut across the layers of intruded rock, and *sills*, which parallel the layers of intruded rock.

Extrusive rocks. Extrusive igneous rocks cool on the surface of the Earth, typically as *lava* flows or fragmental volcanic deposits (also known as *volcaniclastic* rocks) (Table 7); the latter include *pyroclastic density currents* (flows of hot rock and gas from a volcano). Extrusive rocks are fine grained compared to intrusive rocks because they cool quickly. The textural difference between intrusive and extrusive igneous rocks can be seen with a magnifying glass. Extrusive rocks at Mount St. Helens commonly have a *porphyritic* texture (Fig. 56). This texture, which has larger crystals (*phenocrysts*) in a very fine-grained matrix (the *groundmass*), indicates a compound cooling history. It shows that the magma was not totally molten, but existed as a kind of slush in which minerals with higher melting points remained solid as crystals in the molten magma and had time to grow. When an eruption occurred, the molten magma chilled quickly, and the fine texture of the groundmass was created. Quick cooling also causes *joints* and columns (Fig. 57). Most *Tertiary* rocks (66 Ma to 1.6 Ma) that predate Mount St. Helens are extrusive, and these rocks can be seen on all approaches to the mountain.

Sedimentary Rocks

Sedimentary rocks are rocks that have been deposited in layers by water, wind, or ice, or precipitated by chemical means. Most sedimentary rocks in this area contain volcanic debris. Some of this volcanic material can be seen along Interstate Highway 5 (I-5), along State Route (SR) 503, east of Morton on U.S. Highway 12, west of Cougar, and on the western approach along the new Spirit Lake Memorial Highway, SR 504.

Metamorphic Rocks

Metamorphic rocks are rocks that have been altered by heat, pressure, or fluids deep within the Earth's crust. Metamorphic rocks result when pre-existing

Table 7. Classification of fragmental volcanic rocks found in the Cascades

Clast size	Unlithified	Lithified
<2 mm	ash	tuff
2–64 mm	lapilli	lapillistone
>64 mm	bombs/blocks	volcanic breccia

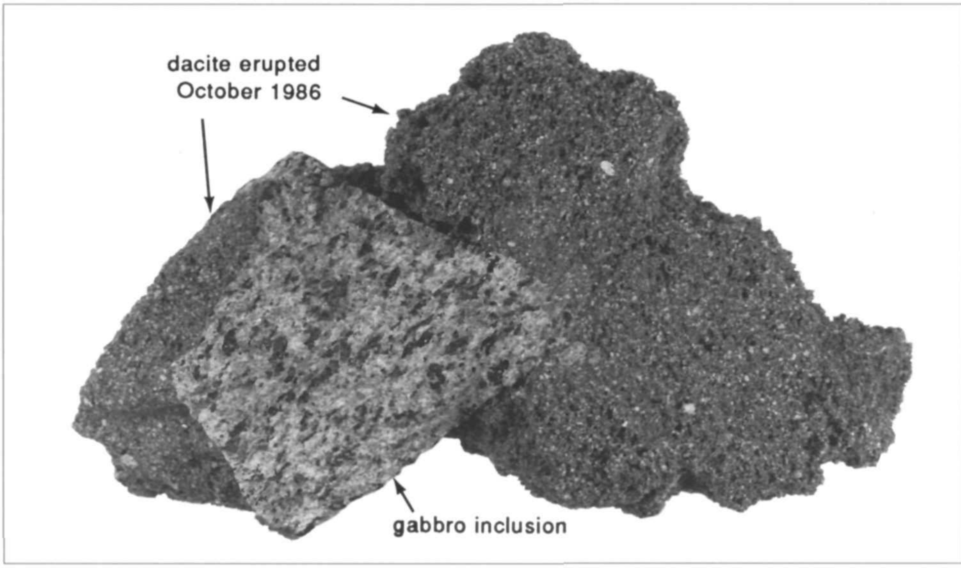


Figure 56. Fragment of Mount St. Helens dacite containing a gabbro inclusion that was incorporated into the magma as it rose in the volcano. The gabbro has a phaneritic texture (meaning that all crystals are visible), which indicates it cooled fairly slowly. The dacite has a porphyritic texture (larger crystals in a finer grained groundmass), indicating a compound cooling history. The light-colored plagioclase crystals (phenocrysts) grew as the magma was stored below the volcano; during the eruption, the darker colored groundmass chilled too quickly for large crystals to form in the liquid part of the magma.

rocks are deeply buried, squeezed by tectonic forces, or baked by nearby intrusions of molten rock. Most metamorphism of rocks in the Mount St. Helens area is "low grade" (formed in low-temperature and (or) low-pressure environments), although rocks that have been totally recrystallized, called *hornfels*, are found nearby.

In this area, the rocks that have undergone low-grade metamorphism have been partly altered to chlorite (a mica) and other clay minerals by hot fluids passing through tiny cracks in the rock mass both during and after the intrusion of magma. They typically have the greenish color of chlorite. Good examples of altered volcanic rocks are found in the Elk Rock and Johnston–Coldwater Ridge areas along SR 504, and along FRs 26 and 99

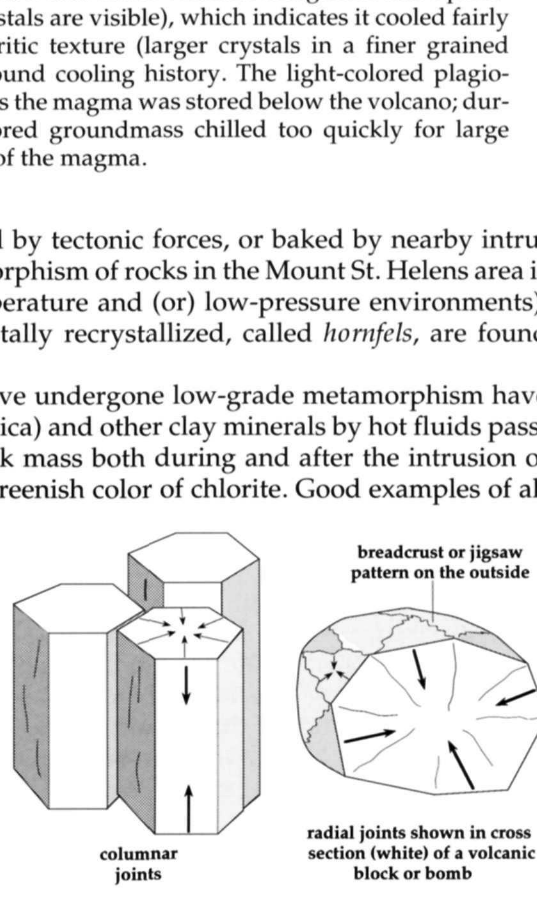


Figure 57. Sketch of columnar jointing in a lava flow and prismatic or radial jointing in a volcanic bomb/block. Small arrows show the direction of contraction during cooling; thicker arrows show the direction of cooling. Joints are caused by contraction.

where those roads enter and exit the area intruded by the Spirit Lake *pluton* or other Miocene intrusions.

GEOLOGIC TIME: THE FIRST REVOLUTION IN GEOLOGY

One of the great challenges of compiling a history of the Earth has been establishing the ages of the various rocks, sediments, and geological events. For thousands of years, people have speculated about the age of the Earth and the universe. But during the nineteenth-century, geologists observed geologic processes that suggested the Earth was older than previously accepted. They pondered the great length of time it must have taken for the Earth to cool down from an initial molten state; for salt to form in the oceans; for the formation of igneous, metamorphic, and sedimentary rocks and the upheaval of those rocks into mountains; for the erosional destruction of those mountains. Did these processes take millions, tens or hundreds of millions, or billions of years?

The Geologic Time Scale

The product of nineteenth-century geologic thought was the geologic time scale (Fig. 11), a kind of geologic calendar that reflected the vast amounts of time in the Earth's history. It was the first revolution in the science of geology. Philosophically, the concept of geologic time has probably had as big an impact on science as astronomers' discovery of the vastness of the universe and physicists' discovery of the connection between matter and energy.

The geologic time scale is divided into Eras, Periods, and Epochs on the basis of the sequential appearance of fossils and using the fundamental laws of *stratigraphy* to establish the age of one rock unit relative to another (relative age). (Geologists who study deposits of the Quaternary Period commonly use the analysis of soil development to estimate relative age.) In this guide, we will be using time terms from the Cenozoic Era because all of the rocks accessible via this road guide are of Eocene age or younger.

Radiometric Age Determination

Radiometric age determination or *radiometric dating*, developed in the early 1900s, soon became the most reliable method of establishing the absolute (as opposed to relative) age of a rock and led to the refinement of the geologic time scale. Radiometric age determination uses the nuclear decay of naturally occurring *isotopes* in geologic materials to calculate the age of the rock or crystal in years. *Potassium-argon dating*, *fission-track dating*, and *radiocarbon dating* are radiometric methods used in the Mount St. Helens area.

Potassium-Argon Dating. Potassium-argon (K-Ar) dating uses the fact that 11 percent of the potassium isotope ^{40}K in rocks disintegrates to the stable argon isotope ^{40}Ar at a constant rate (the remaining 89 percent of the ^{40}K atoms decay to ^{40}Ca). The *half-life* of ^{40}K is 142 million years, so half of the original ^{40}K will be gone in that amount of time. If the amounts of those respective isotopes in the rock are determined, the age of the rock can be estimated. However, this method does not work well for rocks younger than about 400,000 years.

Fission-Track Dating. The fission-track method estimates the age of a rock by counting the density of fission tracks, scars left by the spontaneous nuclear

Figure 58. Segment of a sanded and polished tree core showing the sequence of narrow tree rings that followed the eruption of 1800. Heavy tephra fall from this eruption (T tephra layer) traumatized the tree, causing slow growth (narrow rings) and missing rings (1801–1803?). By cross dating the ring pattern that precedes the narrow rings with that of nearby old-growth trees, dendrochronologist David Yamaguchi was able to precisely date this eruption to the period between the end of the 1799 growing season and the beginning of the 1800 growing season (marked with three dots). Photo by David Yamaguchi, University of Washington.

breakdown of uranium isotopes in a crystal. This method can be used on rocks of nearly all ages.

Radiocarbon Dating. Radiocarbon (^{14}C) dating relies on the disintegration of the carbon isotope ^{14}C to determine the age of an organic sample on the basis of an assumed natural abundance of that isotope. This method is useful for determining the age of a deposit between 35,000 and 200 years old when wood or another contemporaneous organic material can be found in the deposit.

Tree-Ring Dating. Tree-ring dating (*dendrochronology*) has been used to precisely date prehistoric lahars, eruptions, and lava flows at Mount St. Helens. This technique not only provides a detailed chronology of relatively recent events for individual volcanoes, but the greater precision also allows a better characterization of chemical trends at a volcano.

By comparing (*cross dating*) the ring patterns of trees injured by tephra falls, lahars, and lava flows (Fig. 58) with those of uninjured old-growth trees in the area, David Yamaguchi (1983) has been able to date numerous eruptive events of the past 500+ years.

PLATE TECTONICS: THE SECOND REVOLUTION IN GEOLOGY

A second revolution in the science of geology began in the early 1960s, brought about by the general acceptance of the theory of plate tectonics. This theory states that the Earth's crust is made up of rigid plates that move slowly across the surface. The plate-tectonic theory helps to explain (albeit with many unanswered questions!) the causes of volcanoes and magma; the origin of mountain ranges, *faults*, *folds*, and uplift; the origin of deep basins of sedimentary rocks; and even the origin of the Earth's magnetic field.

The notion of moving continents was first put forth by Francis Bacon in about 1620. However, the idea first became a serious scientific issue when it was postulated by a German meteorologist named Alfred Wegener in 1912. Wegener's theory of "continental drift" was widely criticized, although he had much geologic evidence in support of the idea. The theory had fallen out of favor by the time Wegener died in 1940 because he had failed to come up with a plausible explanation of what caused the continents to move. Continental drift was revived after World War II because of new evidence uncovered by the study of paleomagnetism in the rocks of the ocean floor.

Paleomagnetism: Volcanoes as Tape Recorders

Geophysicists study paleomagnetism, the natural magnetization in rocks, to determine the history of the Earth's magnetic field. Atoms in magnetite or other iron-rich minerals crystallizing from molten magma or lava orient themselves with the Earth's magnetic field just like a compass needle. As the rock solidifies, this magnetic orientation is preserved and can be detected with a sensitive instrument called a magnetometer. Under the right conditions, this magnetic alignment can also occur in sediments. Changes in the Earth's magnetic field can, therefore, be interpreted from the magnetic orientations recorded in rocks and compared with the orientation of the present magnetic field.

In 1929, a Japanese geophysicist named Motonari Matuyama published the results of his research on changes in the magnetic field. He had noticed that the magnetism of rocks generally pointed either north (like today's magnetic field) or south. He deduced that the Earth's magnetic field reverses about every few hundred thousand years. Although his theory was controversial and not accepted for many years, eventually a history of the Earth's magnetic reversals was compiled with the help of advances in the radiometric dating of rocks.

During the 1950s, technological advances made during World War II became available for more detailed studies of the ocean floor (including topography, gravity, seismic studies, heat flow, and paleomagnetism). Geophysicists on research ships towing magnetometers discovered a pattern of multiple magnetic stripes, each 12 to 18 mi (20–30 km) wide, across the sea floor. (In Figure 59, these stripes are shown in cross section.) The stripes seemed to be parallel to and symmetric across mid-ocean ridges. Meanwhile, other geophysicists were compiling data about apparently anomalous magnetic orientations in rocks worldwide. These deviations made it appear that the Earth's magnetic poles had gradually changed position. Plots of these pole positions that show this apparent movement of the magnetic poles are called "polar wandering curves".

Sea-Floor Spreading

The magnetic stripes in lavas on the ocean floor were explained in 1963 by two British scientists, Fred Vine and Drummond Matthews. They reasoned that new ocean floor was being created where lava comes up along a mid-ocean ridge (Fig. 59). As it cools, the lava records the current orientation of the Earth's magnetic field. This cooled lava breaks apart to allow new lava to erupt (and hence new sea floor to be produced). The new lava records the magnetic orientation that exists when it cools. Every several hundred thousand years, when a reversal of the magnetic field takes place, this ocean floor "tape recorder" makes a record of the

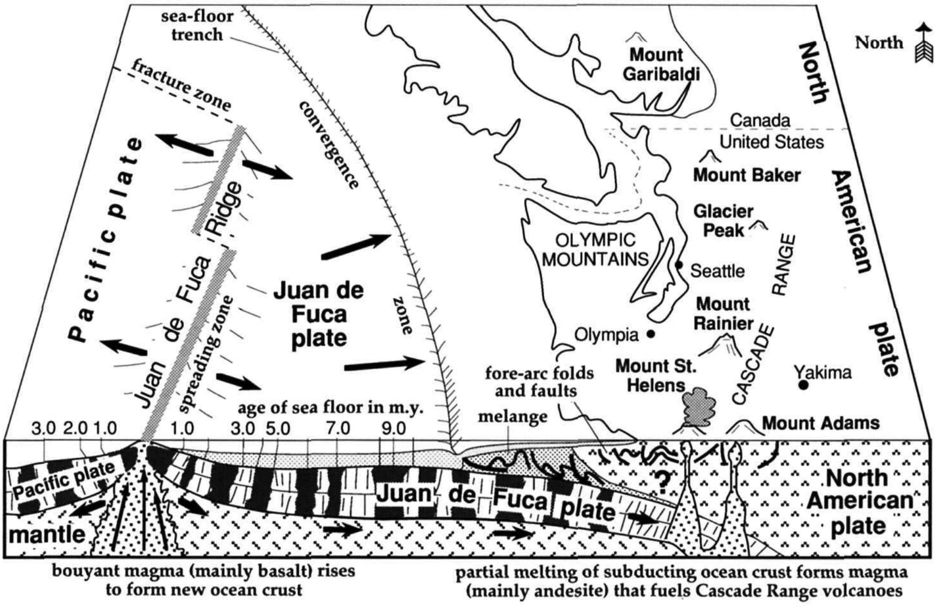


Figure 59. A diagrammatic cross section through the Juan de Fuca spreading ridge and the Cascadia subduction zone (the area from the trench east to where the Juan de Fuca plate sinks beneath the North American plate) showing the magnetic orientations of the sea floor recorded at the Juan de Fuca spreading ridge. Darker shaded areas shown in the cross section of the sea floor indicate times when rock was created with a magnetic orientation of north. Notice that the age of the ocean floor is progressively older with distance from the spreading zone. The pattern of ages approximately parallels the ridge on both sides. Melange is a jumbled mixture of continental shelf blocks and oceanic sediments that is faulted and sheared at shallow depths in the subduction zone. Fore-arc folds and faults occur in a zone of crustal deformation between the subducting sea floor and the volcanic arc. Redrawn from Foxworthy and Hill (1982) and Uyeda (1978).

change. The lava from subaerial volcanoes records magnetism in the same way. The age of the magnetized rock is determined by radiometric methods.

Although scientists do not understand why magnetic reversals take place, the dramatic movement of ocean floors, called "sea-floor spreading", could now be demonstrated by paleomagnetism. Polar wandering curves could be explained too: the mantle–ocean floor "conveyor belt" system was moving continental land masses around, changing the apparent location of the recorded ancient pole position.

Sea-floor spreading hypothesizes that ocean crust is created by upwelling magma at mid-ocean ridges like the Juan de Fuca Ridge (Fig. 59). The new crust cools and then moves away from the rift (ridge) at a rate of about an inch (several centimeters) per year. The mechanism driving the process is convection of the hot material in the Earth's mantle.

When older, cooled ocean crust (averaging 5 mi or 8 km thick) finally collides with lighter, "floating" continental crust (averaging 28 mi or 45 km thick), the ocean crust tends to sink (subduct) beneath the continental crust, carrying incor-

porated ocean sediments and water toward the mantle. *Composite volcanoes* commonly occur in regions where subduction takes place; the sinking slab of ocean-floor *basalt* and water-rich sediment melts as it sinks down into the mantle. The melted, lighter rock finds its way up through the crust along weak zones as igneous intrusions, which may fuel volcanic eruptions like those at Mount St. Helens.

The theory of sea-floor spreading gave rise to the theory of plate tectonics, which states that the Earth consists of about 10 major plates that float on the underlying mantle. The mantle acts as a conveyor belt. The conveyed oceanic crust moves the continents apart or together, slides by them, or sinks under them.

Plate tectonics solves the mystery of the youth of the ocean basins. No sea-floor material older than about 170 Ma has been found in these basins, for in that time or less the oldest ocean floor has moved across an ocean basin and been subducted under a continent.

THE ROCK CYCLE

The rock cycle is a sequence of events involving the formation, alteration, destruction, and re-formation of rocks as the result of processes such as *magmatism*, erosion, transportation, deposition, *lithification*, and metamorphism. Figure 60 diagrammatically shows changes that may occur in a rock over time in response to various geologic processes. It is easy to see that the path can be complex. Weathering and erosion can break a rock into particles and carry them away to be deposited and lithified into sedimentary rock. Or rock can be baked or squeezed to become metamorphic rock. Or totally remelted into igneous rock. Or any combination of the above!

Weathering

Weathering is any process by which rocks exposed to the atmosphere are broken down and decomposed. The two types of weathering, mechanical and chemical, work harmoniously.

Mechanical weathering comprises the physical processes that cause a rock to disintegrate, such as daily or seasonal heating and cooling, differential thermal expansion, frost action, or abrasion as rocks grind against one another.

Chemical weathering or decomposition is more complicated and includes processes in which the original rock breaks down into different chemical products. The rate of chemical weathering depends on the composition of the rock, the climate of the area, and the chemicals available. Moist climates tend to accelerate chemical weathering processes, as do volcanic *hydrothermal* systems with their corrosive fluids. The yellowish or reddish stain visible on rocks and on layers of fragmental rock in a soil is evidence of oxidation associated with chemical weathering. The weathering of geologic materials makes them more readily transportable by mechanical processes, such as erosion. Soil formation is primarily controlled by the weathering of geologic material.

Erosion and Deposition

The Cascades landscape, or any landscape for that matter, is constantly being modified by erosion and deposition. These processes, although at work everywhere, operate at different rates and with different styles depending on the local

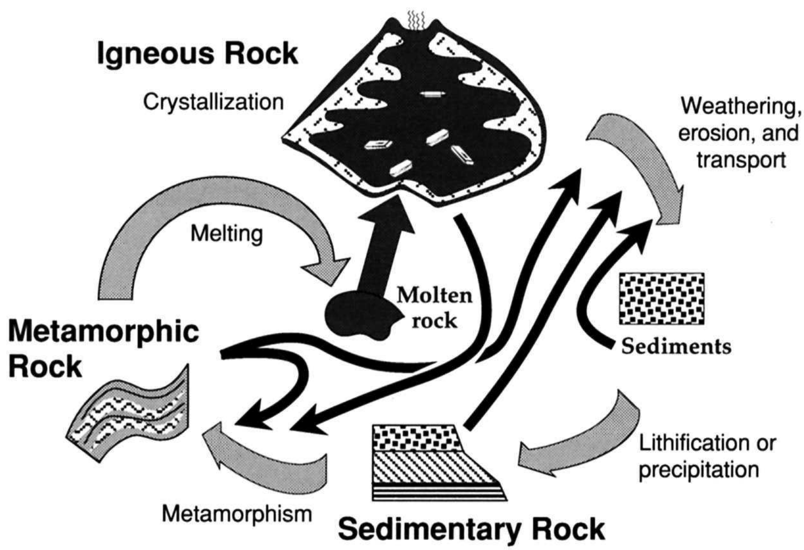


Figure 60. The rock cycle. Earth materials are continually being eroded, transported, and (or) recycled to become rock again. Redrawn from Robbins (1990).

climate and geologic material. Events that upset the equilibrium of a landscape, such as the devastating eruption of Mount St. Helens in 1980, can trigger tremendous accelerations in the rates of some natural processes. Sometimes these secondary effects, such as accelerated erosion and downstream deposition, are nearly as costly to recover from as the primary effects of an eruption.

Running water is the most significant agent of landscape change in a humid climate. Most of the precipitation that falls in the Mount St. Helens area becomes runoff, which includes sheets of water (slope wash), rills (small streams), and ultimately rivers. All forms of runoff are agents of erosion as they wear away and transport materials. They further transform the landscape by deposition of the transported debris.

River processes operate in a state of dynamic equilibrium; the interrelation of a variety of factors affects a river's form. Stream gradient or slope is the amount of drop in a given channel length. As the locations and gradients of stream channels shift through time, their overall geometry adjusts to maintain equilibrium along the entire extent of the river. The eruption of Mount St. Helens drastically upset the equilibrium of the rivers draining the area.

Pyroclastic flows and *lahars* left deposits in river valleys close to the volcano throughout their length. The *debris avalanche* filled the upper North Fork Toutle River valley with as much as 670 ft (200 m) of material, and the *blast*, pyroclastic flows, and *ash cloud* covered much of the area with highly erodible tephra deposits. These deposits changed the stream gradients, resulting in much erosion and incision on and near the volcano.

Rain and snowmelt carried the newly deposited sediments off slopes at high rates for about the first 3 years. Erosion, both downcutting and sidecutting, occurred at tremendous rates (Fig. 23) during the first 6 years following the eruption as running water carved into the thick debris avalanche and other deposits in the

North Fork Toutle River valley. This erosion choked rivers with sediment that was transported both in a state of suspension (*suspended load*) and as moving bed material (*bed load*). (See p. 43.)

Alternating episodes of erosion and deposition create alluvial *terraces*. These form where a stream cuts into sediments previously deposited in its valley. The complex array of terraces visible in the upper reaches of the North Fork Toutle valley attests to that river's struggle to re-establish equilibrium following the influx of sediments after eruptions.

Mass Movement

The movement of geologic materials under the influence of gravity is called *mass movement* or mass wasting. *Slump*, *creep*, lahars (volcanic debris flows and mudflows), *debris slides*, rockfalls, debris avalanches, and combinations of flow types are all forms of mass movement that have been particularly active in the Mount St. Helens area because of the effects of the May 18, 1980, eruption (Table 8).

Falls. Falls travel most of the distance through the air. Movement is extremely rapid and includes free fall and movement by tumbling and rolling of fragments of bedrock or soil. Rockfalls are common in Mount St. Helens crater.

Slides. Slides move by shear displacement as a unit along one or more zones of weakness, often because of the higher pore pressure of fluids with those zones. Movement along the surface may be rotational, as in a slump, or translational along a more or less planar surface. Scars from debris slides (shallow soil *slips*) commonly appear on steep slopes that have been stripped of vegetation. Numerous studies have shown that live tree roots contribute to holding the soil together and help tie the upper soil horizon to the subsoil. The 1980 tephra deposits increased runoff and surface erosion on hillslopes. This runoff and surface erosion, when combined with the decrease in tree-root tensile strength caused by

Table 8. Types of mass movement in the Mount St. Helens area. Adapted from Keller (1979)

TYPE OF MOVEMENT	TYPE OF MATERIAL		RATE OF MOVEMENT
	ROCK	SOIL	
Falls	rock falls	collapse	rapid
Slides (varied water content)	slump blocks wedge failures translational slides	slump blocks rotational slides shallow slips	varied
Flows	rock creep	soil creep	slow
	UNCONSOLIDATED MATERIALS		
	Saturated	**Dry to mostly dry**	
	plastic flows mudflows debris flows	debris avalanche	slow to rapid
Complex	combinations (earthflows)		

the stripping of vegetation and soil by the blast, has contributed to many shallow landslides in the *devastated area*.

Slumps. A slump is a type of slide where the movement is rotational, producing a rupture that is concave upward. Slumps and slump *earthflows* (Fig. 61) are common in the thick deposits of the 1980 debris avalanche and pyroclastic flows. Rapid incision into these deposits by streams has resulted in steep valley walls that are unstable. Clay-rich, *hydrothermally altered* zones within the debris avalanche deposit are especially vulnerable to *plastic flow* when saturated. If enough water is present, the material can "liquefy" and flow as a mudflow. During one such mudflow, which was triggered by a rainstorm in January 1990, a saturated mass of the 1980 debris-avalanche deposit flowed from the area of the Pumice Plain down along the North Fork Toutle River to its confluence with Coldwater Creek (6 mi or 10 km). When slumps and slump earthflows occur, they typically leave behind a steep scarp that is itself vulnerable to further slumping. Slumps also commonly occur in areas underlain by *till* and (or) glacial lake deposits (p. 21), both of which are vulnerable to plastic flow when they are saturated. Slumping commonly occurs in conjunction with the plastic flow of sediments underneath the slumping unit.

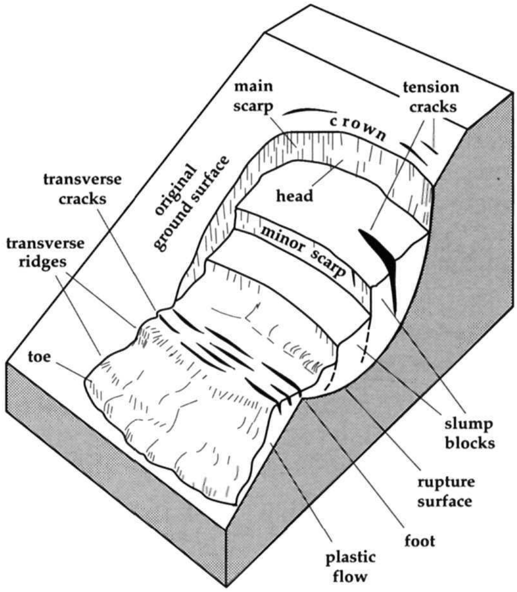


Figure 61. Sketch showing a typical slump earthflow, a complex movement involving both slump and plastic flow. Tension cracks and ridges form in response to the shape of the surface on which the flow is moving. Redrawn from Varnes (1978).

Flows. Flows move as if they were viscous fluids. Properties of flows vary according to their sediment concentration, amount and nature of clay minerals, and energy. Creep is a flow that moves at an almost imperceptible rate.

Complex movements. Complex movements are combinations of two or more of the five principal types of movements shown in Table 8, such as the slump earthflow.

VOLCANOES AND VOLCANIC PROCESSES

A volcano is a vent in the surface of the Earth (or other planet) through which magma (molten rock, called lava when it reaches the surface) and associated gases erupt. Volcano is also the term used to describe the structure produced by the material ejected through the vent. Tephra is a general term for ejected fragmental material of any size, whereas ash is defined as ejected volcanic debris that is less than 2 mm in diameter (sand size or smaller).

There are at least five types of volcanoes near Mount St. Helens. The first, typified by Mount St. Helens, is a composite volcano (also known as a stratovolcano). Composite cones are commonly associated with subduction zones. Mount St. Helens is situated on the Circum-Pacific Rim ("Ring of Fire") where subducting ocean floor sinks beneath the edges of continents and is remelted at depth (Fig. 59). Some composite volcanoes are also found in the Mediterranean–Himalayan Belt where collisions between continental plates are occurring.

Composite volcanoes can have their own individual eruptive personalities; however, they are typically characterized by the following traits:

- Their lava has an intermediate *viscosity*, which causes it to pile up and form steep slopes around the vent and to form *domes*. The lava contains about 55 to 65 percent silica, which defines it as *andesite* and *dacite*. (See Table 6, p. 94.)
- They have a moderate to high potential for violent explosions compared to volcanoes with lavas that contain less silica. (The higher the silica content of the magma, the higher the viscosity and the potential for explosive eruptions.)
- They consist of interbedded pyroclastic debris and lava flows. The ratio is generally about 50:50, but, for example, at Mount Rainier and Mount Baker the ratio is about 10:90.
- Lava flows tend to be thick: 65 to 330 ft (20–100 m).
- They generate lahars (volcanic debris flows) and debris avalanches because of the large amount of fragmental material and their steep slopes. Lahars are caused mainly by the interaction of pyroclastic debris with snow and ice, by collapse of weakened parts of the volcano, and by erosion of fragmental debris.

Glacier Peak and Mounts Adams, St. Helens, Rainier, and Baker are Washington's modern composite volcanoes. Other types of volcanoes found in the region are *calderas*, *shield volcanoes*, *cinder cones*, and maar volcanoes. The nearest postglacial shield volcanoes and cinder cones can be found at the Indian Heaven volcanic field about 18 mi (30 km) southeast of Mount St. Helens. These features are generally formed by eruptions of fluid basaltic lava. The nearest maar volcano is at Battleground Lake, about 30 mi (50 km) south-southwest of Mount St. Helens. Maars are formed by explosion of shallow superheated ground water in contact with magma: in a sense, they are larger versions of the *phreatic explosion* pits. Calderas are large, roughly circular volcanic depressions whose diameter is many times larger than the volcanic vent itself. They are typically formed by eruptions in which such a large part of the magma chamber is emptied that the volcano collapses on itself. Crater Lake, in Oregon, is the nearest postglacial caldera. Nearby relics of ancient calderas are the Fifes Peaks caldera east of Mount Rainier (not recognized as a caldera until 1991) and a possible caldera associated with the Spirit Lake pluton. Yellowstone (Wyoming) and Newberry (Oregon) calderas are the other Quaternary calderas in the Northwest.

Lava Flows and Domes

Viscous lava tends to pile up and form domes because it does not flow very readily. Lava that has a lower viscosity, such as Hawaiian basaltic lava, can flow for many miles. The main hazard from the more fluid lava flows is damage or total destruction by burying or burning everything in their path—and they can cover

Table 9. Types and characteristics of volcanic mass movements. Modified from Eisbacher and Clague (1984)

Type of movement		Temp. (°C)	Water content	Gas content	Clay content	Solid constituents	Relation to eruption
pyroclastic density current		>100 <850	low	high	low	pyroclastics	during
lahars	hot debris flow (noncohesive)	30-100	high	low	low	pyroclastics; crystalline volcanic rocks[1]	during
lahars	cold debris flow (noncohesive)	<30	high	low	low	pyroclastics, crystalline volcanic rocks[1]	during or unrelated
lahars	cold mudflow (cohesive)	<30	high	low	high	crystalline volcanic rocks; clay from hydrothermal alteration[1]	during or unrelated
rock avalanche		<30	low	low	low	crystalline volcanic rocks	during or unrelated
debris avalanche		<30	low	low	low to high	pyroclastics	during or unrelated
rockfall		<30	low	low	low	crystalline volcanic rocks	during or unrelated

[1] The solid constituents of mudflows (cohesive lahars) are mainly dust (clay and silt size), ash, and lapilli; in contrast, debris flows (noncohesive lahars) consist of both fine and coarse pyroclastic material or a mixture of such material and fragments of lava flows, domes, plugs, dikes, or sills.

very large areas. Lava flows of higher viscosity, such as the andesitic Worm Flows at Mount St. Helens, generally do not flow great distances from the volcano. Dome collapses, however, can produce hazardous pyroclastic flows and surges when the lava is still fairly hot, because of the greater tendency of their more viscous lava to fragment and turbulently interact with snow and ice.

Pyroclastic Density Currents: Flows, Surges, and Blasts

The word pyroclastic literally means "broken by fire". The general name for several different kinds of pyroclastic phenomena is *pyroclastic density currents* (Table 9). These include pyroclastic flows, surges (hot and cold), and explosive blasts (Tilling, 1989).

As the silica content of a volcano's products increases, so does the viscosity. The higher viscosity (greater resistance to flow) of magmas having a high silica content makes it more difficult for the gases driving the eruption to escape. To relieve gas pressure and move, the magma tends to blow apart to form pyroclastic flows instead of flowing cohesively as a lava flow. Typically, pyroclastic density currents have two components: a ground-hugging, basal portion (pyroclastic

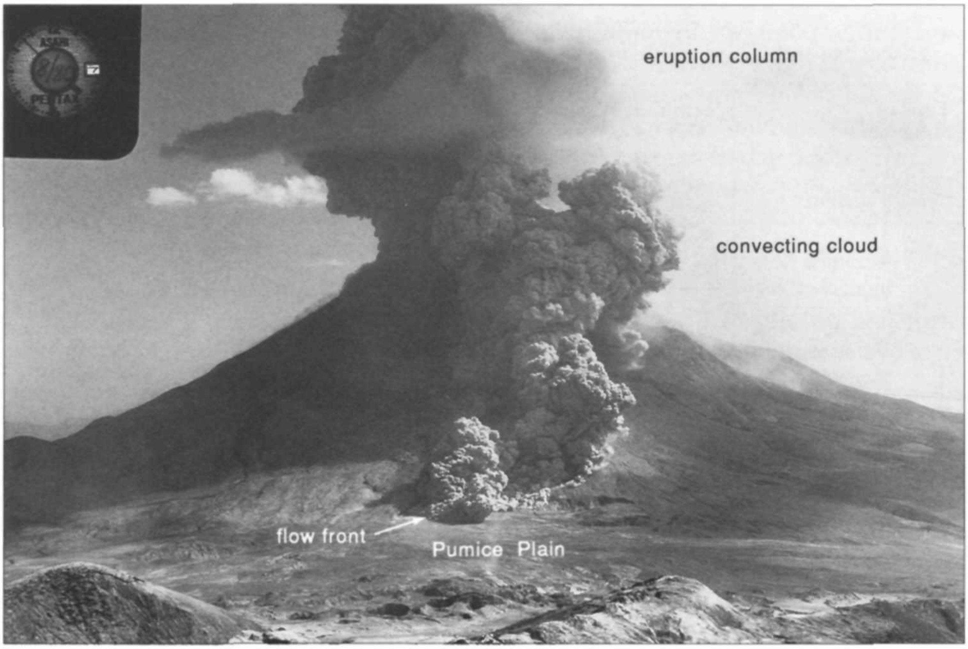


Figure 62. The August 7, 1980, pyroclastic density current at Mount St. Helens, showing a convecting cloud of ash and gas. View is to the south from Coldwater Peak, about 6.5 mi (11 km) from the crater. The photo was taken about 8 minutes after the start of the eruption, about 2.5 minutes after the main flow front exited The Breach, and about 18 seconds after it flowed onto the apex of the Pumice Plain at the base of the mountain. The average velocity of the flow for this interval was about 55 mi/hr (25 m/s). Photo by Richard Hoblitt, U.S. Geological Survey.

flow) and a turbulent *pyroclastic surge* of finer particles that rides above the flow (Fig. 62).

Pyroclastic Flows

Pyroclastic flows are masses of hot (about 570°–1470°F or 300°–850°C), fairly dry pyroclastic debris (large rock fragments) and gases that move rapidly along the ground at velocities ranging from 8 to 140 mi/hr (3.5–60 m/s) (Fisher and Schmincke, 1984). Direct hazards of pyroclastic flows are incineration, asphyxiation, impact, and burial. Pyroclastic flows can also generate lahars and floods by quickly melting snow and ice. At some volcanoes, these flows have dammed tributary valleys to form lakes or have started fires. Pyroclastic flows are strongly controlled by topography and are usually restricted to valley floors. Most pyroclastic flows from composite volcanoes travel less than 15 mi (25 km) from the vent.

Pyroclastic Surges

Pyroclastic surges are hot, turbulent clouds of finer particles that ride above, and develop from, a pyroclastic flow. Surges are driven by gases and heat escaping a flow. They have a lower concentration of particles than flows and can affect larger areas. Pyroclastic surges can travel many tens of miles or kilometers from the

volcano and are not necessarily confined to the valleys. Hot pyroclastic surges can generate secondary pyroclastic flows like the one down the valley of South Coldwater Creek during the 1980 eruption. (See p. 59.) Surges are responsible for many catastrophes, including 30,000 deaths at Mount Pelée in Martinique, West Indies (1902), and 2,000 at El Chichón in Mexico (1982).

Blasts (Blast Density Flows)

Blasts or blast density flows are very powerful laterally directed explosions such as those at Mount St. Helens in 1980 and at Bezymianny, Kamchatka, in 1956. As demonstrated at Mount St. Helens, this type of explosion can affect a large area (216 mi^2 or 600 km^2). Debris carried by the blast (the "stone wind") can flatten trees and plane off nearly everything in its path.

Lahars: Volcanic Debris Flows and Mudflows

Lahars are debris flows or mudflows, rapidly flowing mixtures of rock debris and water that originate on the slopes of a volcano. They can be cold or carry hot pyroclastic material. Lahars are one of the greatest hazards at composite volcanoes because they can travel great distances from the volcano, placing people living in valleys draining the volcano at risk.

Composite volcanoes have all the necessary ingredients for lahars. Their average silica composition (andesite–dacite range) yields a moderately explosive magma of relatively high viscosity that produces a significant amount of fragmental debris. The resulting steep-sided volcanic pile is extremely vulnerable to slope failures and collapse, especially where rocks have been weakened by hydrothermal activity. In hydrothermal action, a combination of heat and acids and salts in solution alters volcanic deposits to clay minerals. Clay minerals act as a lubricant and lower the stability of the volcano's slopes. Volcanoes at which hydrothermal alteration occurs are typically those with large amounts of snowpack and glacial ice, a source of water ready to be melted during an eruption.

The driving force in a lahar is gravity. In a normal river flood, the water is carrying individual rock particles along. In a lahar, the particles are so concentrated that they flow downslope en masse carrying the water. Lahars are restricted to stream valleys, although some lahars that have very large volumes can pass over topographic barriers under rare circumstances.

Noncohesive Lahars

Lahars with a low clay content (less than 4 percent) typically begin as a flood surge that incorporates enough sediment to become a debris flow. They can transform downstream to more diluted flow types such as *lahar-runout* flows and floods. These flows are sometimes called noncohesive lahars. The South Fork Toutle and Muddy River lahars of 1980 (Fig. 63) were formed when hot pyroclastic material melted snow and ice. The causes of noncohesive lahars can include:

- Interaction of a pyroclastic density current with snow and ice
- Severe rainstorms and (or) rapid snowmelt that causes erosion of tephra (or other fragmental debris) or landslides from the slopes of a volcano
- Flood caused by failure of a landslide-dammed lake on a volcano's flank
- Glacial *outburst flood* (jökulhlaup) on a volcano's flank

Figure 63. Coatings of mud, sand, and fine gravel left on tree trunks and rocks by the May 18, 1980, Muddy River lahar show its depth (about 40 ft or 12 m). Person on the bank (arrow) for scale. Arrow also shows direction of flow. Photo taken in 1980 by Lyn Topinka, U.S. Geological Survey.

Cohesive Lahars

Lahars rich in clay-sized particles (more than 4 percent) are sometimes called mudflows or cohesive lahars. *Cohesive lahars* can originate when an entire sector or sizeable mass of a volcano collapses or slides away. This might be triggered by regional or *volcanic earthquakes*, steam explosions, or by means other than eruptions. Cohesive lahars can have huge volumes and flow great distances without undergoing significant dilution. The Electron and Osceola Mudflows at Mount Rainier and the Middle Fork Nooksack flow at Mount Baker are examples of fairly clay-rich lahars. The Osceola Mudflow had a volume of at least 0.6 mi^3 (3 km^3) and flowed more than 60 mi (100 km) from Mount Rainier. An ancient cohesive lahar from Mount Hood crossed the Columbia River. The 1980 North Fork Toutle mudflow was a cohesive lahar. (See p. 30.)

GLACIERS AND GLACIAL DEPOSITS

A glacier is a large mass of ice that moves slowly downslope and spreads (where not constrained) under the force of its own weight. Glaciers are formed by the compaction and recrystallization of snow (Fig. 64). When an ice mass develops enough depth and weight, it deforms (becomes plastic) and can begin to move. Two signs of glacier movement are *crevasses* and *rock flour*. A crevasse is a deep fissure or crack in the ice caused by the glacier's movement over an uneven surface.

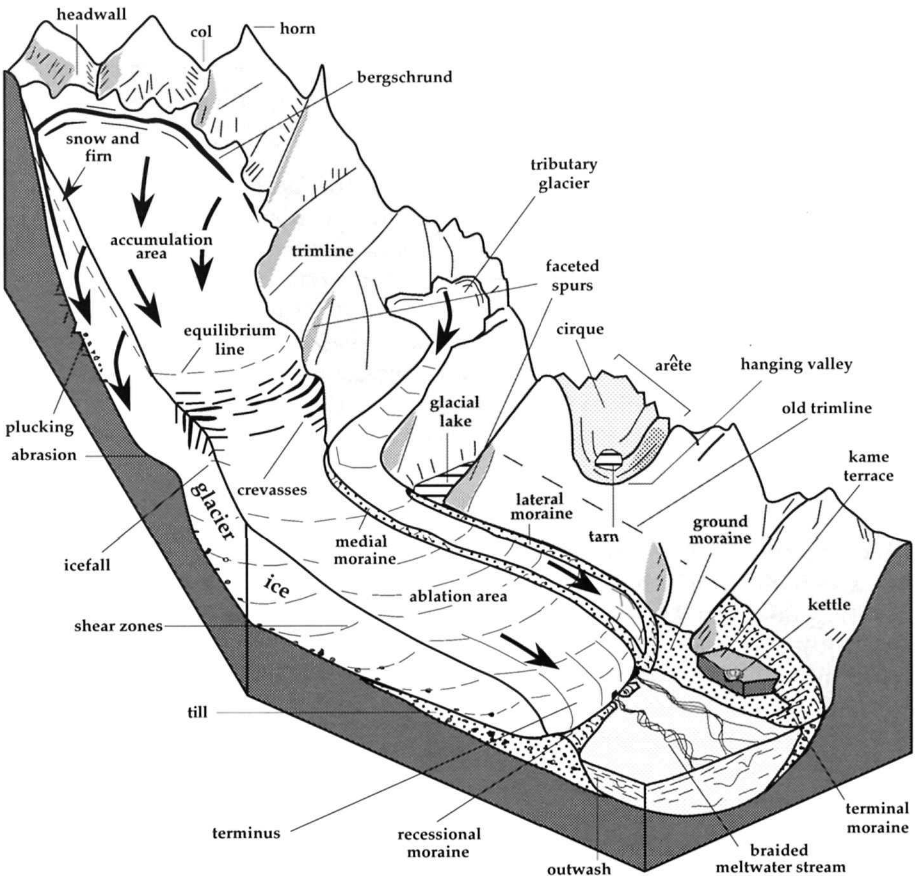


Figure 64. Oblique cross-sectional sketch showing structural and depositional features of a valley glacier, including zones of snow and ice accumulation and ablation and alpine erosional features. Redrawn from Skinner and Porter (1992).

The turbid, white meltwater from a glacier contains finely crushed or ground rock particles (rock flour) in suspension.

Glaciers have radically modified the Cascades landscape. Figure 64 shows the structural and depositional features of an alpine glacier. Piles of debris called *moraines* form at the terminal and lateral edges of the ice when a glacier has occupied the same location for some time. Terminal moraines that cross stream valleys are particularly vulnerable to erosion. Moraines are eroded away like any other sedimentary deposit; commonly only fragments of the moraine are preserved along the edges of valleys.

Till is a glacial deposit formed under, in, or on a glacier. Stratified drift includes bedded deposits consisting of layers of glacial material deposited as *outwash* from a melting glacier or deposited in quiet water adjacent to a glacier. The effects of glacial erosion on rock include smoothing, gouging, and glacial *striations*. Striking examples of glacial erosion are exposed along the Harmony Trail (Fig. 49).

GEOLOGIC STRUCTURES IN THE MOUNT ST. HELENS AREA

About 18 million years ago, localized compression of the Earth's crust began to fold and fault the rocks of the Cascades. That process may still be going on today.

Folds

Folds are curves or bends in the rock strata. Folds that arch upward in the middle are called *anticlines* and those that are bowed downward, *synclines* (Fig. 65). While driving through the Mount St. Helens National Monument and adjacent areas, you will pass along or across the axes of several broad anticlines and synclines. West of Mount St. Helens these structures trend northwest, whereas east of the volcano they trend nearly north. The Lakeview Peak anticline, west of Mount St. Helens, plunges downward at both its northwest and southeast ends, giving the anticline a sort of whaleback look. This configuration suggests a minor component of crustal compression has, at some time, been parallel with the fold as well as perpendicular to it.

Faults

Faults are fractures in rock along which movement has occurred (Fig. 66). They are the result of brittle failure of rock. No major faults are visible in outcrop within the monument. However, offsets along small faults can be seen in several roadside outcrops and in the back country. (See mile 25.0, p. 45.) Generally, these have displacements of only a few meters at most. Smoothly polished and grooved surfaces called *slickensides* are visible in some zones of faulting.

Normal fault. A *normal fault* is a steeply dipping fault in which the hanging wall has moved downward relative to the footwall. The dip of the fault plane is usually between 45° and 90°).

Reverse fault. A reverse fault is a steeply dipping fault in which the hanging wall appears to have moved upward relative to the footwall. The dip is usually greater than 90°).

Thrust fault. A *thrust fault* is a low-angle fault (less than 45°),

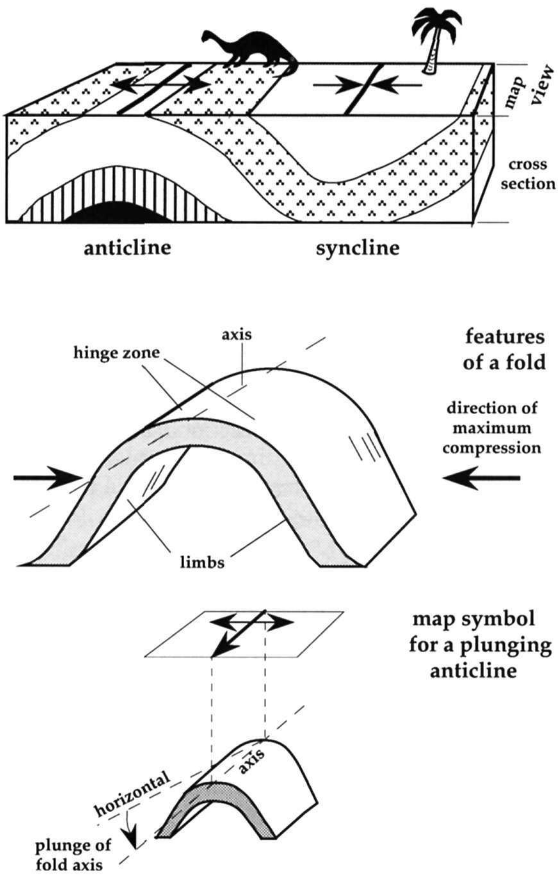


Figure 65. Sketch showing the features of synclines and anticlines and the map symbols for each.

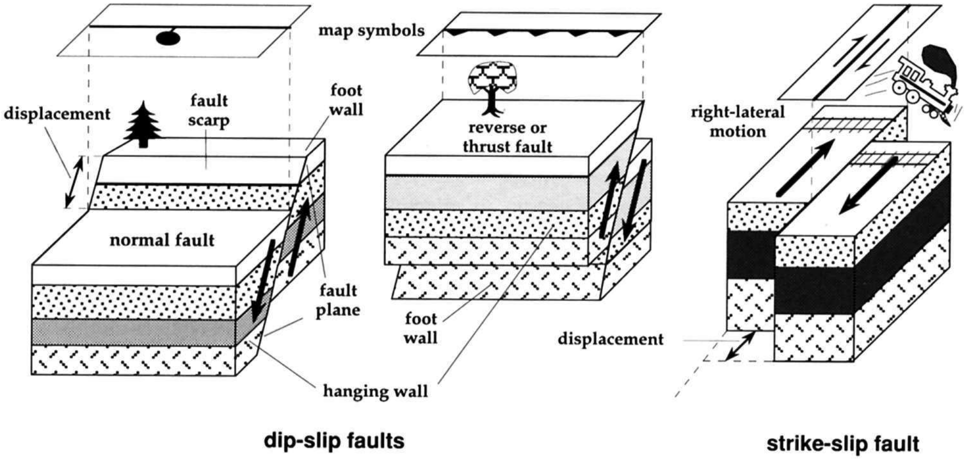


Figure 66. Types of faults in the Mount St. Helens area.

typically caused by horizontal compression, in which the hanging wall has moved upward relative to the footwall. Small thrust faults in the crater floor were used in the early 1980s to monitor the deformation that preceded extrusion of lava from the dome. (See Fig. 20 and discussion on p. 33.) Slickensides on lava dome rocks indicate that similar brittle failure takes place within, or immediately under the dome.

Strike-slip fault. A *strike-slip fault* is a fault in which displacement occurred parallel to the strike of the fault plane, that is, sideways instead of up and down.

Fault Zones

The Chelatchie Prairie fault zone is an east-northeast-trending *normal fault* system a few kilometers south of, and generally parallel to the Lewis River. Tumtum Mountain is situated on this fault zone. Rocks north of faults in the zone have dropped downward with respect to the rocks on the south side. Geologists have not noted any recent activity on this fault zone.

The *St. Helens zone* is a north-northwest-trending zone of active seismicity that extends for about 80 mi (130 km) and passes through Mount St. Helens. (See the various road-guide maps.) This seismic zone is apparently a series of strike-slip faults that are related to the collision between the North American plate and the Juan de Fuca plate. The St. Helens zone and nearby faults create a zone of weakness in the crust that probably controls the location of the vent that feeds Mount St. Helens as well as the vents of the Marble Mountain–Trout Creek Hill volcanic zone to the south.

A strong (*magnitude* 5.1) earthquake occurred along the St. Helens zone in 1981. The epicenter was near Elk Lake, about 10 mi (15 km) north-northwest of the Mount St. Helens crater. Seismologists have estimated that this fault zone could generate an earthquake as large as magnitude 6.2 to 6.8—depending on the length of the fault segment that ruptured.

PART IV: REFERENCES, GLOSSARY, AND UPDATE

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GLOSSARY

ablation – the loss of snow and ice from a glacier due to melting, erosion, evaporation, or sublimation.

accretion – that process by which one terrane, a fault-bounded body of rock of regional size, is attached to another having a different history. Typically accretion occurs during tectonic collision.

accretionary lapilli – a mass of cemented ash 1-10 mm in size.

alluvium – a general term for stream deposits.

amphibole – a group of dark, rock-forming ferromagnesian silicate minerals; for example, hornblende.

andesite – a fine-grained extrusive igneous rock generally containing abundant plagioclase, lesser amounts of hornblende and biotite, little or no quartz; 54 to 62 percent silica.

anticline – a convex-upward fold having stratigraphically older rocks in its core.

ash – see *volcanic ash*.

ash cloud – an eruption cloud of volcanic gas and fine particles.

basalt – a fine-grained volcanic rock, typically dark, that contains 45 to 54 percent silica.

bed load – sediment, such as cobbles, pebbles, and granules, that is transported along the bed of a river but is not in suspension.

biotite – "black mica"; a common mafic mineral.

blast – the enormous volcanic explosion and pyroclastic density current on May 18, 1980.

blast dacite – the bluish-gray to gray rocks, chilled pieces of the cryptodome, that were erupted in the blast on May 18, 1980.

blast density flow – see *blast*.

blast zone – see *devastated area*.

breadcrust bombs – volcanic bombs that have a breadcrust-like (open cracks) texture on their outer surface caused by contraction during sudden cooling.

breccia – a rock composed of coarse, angular fragments in a matrix of finer particles.

calcite – a common mineral composed of calcium carbonate ($CaCO^3$).

caldera – a large, typically steep-sided, volcanic basin produced by collapse of an underlying magma chamber.

cinder cone – a fairly small, cone-shaped volcanic vent consisting mainly of accumulated cinders and other pyroclastic fragments.

cirque – a glacially carved, horseshoe-shaped hollow at the head of a valley.

clast – general term for any fragment or individual piece of rock.

coal – a black, combustible sedimentary rock formed by compaction of plant matter.

cohesive lahar – a volcanic debris flow or mudflow that contains more than 4 percent clay minerals in its matrix.

composite volcano – a steep-sided volcano consisting of alternating layers of lava and pyroclastic debris. A stratovolcano.

conglomerate – a coarse-grained sedimentary rock consisting of rounded rocks cemented together in a finer matrix.

contact metamorphism – a type of recrystallization or change in rocks that takes place adjacent to a magma body; also known as "thermal metamorphism".

creep – slow downhill movement of surficial materials (such as soil).

crevasse – a deep fissure in the surface of a glacier.

cross dating – a method of matching tree rings that uses the known patterns or characteristics of tree rings in an area to precisely date wood or trees such as those buried in volcanic deposits or injured by volcanic activity.

cryptodome – the near-surface intrusion of magma that produced the pre-May 18, 1980, bulge in the north flank of Mount St. Helens.

dacite – a fine-grained extrusive igneous rock typically having 62 to 69 percent silica.

debris avalanche – a granular flow of unsorted rock debris that typically moves at high velocity.

debris flow – a moving mass of debris, typically saturated.

debris slide – a shallow mass movement of the soil layer or other geologic material.

dendrochronology – the scientific study of tree rings.

devastated area – the area of downed and singed vegetation created by the volcanic events at Mount St. Helens on May 18, 1980.

dike – a tabular intrusive rock body that forms where magma cuts across the bedding planes of other rock bodies.

diorite – a coarse-grained intrusive igneous rock having roughly the same chemical composition as andesite (54 to 62 percent silica).

discharge – the rate of stream flow at a given time in units of volume per unit of time (ft^3/s or m^3/s).

dome – see *volcanic dome*.

drift – a general term for any glacial deposit.

earthflow – a type of mass movement that typically takes place along well-defined failure planes and may involve more than one failure process, such as slumping and plastic flow.

faceted spur – the end of a ridge that has been ground down by the action of ice or water.

fault – a fracture along which a rock mass has been displaced.

feldspar – a common rock-forming mineral group consisting of silicates of aluminum, sodium, potassium, and calcium.

ferromagnesian minerals – silicate minerals such as olivine, pyroxenes, and amphiboles, that contain considerable amounts of iron and magnesium.

firn – a material that is transitional between snow and glacier ice.

fission-track dating – a method of determining the age of a rock based on the number of tracks recording emission of subatomic particles during radioactive deterioration.

flood basalt – plateau basalt; the lava produced by enormous fissure eruptions, such as the Columbia River basalt flows.

flow breccia – a deposit of angular rock fragments, some of which are welded together, that is produced in association with a lava flow.

fold – a bend in a rock stratum or layer.

fumarole – a volcanic vent that emits gases.

gabbro – a coarse-grained intrusive igneous rock consisting mainly of calcium-bearing plagioclase and pyroxene minerals and having roughly the same chemical composition as basalt (45 to 54 percent silica).

glacier – a mass of ice, mainly recrystallized snow, that is heavy enough to move under its own weight.

granite – a coarse-grained intrusive igneous rock composed of potassium feldspar, plagioclase, quartz, and some mafic minerals; more than 69 percent silica.

granodiorite – a coarse-grained intrusive rock, similar to a granite, in which plagioclase minerals are more common than potassium feldspar; 62 to 69 percent silica.

groundmass – the fine-grained matrix of a porphyritic igneous rock.

half-life – the time required for half of the atoms in a sample of a radioactive isotope to decay.

heavy mineral – slang for ferromagnesian or mafic minerals.

hornblende – a mafic mineral of the amphibole group.

hornfels – a fine-grained metamorphic rock formed by recrystallization.

hydrothermal activity – the migration of hot, typically mineral-rich fluids produced by magma or by reactions of magma with adjacent rocks and (or) ground water.

hydrothermal alteration – the alteration of rocks or minerals owing to contact with hydrothermal waters.

igneous rock – a rock formed by the cooling of magma.

intrusive rock – an igneous rock that solidifies under the surface of the Earth.

isotope – one of two or more forms of an element having different atomic weights.

joint – a fracture in a rock along which movement has not occurred.

juvenile material – volcanic rocks derived directly from magma that has reached the surface.

K-Ar dating – see *Potassium-Argon dating*.

lahar – general term for a volcanic debris flow, a moving mixture of pyroclastic material and water that originates at a volcano.

lahar runout – the muddy flood caused by dilution of a lahar as it mixes with streamwater. The deposits are typically very sandy and have fewer large rocks than lahar deposits.

lapilli – volcanic particles in the range of 2 to 64 mm.

lateral blast – see *blast*.

lateral moraine – an accumulation of till along the sides of a glacier where it meets the valley wall.

lava – magma that reaches the Earth's surface.

levee – an area of deposits marginal to a flow that roughly records the maximum height of the flow.

lithic pyroclastic flow – a pyroclastic flow that contains a significant percentage of previously formed rock fragments mixed in with the juvenile rocks.

lithification – the process by which sediment is converted into solid rock.

mafic rock – a rock that contains more than 50 percent ferromagnesian minerals.

magma – molten rock; can contain liquids, gases, and crystals.

magmatism – the formation and movement of magma.

magnitude – a scale for measuring the energy released by an earthquake.

mass movement – the movement of geologic materials downslope under the influence of gravity.

mass wasting – see *mass movement*.

metamorphic rock – a rock whose composition and (or) texture has changed because of heat and (or) pressure.

mineral – a naturally formed solid chemical substance having a fixed crystal structure and range of chemical compositions.

moraine – a landform composed of till or drift.

mudline – the maximum level of inundation by a lahar or flood based on the height of mudmarks on trees or rocks. See Fig. 63.

normal fault – a steeply dipping fault in which the hanging wall has moved downward relative to the footwall. See Fig. 66.

outburst floods – jökuhlhaups; sudden releases of water stored in or adjacent to a glacier or in a glacial lake.

outcrop – an exposure of rock or a deposit.

outwash – stratified deposits produced by glacial meltwater.

pahoehoe – [pä.hoy'.hoy] a Hawaiian term for basaltic lava flows having a smooth or ropy surface.

phenocryst – a large individual crystal in a porphyritic igneous rock.

phreatic explosion or eruption – an explosive mixture of steam and fine rock debris produced when water contacts hot rock.

plastic flow – change in shape of a solid that takes place without rupture.

Plinian column – a strong, turbulent, and sustained vertical eruption column.

pluton – the cooled body of a large intrusive igneous rock mass.

porphyritic – a texture of igneous rock in which coarse mineral crystals are scattered among finer grains and (or) glass.

porphyry copper deposit – a type of hydrothermal mineral deposit associated with plutons that contains associated copper minerals.

potassium-argon dating – the radiometric determination of the age of a rock sample based on the ratio of argon-40 to potassium-40.

proglacial – immediately in front of or just beyond the limits of the glacier.

pumice – solidified rock froth; a porous volcanic rock that floats.

pyroclastic density current – a general name for any of the mixtures of volcanic gas and particles (including surges and flows) that move downslope on the flanks of a volcano under the influence of gravity. See Table 9.

pyroclastic flow – a mass of hot, dry, pyroclastic debris and gases that move rapidly along the ground surface. They can be caused by an eruption or collapse of a dome.

pyroclastic surge – a turbulent, mixture of gases and particles that flows above the ground surface at high velocities. It can develop from a pyroclastic flow and is highly mobile.

pyroxene – a group of mafic silicate minerals.

Quaternary – the geologic period lasting from about 1.7 Ma to the present. It consists of the Pleistocene Epoch (ending about 10 ka) and the Holocene (10 ka to present).

radiocarbon dating – the calculation of the age of geologic material by any of the methods based on nuclear decay of natural radioactive elements in carbonaceous material.

radiocarbon years – years before 1950 (by convention) based on the proportion of the 14C isotope to normal carbon atoms. Typically radiocarbon years differ from "calendar years" because of variations of the carbon isotope content of atmospheric carbon dioxide through time. A calibration to adjust these ages on the

basis of tree rings (for about the last 8,000 years) has been devised; however, for simplicity, only the raw radiocarbon ages are presented in this guidebook. For the most part, these ages do not differ radically from actual calendar years. Tree-ring dates for Mount St. Helens deposits laid down since A.D. 1480, however, are given in calendar years.

radiometric age – see radiometric dating.

radiometric dating – a method of estimating the age of a rock or mineral by measuring the proportion of radioactive elements to their decay products in a rock sample.

raveling – erosion involving the movement of individual rocks and grains down a slope.

rock flour – fine rock particles produced by glacial pulverization.

rootless explosion crater – small, shallow craters produced by phreatic explosions.

St. Helens zone – a linear zone of earthquake activity that extends from north of Mount St. Helens through the volcano almost to the Columbia River.

scoria – an igneous rock containing abundant cavities (vesicles) but which does not float.

shield volcano – a large, broad volcano having fairly shallow slopes formed by the eruption of highly fluid basalt lava.

sill – a tabular intrusive rock body that forms where magma is injected between two layers of rock.

singe zone – the zone at the periphery of the devastated area in which trees were scorched or damaged but not blown down.

slickensides – striated or polished surface of a rock produced by abrasion along a fault.

slips – debris slides.

slosh line – see *trimline*.

slump – a type of mass wasting in which blocks of material fail with a backward rotational motion.

snag – the trunk of a dead tree.

stratigraphy – the study of strata, its succession and composition, fossils and other characteristics.

striation – a scratch or groove on a rock produced by the passage of a glacier or other geologic agent.

strike – the bearing or azimuth along which a fault or fold or other planar feature is oriented.

strike-slip fault – a fault in which displacement has been parallel to the strike of the fault. See Fig. 66.

suspended load – fine sediment carried in suspension by a river.

syncline – a fold that is concave upward, like a trough.

talus – rock debris, typically coarse, that accumulates at the base of a cliff or slope.

tarn – a small mountain lake that occupies a cirque.

tephra – a general term for all sizes of rock and lava that are ejected into the air during an eruption.

terrace – a long, narrow, nearly flat surface that forms a step-like bench in a slope.

terrane – a large block of the Earth's crust, bounded by faults, that can be distinguished from other blocks by its geologic character.

Tertiary – the geologic period lasting from about 67 Ma to 1.7 Ma.

thrust fault – low-angle fault (less than 45°) in which the hanging wall has moved upward relative to the footwall; typically caused by horizontal compression.

till – an unsorted glacial deposit produced directly under, within, or on top of a glacier.

transform fault – strike-slip faults that separate major geologic plates or plate segments.

trimline – boundary between the area affected by scour or scrape and undisturbed terrain that denotes the maximum height of runup or inundation by an avalanche, debris flow, flood, wave, or glacier.

tuff – a fine-grained rock composed mostly of volcanic ash.

valley glacier – a glacier that heads at a cirque or cirques and then flows into, and is confined by, a valley; an alpine glacier.

viscosity – resistance to internal flow.

volcanic arc – a curved belt of volcanoes and volcanic rocks associated with a subduction zone.

volcanic ash – fine-grained pyroclastic particles (less than 2 mm in diameter).

volcanic dome – a steep-sided bulbous mass of lava, such as the Lava Dome, that is commonly formed by eruptions of highly viscous dacite or rhyolite lava.

volcanic earthquakes – the sudden release of strain energy under or in a volcano as magma or volcanic gas pushes its way to the surface.

volcaniclastics – a general name for all fragmental material produced by a volcano.

vug – a cavity in a vein or rock. Some vugs are lined with crystals. ■

UPDATE 1993–2001

Since the second printing of this book (1993), the Spirit Lake Highway (SR 504) has been completed to the new Johnston Ridge Observatory (JRO). Along SR 504 several other new facilities are available for visitors and new hiking trails have opened, such as the Hummocks Trail and Winds of Change Trail. These trails allow the visitor to observe the deposits and effects of the 1980 eruption and to witness the ecosystem recovery and post-disturbance landscape adjustments.

This update describes or lists: post-1993 road changes and new trails, volcanic and geomorphic activity at the volcano since 1993, a growing glacier in the crater, results of selected new geological research at the mountain, as well as citations and books that may help visitors, new references and further reading, selected internet resources.

Road Changes and New Trails

SR 504 now extends 8 mi (13 km) past Coldwater Creek to the top of Johnston Ridge and the spectacular Johnston Ridge Observatory (JRO). JRO hosts interpretive programs and exhibits and an unparalleled view of Mount St. Helens, the effects of the 1980 and subsequent eruptions, and ecosystem recovery (Fig. 34, p. 57). Along the new Hummocks Trail (p. 52), visitors can hike among the gigantic chunks of the debris avalanche, the world's largest historic landslide deposit. Those who revisit the Hummocks Trail periodically will see geomorphic changes, such as slumping and erosion of the debris avalanche, and channel changes of the North Fork Toutle River. The hummocks and the ponds among them are also of interest because of the nature of the vegetation and ecosystem recovery taking place there.

Volcanic and Geomorphic Activity Since 1993

Mild background seismic activity has continued since 1993, with noteworthy episodes of increased activity in the spring and summer of 1998 and the fall of 2001. The level of earthquake activity at Mount St. Helens had been gradually increasing in early 1998 and accelerated during May, June, and early July 1998. Rates of activity increased from an average of about 60 well-located events per month in January 1998 to 318 in June and 445 in July. Most of these earthquakes were very small, with only three events exceeding magnitude 2. The largest earthquake was on 1 May, at magnitude 2.2. These earthquakes occurred in two clusters directly beneath the lava dome in the crater. One cluster was at 1.2 to 3.1 mi (2–5 km) depth and the other 4.4 to 5.6 mi (7–9 km) below the dome. Airborne surveys of volcanic gases have revealed the discharge of magmatic carbon dioxide at a rate of about 2000 tons/day. Under high pressure deep within Earth's crust, carbon dioxide is dissolved in magma.

The 1998 seismic activity seems to be similar to that which occurred in 1995, although the activity of May 1998 was more energetic. The 1995 activity lasted for several months, had a maximum earthquake rate of 95 events per month, and resulted in no volcanic activity. Earthquakes returned to background levels by August 1998. A similar increase in earthquake activity in the St. Helens system occurred from 1989 to 1991. However, at that time there were also a number of very

Figure 67. Aerial-oblique photograph of the Lava Dome and growing glacier in the Mount St. Helens crater. View is to the southwest. Note the crevasses visible on the far right side of the photograph. This snow, ice, and rock glacier is now more than 500 ft (~150 m) thick, which is more than half the height of the 876-ft-tall (267 m) Lava Dome. Photo courtesy of Jon Major (USGS), 2001.

shallow earthquakes accompanied by a series of sudden steam explosions. These explosions ejected rocks and ash from cracks in the dome. Rocks were thrown as far as 0.6 mi (1 km) from the dome, ash clouds reached altitudes of 3.7 mi (6 km), and a dusting of ash was deposited locally downwind. By the end of 1998, earthquake activity had subsided to background levels of less than five events per day, but future earthquake episodes could lead to steam emissions or another eruption of the volcano.

A Growing Glacier in the Crater

In the 1993 edition of this book, I mentioned that a small glacier was growing in the crater south of the Lava Dome (Fig. 15). That body of rock, ice, and snow has continued to grow throughout the 1990s and is now more than 500 ft (~150 m) thick (Fig. 67) and has a volume greater than 100 million yds^3 (76 million m^3)(Hill, 2001; Schilling and others, 2002). Mills and Keating (1992) suggested that rock debris made up a significant fraction of the material accumulating on the crater floor. U.S. Geological Survey scientists estimate that rock may account for about one-third of the volume of the new glacier. The new glacier is a source of perennial water that will contribute to the ground water in the volcano and also be available for incorporation into future lahars.

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Selected Internet Resources (as of April 2002)

Cascade Volcano Observatory	http://vulcan.wr.usgs.gov/
DNR Division of Geology and Earth Resources	http://www.wa.gov/dnr/htdocs/ger/
Mount St. Helens National Volcanic Monument	http://www.fs.fed.us/gpnf/mshnvm/
Mount St. Helens Institute	http://www.mshinstitute.org/
Mount St. Helens seismicity	http://spike.geophys.washington.edu/SEIS/PNSN/HELENS/

First walk on the Mount St. Helens crater rim after the 1980 eruption. The crater rim can now be reached by several popular climbing routes (Beckey, 1987; Phillips, 1987). Climber is the late Dick Janda, to whom this book is dedicated. Photo taken in the fall of 1983 by Barry Voight, Pennsylvania State University.

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ROADSIDE GEOLOGY OF MOUNT ST. HELENS

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